JPRS L/9725

11 May 1981

USSR Report

ELECTRONICS AND ELECTRICAL ENGINEERING

(FOUO 5/81)

FBIS FOREIGN BROADCAST INFORMATION SERVICE

NOTE

JPRS publications contain information primarily from foreign newspapers, periodicals and books, but also from news agency transmissions and broadcasts. Materials from foreign-language sources are translated; those from English-language sources are transcribed or reprinted, with the original phrasing and other characteristics retained.

Headlines, editorial reports, and material enclosed in brackets [] are supplied by JPRS. Processing indicators such as [Text] or [Excerpt] in the first line of each item, or following the last line of a brief, indicate how the original information was processed. Where no processing indicator is given, the information was summarized or extracted.

Unfamiliar names rendered phonetically or transliterated are enclosed in parentheses. Words or names preceded by a question mark and enclosed in parentheses were not clear in the original but have been supplied as appropriate in context. Other unattributed parenthetical notes within the body of an item originate with the source. Times within items are as given by source.

The contents of this publication in no way represent the policies, views or attitudes of the U.S. Government.

JPRS L/9725

11 May 1981

USSR REPORT

ELECTRONICS AND ELECTRICAL ENGINEERING

(FOUO 5/81)

CONTENTS

CERTAIN ASPECTS OF PHOTOGRAPHY, MOTION PICTURES AND TELEVISION

UDC 621.385.832.564.4(088.8)(47)

VIDICON TARGET

USSR Patent Class H 01 J 29/36, No 2,543,928 17 Mar 80 (disclosure No 721,865 15 Nov 77)

MATVEYEV, V. G. and TAZENKOV, B. A.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1A110 P]

[Text] The vidicon target consists of a translucent dielectric substrate with a photoconducting layer. In order to increase the signal multiplicity and the sensitivity while reducing the inertia, a reticular electrode is deposited on the substrate on the side of the photoconducting layer and this layer contains a mosaic of conducting electrodes which pass across it, each aligned with the center of a cell of the reticular electrode.

[177-2415]

ELECTRICAL ENGINEERING EQUIPMENT AND MACHINERY: APPLICATIONS AND THEORY

UDC 621.316.54.001.4

STUDIES OF THE OVERLOAD CAPACITY OF HIGH-VOLTAGE BREAKERS

Moscow ELEKTROTEKHNIKA in Russian No 1, Jan 81 pp 56-57

[Article by V. I. Shutskiy, doctor of technical sciences, professor, V. B. Narozhnyy, candidate of technical sciences, Yu. A. Fominykh, engineer]

[Text] One way of improving the efficiency of the application of high voltage electrotechnical equipment and, above all, commutation equipment (breakers and disconnects) is use of their overload capacities. When designing the high-voltage breakers, disconnects or other high voltage equipment certain relations cannot be determined in advance which are especially important for operation. For example, these are the admissible load currents as a function of the ambient temperature or the time of their operation. These values usually are found experimentally when testing the already built units.

The relations constructed on the basis of the experimental data have, as a rule, the following basic deficiencies: a) in all cases the coordinates of the points are distorted as a result of unavoidable experimental errors, and they must be "smooth," that is, averaged; b) the values of a number of intermediate points are unknown; c) it can become necessary to extrapolate the relation obtained, that is, find values of the points lying outside the experimental range. It is possible to avoid such deficiencies if a functional relation between the investigated parameters is found by the experimental data. The problem reduces to determining the relation which corresponds to the true relation with a sufficient degree of accuracy.

In electrotechnical calculations, just as in other fields of engineering, for processing experimental data the most widespread accuracy criterion of the approximating function is the least squares criterion [1]. Let us consider the prolonged admissible load current of an oil-filled VMB-10-630-10 breaker as a function of its operating time. This relation can be described by the expression [1]

$$I_{\text{дл}} = at^b e^{ct} + I_{\text{ном}}, \qquad (1)$$

(1) (2)

Key: 1. long 2. rated

where t is the operating time of the load current, minutes; I_{rated} is the rated current of the investigated breaker, amps; a, b, c are the desired coefficients of the curve equation.

The coefficients a, b, c are defined by the known transformations, as a result of which we obtain the system of equations:

$$\left.\begin{aligned} nF + b\sum_{i=1}^{n} D_i + c\sum_{i=1}^{n} t_i &= \sum_{i=1}^{n} y_i; \\ F\sum_{i=1}^{n} D_i + b\sum_{i=1}^{n} D^2_i + c\sum_{i=1}^{n} t_i D_i &= \sum_{i=1}^{n} y_i D_i; \\ F\sum_{i=1}^{n} t_i + b\sum_{i=1}^{n} t_i D_i + c\sum_{i=1}^{n} t^2_i &= \sum_{i=1}^{n} y_i t_i. \end{aligned}\right\} \quad (2)$$

In the system of equations (2) the following notation is used:

$$y_i \longrightarrow \ln(I_i - I_{\text{nom}}); \quad F \longrightarrow \ln a; \quad D_i \longrightarrow \ln t_i,$$
(a)

Key: a. rated

where n is the number of measurements taken; i is the order number of the measurement.

For the solution of such systems, that is linear algebraic equations up to third order on a computer usually the Kramer method is used [2]. In the given case this method cannot be used inasmuch as, as the calculations have demonstrated, the value of the determinant of the system turns out to be close to zero, which does not permit us to obtain a stable solution.

From expression (2) it is obvious that the matrix of the system is symmetric. The most exact solutions, as the analysis demonstrated, is provided in this case by the method of one-way rotations [3]. For description of the realized algorithm for the solution of system (2), let us introduce the following notation: A -- the quadratic matrix (system matrix); B -- the vector of the free terms; X -- vector of unknowns.

Then

$$M_{ki} = \frac{A_{ii}}{\sqrt{A^2_{ii} + A^2_{ki}}}; \quad L_{ki} = -\frac{A_{ki}}{\sqrt{A^2_{ii} + A^2_{ki}}}, \quad (3)$$

where i = 1, 2, ..., n - 1; k = i + 1, i + 2, ..., n. For $A_{ii} = A_{ki} = 0$ we have $M_{ki} = 1$, $L_{ki} = 0$.

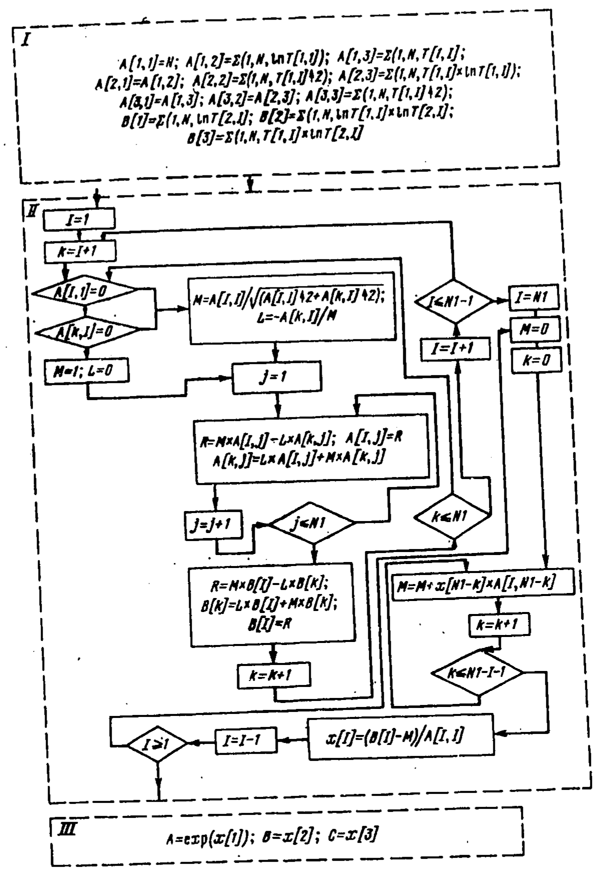
Then the system is transformed by the formulas:

$$\left.\begin{aligned} M_{ki} y_i - L_{ki} y_k &= M_{ki} B_i - L_{ki} B_k; \\ L_{ki} y_i - M_{ki} y_k &= L_{ki} B_i - M_{ki} B_k. \end{aligned}\right\} \quad (4)$$

where y_i, y_k are the left-hand sides of equations i and k, respectively; B_i, B_k are the right-hand sides of equations i and k, respectively.

After n(n - 1)/2 steps we arrive at the system

$$A_{(1)} X = B_{(1)}. \quad (5)$$



Block diagram of the program for calculating the admissible load current of high-voltage breakers as a function of the time of its effect.

Table 1. Experimental and calculated values of the overload current as a function of the time of its effect (VMB-10-630-10 breaker)

Parameter	Time the overload current flows, sec											
	6	9	25	120	180	240	420	720	3000	5400	28 800	∞
Experimental values of overload current, amps	10 000	9000	8000	6300	4700	4270	3650	3000	2000	1500	1000	630
Calculated values of overload current, amps	10 400	9700	7800	5700	4300	3900	3300	2700	1950	1500	—	630
Error, %	+4,0	+7,7	—2,5	—10,5	—9,2	—9,5	—10,5	—11,0	—2,5	0	—	—

Table 2. Experimental and calculated values of the overload current as a function of the time of its effect (MKP-35-1000-25 and VMO-27.5-1000-25 breakers)

Parameters	Time the overload current flows, sec													
	4	6	10	25	30	40	50	270	600	1800	3600	18 000	32 400	∞
Experimental values of the overload current, amps	25 000	20 000	15 000	10 000	9000	8000	7000	5000	4000	3000	2500	2000	1500	1100
Calculated values of the overload current, amps	19 800	17 100	14 300	10 400	9775	8876	8243	4857	3866	2905	2467	1761	1571	1100
Error, %	+21	+14,5	+4,8	−4,0	−8,6	−11	−17,7	+2,86	+3,35	+3,17	+1,32	+12,0	−4,7	0

System (5) is solved by the usual inverse method, that is,

$$X_m = (B_{m(1)} - A_{m1(1)} x_{m+1} - \cdots - AA_{mn(1)} x_n / A_{mm(1)}, \qquad (6)$$

where m = n, n - 1, ..., 1.

The block diagram of the calculation program is presented in the figure. The program is written in ALGOL-60 and is executed on the BESM-4m computer.

The program consists of three modules: 1 -- shaping the matrix of the system and the vector of free terms; 2 -- execution of the algorithm; 3 · · determination of the unknown coefficients of the equation.

In Tables 1 and 2 the experimental and computer-calculated admissible values of the load currents are presented as a function of the time of their effect. As is obvious from the tables, the values of the load current (that is, the overload) obtained experimentally and calculated by the proposed procedure for certain investigated types of breakers, in particular, for the VMB-10-630-10, MKP-35-1000-25 and VMO-27.5-1000-25, compare satisfactorily.

It is necessary to note that in practice the approximation can be quite accurate when the statistical data are not distorted by random errors. In the presence of the latter (the person conducting the experiment should not be frightened by them), usually a "smoothing" approximation by functions that minimize either the mean square error or the absolute error in the entire experimental range is used. This method is also applied by the authors. From Tables 1 and 2 it is obvious that in individual intervals the divergence of the calculated and the experimental data can be significant (to 21%), but the mean square errors in the calculated data in the entire experimental period do not exceed 5%. This error is entirely admissible for calculating the overload capacity of the high-voltage breakers and also other electrotechnical equipment with the help of a computer.

BIBLIOGRAPHY

1. Yu. A. Fominykh, V. B. Narozhnyy, "Calculating the Overload Capacity of High-Voltage Breakers," ELEKTRICHESTVO (Electricity), No 7, 1974.

2. I. S. Berezin, N. P. Zhidkov, METODY VYCHISLENIY (Calculation Techniques), Vol II, Moscow, Fizmatgiz, 1960.

3. V. N. Kublanovskaya, "Some Algorithms for Solving the Complete Problem of Eigenvalues," ZHURNAL VYCHISLITEL'NOY MATEMATIKI I MATEMATICHESKOY FIZIKI (Journal of Computational Mathematics and Mathematical Physics), Vol 1. No 4, 1961.

[161-10845]

10845
CSO: 1860

ELECTRON AND ION DEVICES; EMISSION;
GAS-DISCHARGE AND ELECTRON-BEAM DEVICES

UDC 621.384.6

GENERAL-PURPOSE SOURCE OF NEGATIVE IONS WITH CATHODE SPUTTERING

Khar'kov VOPROSY ATOMNOY NAUKI I TEKHNIKI: OBSHCHAYA I YADERNAYA FIZIKA in Russian No 2/12 1980 pp 56-58

KOZLOV, V. G., OVSIYENKO, G. P. and CHEKANOV, S. Ya.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1A173]

[Text] The construction of a general-purpose source of negative ions with cathode sputtering is described. The conditions under which a beam of primary negative ions forms are examined. Also established is how the yield of secondary negative ions depends on the energy of primary Cs^+ ions. It is shown that the yield of secondary negative ions reaches the 5% maximum at an energy of Cs^+ ions equal to 8 keV. The composition of a beam of negative ions has been analyzed mass-spectrometrically. With a copper cathode, the Cu^- ions constitute 50% of the total beam current.

[177-2415]

UDC 621.384.6

STABILIZATION OF THE OPERATING MODE OF THE ION SOURCE FOR AN EG-2.5 ELECTROSTATIC ACCELERATOR

Khar'kov VOPROSY ATOMNOY NAUKI I TEKHNIKI: OBSHCHAYA I YADERNAYA FIZIKA in Russian No 2/12, 1980 pp 71-73

NIKITIN, V. A. and YAKUSHEV, V. P.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1A174]

[Text] A system has been developed which stabilizes the operating mode of the ion source for an electrostatic accelerator, the first stage of stabilizing the ion current to the target. The current of the beam leaving the source is equal to the difference between the current in the anode circuit and the cathode current. The current in the anode ciruuit is stabilized by varying the plate voltage of the high-frequency oscillator and the cathode current is maintained at its minimum level by means of an automatic pulling device. This ensures a constant beam current from the source, and, consequently, a more stable ion current to the target. The current in the anode circuit can be regulated over the 15-110 micro-ampere range and the current fluctuations do not exceed 0.5% over a period of 2 h. Figures 3; references 4.

[177-2415]

UDC 621.384.6

ION INJECTOR FOR AN ELECTROSTATIC ACCELERATOR

Khar'kov VOPROSY ATOMNOY NAUKI I TEKHNIKI: OBSHCHAYA I YADERNAYA FIZIKA in Russian No 2/12 1980 pp 81-83

NOVIKOV, M. T. and TSYGIKALO, A. A.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1A175]

[Text] Following an analysis of expressions which relate the parameters of an ion beam at the entrance to and at the exit from, respectively, of an electro-static accelerator, the design of an ion injector for use with a nondischarging accelerator is proposed. Its special features include a preaccelerator with automatic beam focusing at the injector exit, followed by better conditions for matching the operation of the ion source and the operation of the accelerator without impairment of the automatic beam focusing in the accelerator. Such an

injector is an autonomous device. Within certain limits it facilitates regulation of the ion-optical power of the lenses at the entrances to the accelerator and the preaccelerator during operation and at the same time maintains the conditions for better matching of the ion source with the accelerator. Figures 1; references 5.

[177-2415]

UDC 621.384.6

SOURCE OF MULTIPLE-CHARGE IONS OF GASES FOR ELECTROSTATIC ACCELERATORS

Khar'kov VOPROSY ATOMNOY NAUKI I TEKHNIKI: OBSHCHAYA I YADERNAYA FIZIKA in Russian No 2/12, 1980 pp 69-70

PISTRYAK, V. M., KUZ'MENKO, V. V. and LEVCHENKO, Yu. Z.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1A176]

[Text] The design and the results of bench testing of a source of multiple-charge ions of gases are described. It is a source with cold cathodes and a Penning discharge. Its outside dimensions are a 200 mm diameter and a 100 mm height; its maximum power requirement is 150 W. With neon as the working gas, the following currents were recorded behind the exit gap of the mass-analyzer: Ne^{+} 160 microamp, Ne^{2+} 11 microamp, Ne^{3+} 0.8 microamp, Ne^{4+} 0.05 microamp. Figures 3; references 3.

[177-2415]

UDC 621.384.6

INSTRUMENT FOR MEASURING THE EMITTANCE OF CHARGED PARTICLE BEAMS

Khar'kov VOPROSY ATOMNOY NAUKI I TEKHNIKI: OBSHCHAYA I YADERNAYA FIZIKA in Russian No 2/12, 1980 pp 74-77

KUZ'MENKO, V. V., BOGDALIN, V. G. and PISTRYAK, V. M.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1A178]

[Text] The operating principle of this instrument for measuring the phase characteristics of particle beams is based on the "two gaps" method with mechanical

scanning of the gap diaphragms. Both diaphragms can be moved through a distance of ±10 mm relative to the system axis, the first diaphragm either continuously or discretely in controllable steps and the second diaphragm continuously. The transit base of the instrument is 330 mm long, the angle resolution is 0.3 mrad, and the average measuring time is 10 min. The instrument can operate in three modes: measure the current density distribution over the beam cross section, plot curves of the phase density distribution characterizing the current in the beam, and map the phase pattern of the beam component with a current density above a preset level. Figures 9; references 3.

[177-2415]

UDC 621.384.6

LINEAR ION ACCELERATOR

USSR Patent Class H 05 H 9/00, No 2,628,375 15 Mar 80 (disclosure No 720,833 13 Jun 78)

AUSLENDER, V. L., BARANOV, I. A., LAZAREV, V. N., PANFILOV, A. D., SMIRNOV, B. M., TROFIMENKO, S. M., SHILOV, V. P. and EYSMONT, V. P.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1A179 P]

[Text] This linear ion accelerator consists of a coaxial resonator with a drift tube, a vacuum space and a high-frequency pulse generator. In order to facilitate acceleration of several ion beams with generally different charge-to-mass ratios and also to reduce the losses with producing several accelerated ion beams, on the inner tube of the coaxial resonator are mounted several drift tubes which form with its outer tube the same number of accelerating gap pairs.

[177-2415]

UDC 621.384.6

ACCELERATING TUBE FOR AN EG-1 ELECTROSTATIC ACCELERATOR

Khar'kov VOPROSY ATOMNOY NAUKI I TEKHNIKI: OBSHCHAYA I YADERNAYA FIZIKA in Russian No 2/12, 1980 pp 100-102

ROMANOV, V. A., IVANOV, V. V., KRUPNOV, Ye. P., DEBIN, V. K., DUDKIN, N. I. and VOLODIN, V. I.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1A180]

[Text] The construction of an accelerating tube for an EG-1 electrostatic accelerator is described. Most attention in its design was paid to increasing the electrical strength of the accelerating gaps and to the conduction in vacuum as well as to a better shielding of the insulators from charged particles. After vacuum and high-voltage aging of this accelerating tube, nonanalyzed beams of hydrogen ions with a current up to 80 microampere were found to form satisfactorily with an energy within the 1.8-5.0 MeV range. Figures 4; references 6.

[177-2415]

UDC 621.384.6

PULSE OPERATION OF THE EG-1 ELECTROSTATIC ACCELERATOR AT THE PHYSICO-ENERGETICS INSTITUTE

Khar'kov VOPROSY ATOMNOY NAUKI I TEKHNIKI: OBSHCHAYA I YADERNAYA FIZIKA in Russian No 2/12, 1980 pp 84-88

BOKHOVKO, M. V., VOLODIN, V. I., GLOTOV, A. I., DUDKIN, N. I., KANAKI. V. I., KONONOV, V. N., POLETAYEV, Ye. D. and ROMANOV, V. A.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1A181]

[Text] For the purpose of broadening the scope of physical experiments with the EG-1 accelerator as well as increasing its reliability and making it more convenient to operate, the entire complex has been redesigned to include a better ion source and a new chopping system with klystron bunching. The service life of the ion source has been extended beyond 1000 h by changing the cathode material and more smoothly regulating the magnetic field in its plasma discharge space. The beam is chopped by rectangular voltage pulses and bunched by a sinusoidal voltage of 15.6 MHz frequency. The accelerator produced on a physical target ions beams with the following parameters within the 1.8-3.5 MeV energy range: ion current pulses of 0.3-0.5 mA amplitude and 15-25 ns duration in the plain chopping mode and of 1.5-2.5 mA amplitude and 2-2.5 ns duration in the chopping with bunching mode. In the microsecond mode of operation, moreover, the pulse duration was 0.1-1 microsecond, the pulse repetition rate was 1.5-30 kHz and the pulse current was 0.3-0.5 mA. Figures 6; references 8.

[177-2415]

UDC 621.384.6

DEVICE FOR FORMING A PULSED ELECTRON BEAM

USSR Patent Class H 01 J 29/00, No 2,055,638 15 Jun 80 (disclosure No 741,347 20 Aug 74)

MATORA, I. M. and SHVETS, V. A., Joint Institute of Nuclear Research

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1A182 P]

[Text] This device for forming a pulsed electron beam consists of a pulse-type electron gun with a cathode and a grounded anode and a source of accelerating voltage. For monochromatization of the electron beam, the anode is built in the form of a unit consisting of two semicylinders joined on the cathode side through an annular jumper with one end bent back, the opposite base of one semicylinder is grounded and the opposite base of the other cylinder is connected to an additional source of pulse currents, connections also being made to the synchronizer and the source of accelerating voltage.

[177-2415]

UDC 621.384.6

OPTIMIZATION OF QUASI-PERIODIC STRUCTURES IN A LINEAR RESONANCE-TYPE ION ACCELERATOR

Moscow IZVESTIYA VYSSHIKH UCHEBNYKH ZAVEDENIY: FIZIKA in Russian Vol 23, No 6, 1980 pp 81-85

GARASHCHENKO, F. G., SOKOLOV, L. A. and TSULAYA, A. V.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1A183]

[Text] A linear ion accelerator for operation with a rectangular or trapezoidal accelerating voltage between the tubes is considered, and a method of optimizing its parameters is proposed which carefully takes into account the quasi-periodicity of their spacing. Numerical calculations have demonstrated that the method is efficient and requires a rather simple structure for implementation. The algorithm is shown in detail. The range of input phases is estimated, the maximum range exceeding the earlier predicted limits by a few percent.

[177-2415]

UDC 621.384.6

SYSTEM FOR STABILIZING AND MEASURING THE ENERGY OF AN ION BEAM IN AN ELECTROSTATIC ACCELERATOR WITH OVERCHARGE OF IONS

Khar'kov VOPROSY ATOMNOY NAUKI I TEKHNIKI: OBSHCHAYA I YADERNAYA FIZIKA in Russian No 2/12, 1980 pp 32-34

AD'YASEVICH, B. P., VOROTINKOV, P. Ye., LARIONOV, L. S., POLUNIN, Yu. P. and PCHELIN, Yu. A.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1A184]

[Text] For stabilizing and measuring the energy of accelerated ions in an EGP-8 electrostatic accelerator one uses a beam of neutral atoms formed during overcharge of negative ions. The neutral atoms then become charged into ions and their energy is measured with an electrostatic analyzer. Crystals of CsI(Tl) separated by a thin opaque barrier and connected through light conductors to two photoelectron multipliers serve as the detector. This detector also serves as a sensor of the beam position, its output signal corrects the voltage at the high-potential electrode of the accelerator with the aid of a corona triode. The

system was tested in measurements of (p,γ) resonances and (p,n) threshold reactions. A voltage stability and a beam energy uniformity within $4 \cdot 10^{-4}$ were attained, the solid opaque target contributing most to the nonuniformity of beam energy. Figures 2; references 7.

[177-2415]

UDC 621.384.6

EGP-15 OVERCHARGE-TYPE ELECTROSTATIC ACCELERATOR (DESIGN PROJECT)

Khar'kov VOPROSY ATOMNOY NAUKI I TEKHNIKI: OBSHCHAYA I YADERNAYA FIZIKA in Russian No 2/12, 1980 pp 28-31

ROMANOV, V. A., BASHMAKOV, V. S., BORNOVALOV, N. G. et al.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1A185]

[Text] For the purpose of broadening the scope of physical measurements at the Physico-Energetics Institute, an overcharge-type electrostatic accelerator (EGP-15) is being built there which represents a modern version of the well known EGP-10 developed at the Scientific-Research Institute of Electrophysical Apparatus imeni D. V. Yefremov. Its basic design parameters are: range of proton energies 3-15 MeV, maximum current up to 10 microampere, range of accelerated ion masses 1-60, energy stability within 0.01%. For optimum transfer of continuous and pulsed particle beams through the perforated accelerator target, a high-voltage injector (VTI-300) has been developed for this EGP-15 which can deliver a beam with a maximum energy of 300 keV. For formation of ultrashort ion clusters, twofold bunching along the injection path is available. The operating modes of this EGP-15 accelerator will be monitored and controlled with the aid of the "Elektronika-100I" computer which serves as the basis of the automatic control system for the electrostatic accelerators at the Physico-Energetics Institute. Figures 1; references 14.

[177-2415]

UDC 621.384.6

EXPERIENCE WITH HIGH-VOLTAGE ACCELERATORS IN SERVICE AT THE PHYSICO-ENERGETICS INSTITUTE

Khar'kov VOPROSY ATOMNOY NAUKI I TEKHNIKI: OBSHCHAYA I YADERNAYA FIZIKA in Russian No 2/12, 1980 pp 3-7

ROMANOV, V. A., BASHMAKOV, V. S., VOLODINA, A. P. et al.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1A186]

[Text] Five high-voltage accelerators: EG-2.5, EG-1, EGP-10M, KG-2.5 and KG-0.3 are in operation at the Physico-Energetics Institute. These accelerators are essentially intended for nuclear research. While they are in service, efforts are constantly underway to improve them. In recent years most attention has been paid to a changeover to their operation with automatic control and to development of accelerator tubes with a higher electrical strength, also to further improvement of the pulse modes in accelerators EG-1 and EGP-10M. Performance parameters of these accelerators are given here, based on their operation in 1978. Tables 6; references 1.

[177-2415]

UDC 621.384.6

DESIGN OF THE ION OPTICS FOR THE ESU-2.5 ELECTROSTATIC ACCELERATOR AT THE KHARKOV STATE UNIVERSITY

Khar'kov VOPROSY ATOMNOY NAUKI I TEKHNIKI: OBSHCHAYA I YADERNAYA FIZIKA in Russian No 2/12, 1980 pp 51-54

MASHKAROV, Yu. G.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1A187]

[Text] The optimum conditions for acceleration of an ion beam in an existing electrostatic accelerator are examined. The characteristics of the ion focusing lenses and the parameters of the ion beam are calculated on the basis of the parameters of the actual accelerating tube, ion conductor and rotating magnet. All quantitites are regarded as strictly definite, except the parameter which characterizes the beam convergence at the entrance to the accelerating tube. This convergence parameter is varied till the beam leaves the accelerating tube as a convergent one and the beam crossover point becomes equidistant from the end of the accelerating tube and the lens which focuses the beam on the entrance gap of the rotating magnet, this lens also being equidistant from that gap and that crossover point. Better locations are found for the doublet of quadrupole lenses which focus the beam on the entrance gap of the magnet and for the lens which focuses it on the target. Figures 1; tables 2; references 5.

[177-2415]

UDC 621.384.6

MAGNET SYSTEM

USSR Patent Class H 05 H 7/04, No 2,534,145 5 Jun 80 (disclosure No 736,388 17 Oct 77)

VASIL'YEV, V. V., MILYUTIN, G. V. and FURMAN, E. G., Department of Nuclear Physics, Electronics and Automation at the Tomsk Polytechnic Institute

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1A189 P]

[Text] This magnet system for an induction-type accelerator of charged particles consists of a solid magnetic structure, an excitation coil connected to a pulse voltage supply and a bias-magnetizing coil connected through an inductance to a source of direct current. For reducing the distortion of the magnetic field produced by this electromagnet, an additional source of direct current with a shunting controlled rectifier is connected through a capacitance to the biasing coil.

[177-2415]

UDC 621.384.6

METHOD OF ACCELERATING POSITIVELY CHARGED PARTICLES

USSR Patent Class H 05 H 9/00, No 1,755,855 25 Mar 80 (disclosure No 422,128 6 Mar 72)

LAVRENT'YEV, O. A.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1A192 P]

[Text] The method of accelerating positively charged particles differs from that described in disclosure No 286,808 in that, for a more efficient acceleration, the electron beam is made to radially converge toward the axis of acceleration of positively charged particles.

[177-2415]

UDC 621.384.6

METHOD OF ACCELERATING IONS

USSR Patent Class H 05 I 9/00, No 1,756,267 25 Mar 80 (disclosure No 467,707 7 Mar 72)

LAVRENT'YEV, O. A.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1A195 P]

[Text] In the proposed method of accelerating ions the latter are guided through a sequence of potential wells formed by the space charge of electron fluxes which have been focused on the acceleration axis and have their density or energy modulated in time as well as along the acceleration axis. For a more efficient acceleration, the electrons are injected from a cylindrical surface and retained within the focus region by electric fields encompassing the acceleration axis.

[177-2415]

UDC 621.384.6:53

SMALL-SIZE ACCELERATOR OF HEAVY IONS WITH A 1 MeV ENERGY OF PARTICLES

Khar'kov VOPROSY ATOMNOY NAUKI I TEKHNIKI: OBSHCHAYA I YADERNAYA FIZIKA in Russian No 2/12, 1980 pp 94-95

BEZUGLYY, V. V., BREDIKHIN, M. Yu., IL'YENKO, B. P., NEKLYUDOV, I. M. and KHORENKO, V. K.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1A197]

[Text] A small compact accelerator of heavy ions has been developed for research in field simulation of reactor defects, and its construction is described here. Its main components are an accelerating tube at a 200 kV potential, a source of multiple-charge ions, a beam forming system at the entrance to the accelerating tube, and a target chamber. Use of a modernized source of multiple-charge ions makes it possible to produce, with a 200 kV potential at the accelerating tube, beams of chromium, nickel, copper or other ions with a 1 MeV energy and a 20 uA Current of accelerated particles. Experimental bombardment of targets with ions of various elements has demonstrated that this accelerator can be successfully used for research in the physics of radiation damages. Figures 2.

[177-2415]

UDC 621.384.6

INTERFERENCE OF SYNCHROTRON RADIATION

Moscow ZHURNAL EKSPERIMENTAL'NOY I TEORETICHESKOY FIZIKI in Russian Vol 79, No 3, 1980 pp 763-774

NIKITIN, M. M., MEDVEDEV, A. F., MOISEYEV, M. B. and EPP, V. Ya.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1A201]

[Text] The phenomenon of interference of synchrotron radiation from relativistic electrons is studied, this radiation being in synchronism with the particle beam itself, successively at two points separated by a long straight gap. The spectral characteristic and the polarization-angle characteristic of this radiation are analyzed. A satisfactory agreement is found between experiment and theory. It is demonstrated that this interference of synchrotron radiation in units where the magnetic field intensity drops sharply at the edge leading to a straight gap can be useful, independently or together with synchrotron and undulatory radiation, for solving a wide range of scientific and practical problems.

[177-2415]

UDC 621.385.832.82(088.8)(47)

SCREEN FOR A CATHODE-RAY MEMORY TUBE

USSR Patent Class H 01 J 29/10, No 2,586,392 15 Jul 80 (disclosure No 748,574 1 Mar 78)

PESKOVSKIY, V. I.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1A121 P]

[Text] A screen subassembly for a cathode-ray memory tube is proposed which makes it possible to reproduce a moving semitone image with restoration of the standard field frequency.

[177-2415]

ENERGY SOURCES

UDC 621.039.6.001.1

SOME ELECTROTECHNICAL PROBLEMS OF CONTROLLED THERMONUCLEAR FUSION

Moscow ELEKTROTEKHNIKA in Russian No 1, Jan 81 pp 2-7

[Article by Ye. P. Velikhov, I. A. Glebov, academicians of the USSR Academy of Sciences, V. A. Glukhikh, director of the NIIEFA Institute imeni D. V. Yefremov]

[Text] The solution to the problem of controlled thermonuclear fusion is a most important scientific research goal also having great social significance.

Large-scale physical research connected with the solution of this problem has been performed in a number of areas for three decades, and it is continuing to be performed at the present time. As a result, we have succeeded in significantly increasing the temperature, the density and the confinement time of the energy in a plasma approaching the achievement of near-reactor parameters. It is possible to consider that at this time all of the necessary physical prerequisites have been created, and the corresponding engineering experience has been accumulated permitting the design of a so-called demonstration thermonuclear reaction in the near future in which the power engineering yield of the reaction will exceed the energy spent on heating the plasma. For this purpose it is necessary to create large-scale experimental devices, for the construction of which the solution of a number of complicated engineering problems has important significance.

At the present time more and more projects are developing for the construction of the next generation of devices. They must take the form of experimental thermonuclear reactors (TNR). In the TNR design and operating experience, it is necessary to solve not only the physical and engineering problems of creating devices that will function for a prolonged period of time while generating significant power, but also the economic, technological and other problems characteristic of industrial electric power plants.

The operating principle and the structural characteristics of the various types of TNR have been discussed in considerable detail in the scientific and technical literature.

The study of the possible ways of creating TNR is proceeding in two basic areas; steady-state devices and pulse devices with magnetic or inertial confinement.

The first area includes the tokamak type reactors, and the second, the θ-pinch systems and reactors in which electron beams and lasers are used for heating the plasma.

Example requirements on the reactor parameters appear in Table 1.

As examples Figures 1 and 2 show the schematic diagrams of the "Tokamak-20" devices and a pulsed unit using the "Angara-5" relativistic electron beams.

The program for development of thermonuclear equipment is intersectional. Serious problems must be solved by the electrical engineering industry. The electrotechnical products used in the indicated units can be divided into three types.

The first type can include the standard general-purpose electrotechnical products. These are systems for conversion of thermal power to electic power, pulsed capacitors, thyristors, transformers for rectifying converters, substation equipment, and so on.

The second type of product is the electrical equipment, which although it has prototypes in electrotechnical devices, it requires developments as applied to the TNR devices. Such products include powerful nonstandard thyristor units, capacitor banks with increased energy capacity, electromechanical units for short-term operation with inertial storage elements, special transformers, inductive energy storage elements, and powerful commutators.

Finally, the third type of product is the experimental TNR devices themselves.

The purpose of this article is to define the basic requirements on the electrotechnical equipment, the solution of which to a significant degree determines the success of creating the next generation of thermonuclear devices.

One of the prospective areas in this field is connected with tokamak type devices. Some of the devices of this type that have been designed and built have the specifications presented in Table 2.

At the present time there are 30 large experimental units of this type operating in the world (in the USSR there are 8). New large units are being built: T-15 (the USSR), TFTR (the United States), JET (EEC), JT-60, and so on.

For conversion to the production of industrial thermonuclear reactors with high technical and economic parameters it is necessary to create experimental engineering devices and demonstration thermonuclear reactors on which the basic assemblies of the future industrial reactors must be tested and developed. The design of such an experimental device was begun with the participation of the USSR and on the basis of international cooperation -- INTOR (the international tokamak) -- designed to obtain a thermonuclear reaction of several hundreds of megawatts.

Let us briefly discuss some of the electrotechnical problems arising in the creation of thermonuclear devices.

As is known, the conditions of confinement and heating of a plasma in a tokamak chamber are insured by the mutual effect on it of strong magnetic fields created by a system of large-scale windings. The toroidal winding creates a magnetic field which is directed along the plasma column, and poloidal windings, magnetic fields perpendicular to it.

The high intensity of the toroidal magnetic field and the significant volume of the magnetic field, which is tens of cubic meters (for T-15) and hundreds of cubic meters (in the presently designed devices) and also a number of other factors lead to high complexity of the problem of creating the toroidal field system.

The theoretically required toroidal magnetic field can be created on the basis of two different technical solutions. One of them is based on the appli ation of a magnetic system formed by the usual type conductors and operating in the repeated pulse mode. For excitation of this system it is necessary to have a short-acting power supply with controlled valve converters with a power on the order of 500-1000 megawatts[1]. The second solution is based on the application of superconducting windings that create a stationary magnetic field, for the establishment of which in a few hours it is necessary to have insignificant power of the power supply from hundreds of kilowatts to several megawatts. Thus, the power required to feed the toroidal winding is reduced by hundreds of times.

For a T-15 device the version of a super-conducting magnetic system has been adopted.

Characteristics of a Power System for a Superconducting Toroidal Magnetic Field Winding T-15

Rated current, kiloamps	5
Time required to bring the current up to the maximum value is regulated within the limits of, hours	2-10
Power supply voltage, volts	750
Energy output time constant under emergency conditions, sec	50
Maximum voltage of the winding with respect to the housing in case of emergency lead-out of power, volts	±1250

The further growth of the requirements on the superconducting electromagnetic system by comparison with the T-15 device is considered in the design of the new tokamak type thermonuclear reactor.

Designed Energy Parameters of a Thermonuclear Reactor

Induction on the plasma axis, tesla	6
Maximum induction, tesla	12
Induction of the toroidal winding, henries	16
Power of the toroidal winding, joules	$60 \cdot 10^9$
Height of the toroidal field coil, meters	12
Cycle time, seconds	1000

The analysis shows that the creation of a magnetic toroidal field system of reactors of this scale without the application of superconductor engineering is economically inexpedient.

As the scale of the tokamak devices increases, the power and the energy reserves of the feed systems of the poloidal field windings grow, and the operating conditions become more complicated. A simple increase in power and energy of the devices used previously to supply power to the poloidal field windings of the preceding tokamaks

[1]This technical solution is used as the basis for the large tokamaks built at the present time in the United States, Western Europe and Japan.

Table 1

Name of system	Charged particle concentration, n, 1/cm^3	Plasma confinement time, τ, sec	Energy capacity of the power supply, W, joules	Power supply power, P, watts	Magnetic field in working volume, B, tesla	Working volume, v, m^3
Quasi-stationary	$5\cdot10^{13}$-10^{14}	10	10^{10}	10^8-10^9	5-10	400-1000
Pulsed with magnetic thermal insulation						
Toroidal θ-pinch	10^{16}-10^{17}	10^{-2}	10^{11}	10^{13}	10	300
θ-pinch with liner	10^{18}	10^{-3}	10^8-10^9	10^{11}-10^{12}	--	30
Pulse with inertial confinement						
Laser heating	$3\cdot10^{24}$	10^{-10}	10^6	10^{16}	--	10
Electron beam heating	10^{24}	10^{-8}	10^7	10^{15}	--	10

Table 2

Parameters of the device	T-15	TFTR	INTOR
Large radius of the plasma, meters	2.43	2.48	5.2
Small radius of the plasma, meters	0.7	0.85	1.3
Maximum plasma current, MA	1.4-2.3	2.5	1.3
Time of existence of the maximum plasma current in each pulse, sec	5	1	100
Induction of a toroidal magnetic field on the axis of plasma coil, tesla	3.5-5	5.2	5.5
Maximum induction of the toroidal magnetic field on the surface of the winding, tesla	8	9.5	11
Maximum power reserve of the toroidal magnetic field, Mjoules	700	1000	40,000
Total power supply, megawatts	200	700	1500
Power of additional heating, megawatts	10-20	100	400

is unacceptable for technical-economic arguments, in connection with which the necessity arises for the development of new systems and devices.

For supplying power to the inductor circuit of the "Tokamak-15" device, the inductive power storage element and the controlled thyristor converter are used. As the storage element, the inductor winding is used in which electromagnetic energy is stored in advance, part of which is released in the plasma coil when the inductor circuit is opened.

For realization of this power system it is necessary to create unique dc switching equipment which has a breaking power of 800 megavolt-amperes and a capacity of no less than 10^4 responses and also electromagneic reversal permitting switching of currents up to 80 kA in the inductor circuit.

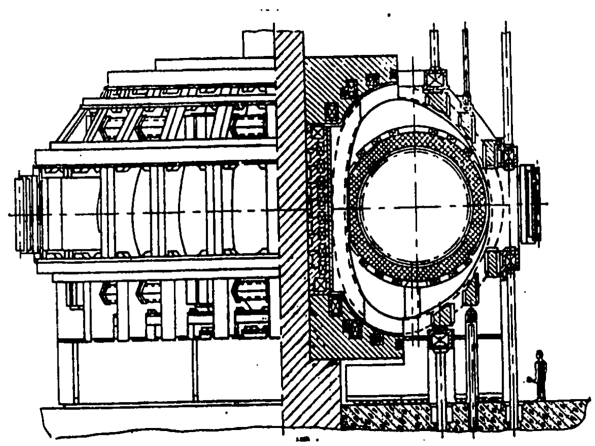


Figure 1.

In connection with an increase in the duration of the existence of the plasma coil, the problem of maintaining its equilibrium becomes more complicated. In order to solve this problem, a special equilibrium control system is provided; three windings of this system are excited by the given program which can be corrected automatically; two windings are fed by the control system with feedback operating as a function of the position of the plasma coil. All of these windings are fed from controlled thyristor converters. The power system has a total of 7 thyristor convertors with a total power of 160 megawatts.

Now let us consider the peculiarities of the pulsed devices with magnetic confinement of the plasma. For generation of electromagnetic fields in reactors by the θ-pinch type system with a liner, it is necessary to solve a number of complex engineering problems, including the problems of creating magnetic systems of great elongation and with high intensity of the magnetic field and the development of pulsed energy sources with an energy capacity on the order of 10^{10} joules and a pulse power of more than 10^{12} watts. The problems connected with commutation of high power and preliminary heating of the plasma are highly complex ones.

Complex problems also arise in the development of reactor equipment with inertial confinement. In particular, for the method using high-current electron beams, it is necessary to create a set of devices that generates a system of high-current electron beams insuring comprehensive irradiation of the target by electrons with an energy of 2-3 Mev and a total current in the tens of millions of amperes and with a pulse duration of less than 10^{-7} sec.

The standard representative of these devices is "Angara-5." The "Angara-5" accelerator must provide for obtaining an electron beam with a total energy to 10 megajoules.

The system is made up of a number of modules, each of which is a high-current electron accelerator. The basic part of the accelerator is the high-voltage pulse generator made up of two stages.

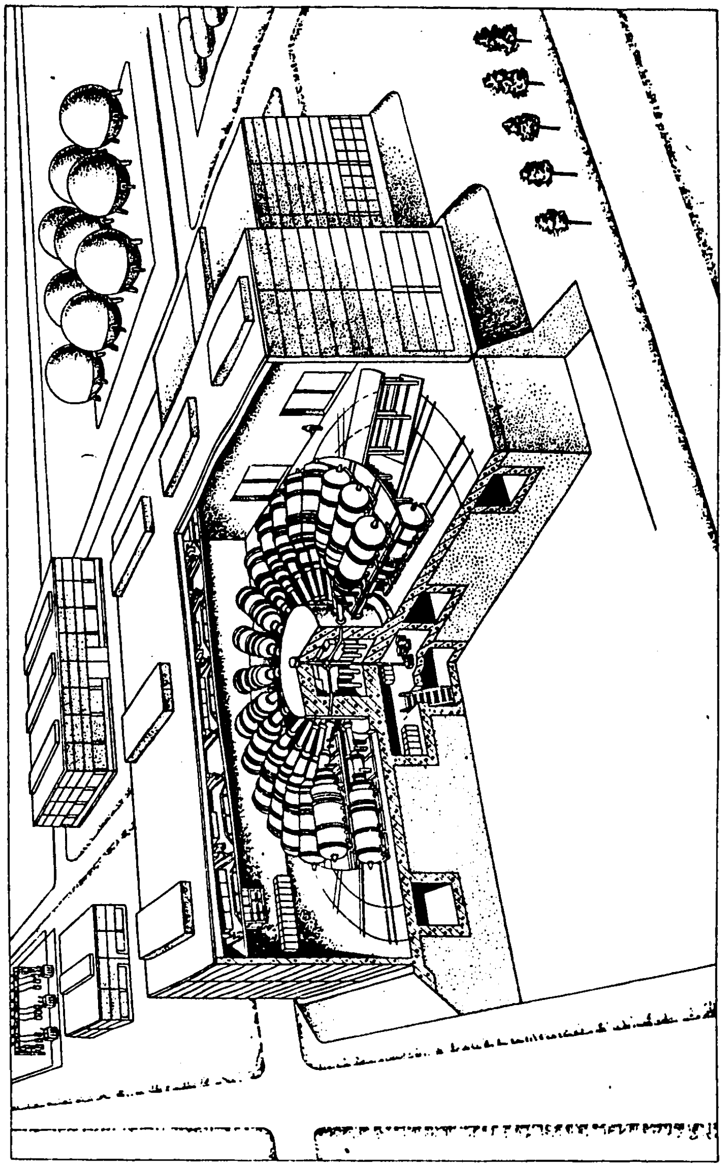


Figure 2.

Table 3

Storage element	Specific energy capacity, joules/g	Specific power, watts/g	τ, sec	Area of application
Capacitive storage elements	0.03+0.07 (0.1)	10^2-10^3 (10^4)	10^{-6}+10^{-1} (10^{-7})	Pulsed systems with a power of 10^6-10^7 joules
DC machine or AC unit with rectifier	1.0 (5.0)	0.2 (1.0)	1-10	Pulse sources 10^8-10^9 joules
AC shock generators	1.5(10)	1-2(5-10)	0.01	Pulse sources 10^7-10^8 joules
Homopolar generators	(3-10)	--	(0.1-10)	Pulse sources 10^7-10^9 joules
Inductive storage elements	10-20 (30-50)	10^3-$2\cdot10^3$ ($5\cdot10^3$)	10^{-3}-1.0 (10^{-5})	Pulsed and quasi-stationary sources

Note. The prospective values are presented in parentheses.

Basic Parameters of the "Angara-5" Device

Maximum electron energy, Mev	2
Electron current amplitude, Mamps	40
Pulse duration, nanoseconds	60-80
Energy in the beam in 100 nanoseconds, Mjoules	10
Operating conditions	Single pulses

The capacitive GIN [pulse voltage generator] with a multiplication circuit by a voltage of $2\cdot10^6$ volts and a pulse duration of 10^{-6} sec is used as the first stage. The pulse charges a high-voltage shaping line with water dielectric. The discharge of the water shaping line to an electron source with cold emission generates an electron beam.

In connection with the future prospects of thermonuclear devices, the projects aimed at the development and the creation of the necessary experimental base and electric power supply systems have great significance. Let us consider the basic types of required equipment. The specifications on the energy storage elements of various types, the application of which can be expedient in thermonuclear fusion devices, are presented in Table 3.

Each of the indicated types of storage elements is a separate scientific-technical area.

Electromechanical Units with Flywheels. For analysis of the future prospects for development in this area it is expedient to consider the requirements on the power supply system in accordance with the design corresponding to the 1985 level of development. For powering these devices it is proposed that a peak power of 1500 megawatts be used, including 300 megawatts from the network. The energy consumption in an operating pulse is $5\cdot10^{10}$ joules.

Even under the conditions of operating several units in parallel, the indicated data characterize the problems of improving the energy capacity of the flywheel [in the existing units $(0.8-1.5)\cdot10^9$ joules]. In the TFTR tokamak design (United States) provision is made for two units with energy stored in the rotating masses of the rotors of $4.5 \cdot 10^9$ joules each.

High prospects are being opened up for the application of flywheels made of synthetic materials. Thus, for a steel flywheel weighing 100 tons the stored energy will be 10^9 joules; for a flywheel weighing the same but made of high-strength light alloys the stored energy will be $5 \cdot 10^9$ joules; flywheels made of prospective composites will store $10 \cdot 10^9$ joules. The composites available at the present time have a specific strength which is many times greater than high-strength steel and alloy. However, the transition to the practical creation of such flywheels requires significant efforts.

The provision of units designed to operate for short periods of time with synchronous generators does not seem to present any technical difficulties at first glance, for they are in the assimilated power range. However, the specific requirements of the short-term loading conditions with variable rpm, the continuous fluctuations of the currents in the stator and rotor windings make it necessary to create special machines with increased resistance to such conditions. The development of shock generators, in particular, generators with shorter pulses than the alternating current halfperiod of 50 hertz appears to be prospective.

Inductive Storage Elements. For a number of cases the only efficient power supply can be an inductive storage element. As is known, the pulsed power supply based on an inductive storage element is a complex system consisting of the inductive storage element itself, the devices for supplying power to it, the output system and the corresponding auxiliary equipment.

One of the basic problems when creating a power supply based on an inductive storage element is the development of a commutating unit.

The commutating units built at the present time have a breaking capacity to 10^{10} watts and an energy output time to load of tens of microseconds. The second stage of such a commutator is presented in Figure 3. The first stage provides the prolonged flow of current, and the second, fast breaking of the circuit. Destructible elements are used as the second stage, in which the dc arc is extinguished using oil, gas or dielectric (for example, paraffin) filling the destructible gap. Three-stage commutators are being developed which must provide for an energy transfer to load time of several microseconds. Destructible foils and wires or destructible nonlinear resistances cooled to low temperatures are used as the third stage. The superconducting commutating devices are of special interest.

Powerful Thyristor Converters. In order to supply power to the inductive storage elements, toroidal windings of prospective thermonuclear devices of the tokamak type, thyristor converters to voltage on the order to 3-5 kilovolts and a power to several thousands of megawatts are required. In order to insure voltage division between the series included thyristors in this converter, series stage inclusion of four valve sections is used. In order to limit the shortcircuit current in the case of breakdown of individual thyristors, parallel inclusion of four valve stages is used. The adopted solution is awkward, and it cannot be considered optimal for prospective converters. The development of prospective converters requires the solution of a number of problems with respect to insuring current division between the parallel valve sections and the protection of the individual valves and the converter in the case of possible emergency shortcircuits in the dc modes and on breakdown of individual thyristors.

Pulse Capacitors. High-voltage pulse capacitors for electrophysical devices must operate both in the vertical and in the horizontal executions at atmosphere and increased pressures.

The operating conditions of the capacitors are as follows: aperiodic charge, oscillatory discharge, cycle repetition frequency no higher than 10 hertz.

The closest problems for the pulse capacitor version are as follows:

Improvement of the size and weight indexes (to units of joules per gram);

A decrease in inductance to 10-20 nanohenries;

Improvement of reliability;

A search for prospective dielectrics.

Cables for Electrophysical Devices. It is possible to note the following problems with respect to the creation of new cables:

Improvement of the rated cable voltage to 200 kv;

Reduction of the cable inductance from 200-300 to 30-50 nanohenries/m (with a simultaneous increase in cross section).

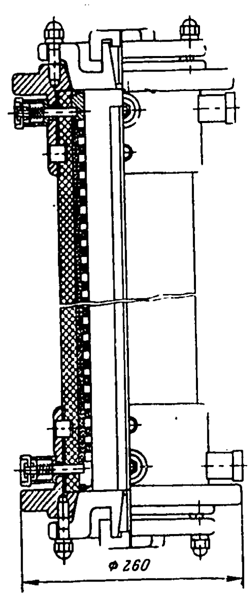


Figure 3.

High-Voltage Electrical Equipment. The power supply systems for the engineering complexes of thermonuclear reactors also consist of a large number of power subsystems of individual ionic sources including high-voltage, high-current electric power supplies which are under high potential relative to ground and powerful high-voltage power supplies for the accelerating electrodes of the ion sources.

The high-voltage electric power supply systems of ion sources have been developed for the following output parameters: U_{rect} = 150 to 200 kv; I_{rect} = 100 to 120 amps; output voltage stability considering pulsations 2-3% with buildup time to the rated value and discharge of it to zero under emergency conditions of no more than $20-30\times 10^{-6}$ seconds. The output parameters of high-voltage electric power supplies are as follows: U_{out} = 20 to 100 volts; I_{out} = 3 to 6 kiloamps; output voltage stability considering pulsations no worse than 0.5-1%.

The creation of electric power supply systems for the engineering complexes of thermonuclear reactors can be realized with the participation of enterprises of the electrotechnical industry in the development of the following electric power supply equipment elements;

High-voltage, step-up transformers -- transformers with a capacity to $400\cdot 10^6$ volt-amperes, insulation class 150-200 kv, with insulated neutral, for operation on high-voltage controllable rectifiers for an output voltage of 150-200 kv with a power to $(250-400)\cdot 10^6$ watts with the capability for outdoor installation;

High-voltage, high-speed commutators based on vacuum arc-suppressing chambers for protecting the ion sources and the electric power supply system equipment during emergiencies, for a commutatable current of 100-200 amps and operating voltage to 200-250 kv;

Powerful high-voltage generating triodes operating in the switching mode capable of switching circuits with a voltage to 250 kv for a prolonged operating current of 100-150 amps.

Superconducting Windings. The design and manufacture of large-scale superconducting magnetic systems has specific difficulties. For high inductions, significant ponderomotive forces acting on the winding and variable poloidal magnetic fields there is a danger of transition of the individual sections of the superconducting winding of a toroidal field to the normal state. This can be avoided by selecting the required reserves, for which it is necessary to use alloys with given properties as the current-carrying element. It is necessary also to insure winding strength under the effect of electromagnetic forces, sufficiently effective liquid-helium cooling, the output conditions of high energies on transition of the coil to the normal state. In the case of emergency transition of a superconducting winding to the normal state, the protection system must respond, and energy is output from the winding to the external load, for otherwise damage to the winding is unavoidable.

The superconducting toroidal field winding (SOTP) must be resistant to the effects of variable magnetic fields created both under operating conditions and on breaking the plasma current. The SOTP of the T-15 device consists of 24 superconducting coils placed in powerful stainless steel housings. The base for the superconducting coils is a superconducting current-carrying element, which is in the form of a transposed system of composite, multi-strand Nb_3Sn-conductors with two copper pipes, connected to it for circulating liquid helium. Each coil consists of six two-layer disc coils placed in a strong stainless steel housing. In order to fix the position of the coils of the toroidal field windings and pick up the loads from the tipping moments, fastenings are provided that insure strong mechanical bindings between the individual elements of the toroidal field windings.

In conclusion, it must be noted that although the final form of the thermonuclear reactors has still not been developed, it is possible to define the basic electrotechnical problems arising in making the transition from plasma physics research to reactor building engineering. As was demonstrated, the electrotechnical support of experimental and, subsequently, experimental-industrial thermonuclear devices is a complex scientific-engineering problem. Its solutions are connected with the improvement and efficient application of standard electrical equipment, just as with the design and the production of complex nonstandard equipment on which very high requirements are imposed. This requires a large volume of scientific research work and the creation of a special experimental base in the electronics industry.

[161-10845]

10845
CSO: 1860

UDC 621.318.3:621.039.5.001.4

ELECTROMAGNETIC SYSTEMS OF TOKAMAKS

Moscow ELEKTROTEKHNIKA in Russian No 1, Jan 81 pp 7-16

[Article by I. F. Malyshev, N. A. Monoszon, doctor of technical sciences, N. I. Doynikov, candidate of physical and mathematical sciences, A. I. Kostenko, B. V. Rozhdestvenskiy, Yu. V. Spirchenko, G. V. Trokhachev, G. F. Churakov, candidates of technical sciences, V. P. Muratov, engineer]

[Text] The electromagnetic system (EMS) is one of the basic systems of the tokamak. It generates magnetic and eddy electric fields providing for the formation, active heating and confinement of the plasma in the discharge chamber, the thermal insulation, stability, configuration control and control of spatial position. The magnetic field can also be used to purify the plasma of the thermonuclear reaction products and impurities getting in from the first wall, protection of the latter from the particles emitted by the plasma. The quality of the magnetic field has a significant influence on the plasma characteristics.

From the engineering point of view the electromagnetic system is a complex electrotechnical device characterized by significant electrical, magnetic, mechanical and thermal loads encompassing the discharge chamber, blanket and shielding and providing access of the particle beams, energy fluxes and diagnostic means to the plasma. The problem of creating the electromagnetic system is greatly complicated when developing the tokamak thermonuclear reactors as a result of the necessity for applying superconducting windings in this case which completely encompass the hot zone of the reactor -- the discharge chamber with the blanket and shielding and the necessity for operational servicing of this zone without dismantling it for long interruption of the normal operation of the EMS [electromagnetic system].

The indicated arguments determine the necessity for developing special structural designs and calculation techniques providing for the possibility of creating EMS for experimental devices and the thermonuclear reactors of tokamaks.

Electromagnetic Systems with Normal Windings. The structural diagram of the EMS with closed ferromagnetic circuit is shown in Figure 1. The EMS is a pulsed transformer in which the toroidal discharge in the vacuum chamber is created by an eddy electric field, and the plasma current in the discharge chamber is the secondary shortcircuited coil of the transformer. In order to suppress the main magnetohydrodynamic instabilities of the plasma, the powerful longitudinal magnetic field of the toroidal solenoid is used, inside which a vacuum chamber is located.

The annular plasma coil striving to expand under the effect of the electrodynamic forces in its own magnetic field and the gas kinetic pressure is kept in equilibrium by means of an external poloidal magnetic field. The basic source of the eddy emf is the inductor winding (OI). In the window of the transformer, in addition to the toroidal field winding (OTP) and the OI, there can be control windings (OU) generating poloidal magnetic fields determining the shape of the transverse cross section of the plasma column and maintaining its equilibrium and also auxiliary windings -- remagnetization, induction heating of the chamber, and so on.

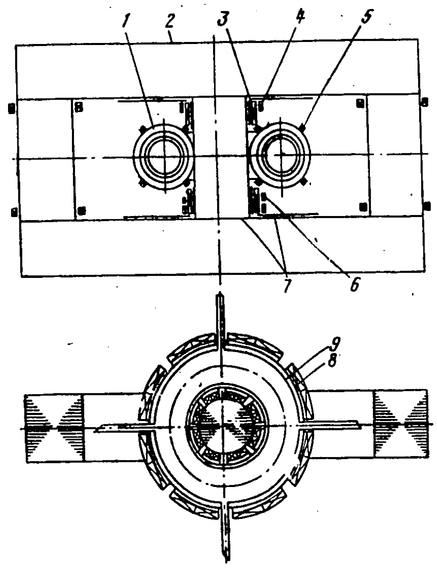


Figure 1. Structural diagram of the T-3. 1 -- OTP [toroidal field winding]; 2 -- magnetic circuit; 3 -- OI [inductor winding]; 4 -- OP [remagnetization winding]; 5 -- KO [correcting winding]; 6 -- OIN [induction heating winding of the chamber]; 7 -- OI shields; 8 -- plasma shields; 9 -- discharge chamber.

In the first experimental devices with short duration of the operating pulse for maintaining equilibrium of the plasma, a copper shield located in direct proximity to the plasma boundary was used. If the operating pulse duration is less than the time of diffusion of the magnetic field through the wall of the shield, then when the plasma approaches it, eddy currents are induced in the shield creating fields which equalize the forces deforming the plasma coil. The electromagnetic systems of the first tokamaks were developed at the IAE [Nuclear Power Institute] imeni I. D. Kurchatov, at which, as is known, the tokamak system was proposed.

The developments of large experimental devices requiring the solution of an entire series of engineering problems connected with the creation of electromagnetic systems and the broad involvement of industry for the manufacture of electrophysical equipment were started at the end of the 1950's. The basic parameters of the electromagnetic systems of these devices are presented in the table.

Basic parameters of electromagnetic systems

EMS parameters	Type of device			
	T-3	T-3A	T-4	T-10
Large radius of the torus R_0, meters	1	1	0.9	1.5
Plasma cross section radius a, meters	0.21	0.21	0.2	0.35
Maximum induction of the longitudinal field on the radius $R_0(B_0)$, tesla	4	4	5.4	5
Total variation of the magnetic flux of the inductor $\Delta\Phi_i$, W-sec	2	2	1.7	4.3
Time of maintenance of the maximum longitudinal field t_i, sec	0.2	0.3	0.3	1
OTP energy reserve W_T, megajoules	25	25	45	130
Peak power of the OTP feed P_T, megawatts	77	77	77	180
Energy of the capacitor bank feeding the OI, W_K, megajoules	2.2	2.2	2.2	5
Induction of the OU on a radius R_0, tesla	---	---	---	0.25
Mass of the active steel of the magnetic circuit, tons	105	105	100	230
Mass of the winding copper, tons	25	18	10	60
Year of development	1959	1963	1965	1971

The T-3, T-3A, T-4 devices were built for experimental studies of a plasma with short duration of the operating pulse (on a scale of 100 milliseconds or less) and differing little from each other with respect to the EMS designs. Their structural diagrams are analogous to that presented in Figure 1.

The electromagnetic system of the T-3 consists of a magnetic circuit, the toroidal field winding (OTP), inductor winding (OI), remagnetization winding (OP), the correcting winding (KO) for correcting the transverse fields and the induction heating winding of the chamber (OIN) which heats it to a temperature of several hundreds of degrees to degas the walls. The plasma current buildup during development of annular discharge and active heating of the plasma are insured by the variation of the magnetic flux $\Delta\Phi_i$ in the magnetic circuit.

In order to decrease the sizes of the OP and the feed power, it is desirable not to permit strong saturation of the magnetic circuit. The remagnetization of the latter before the beginning of the operating cycle permits the solution of this problem and an increase in $\Delta\Phi_i$ and the duration of maintenance of the plasma current. On the T-3 device the magnetic circuit is remagnetized from $B_1 = -1.8$ tesla to $B_2 = 1.8$ tesla. The most responsible part of the magnetic circuit is the core. As a result of limited space, it is used as the supporting column for the OTP coils, and it takes the loads from the force of radial compression of the OTP.

For the tokamak EMS, structural designs of cylindrical monolithic cores were developed from bonded sheets of electrotechnical steel capable of reliably taking significant mechanical loads. The OTP of the T-3 device creates a magnetic field in a toroidal volume of 2.21 m^3 with induction of B_0 = 4 tesla on radius of R_0 and maximum induction on the winding B_1 = 6 tesla. It consists of 8 OTP coil modules uniformly arranged along the azimuth with relatively small gaps between them. In order to reduce the feed power, decrease the mechanical stresses and the heating of the OTP, a great deal of attention has been paid to improving the coefficient of filling of the winding with copper. For this purpose, the sections with coil insulation were worked into a wedge and made monolithic.

The OTP coils are subjected to the effect of significant radial tensile forces caused by interaction of their currents with their own field. As a result of toroidality, the specific pressure from these forces is distributed nonuniformly with respect to the OTP coil circuit, and in the T-3 it varies from $3.6 \cdot 10^6$ to $14.4 \cdot 10^6$ Pa. This nonuniformity in the pressure distribution causes bending moments that act in the plane of the coil and try to elongate it vertically and give it a D-shape. However, the geometric dimensions of the T-3 and the magnetic field level still do not reach values such that the strength problems acquire extraordinarily great significance.

When investigating the stress-strain state of the OTP, along with the forces acting in the plane of the coils it is necessary to consider the forces caused by interactions of the OTP currents with poloidal fields generated by the plasma currents and the polodial windings. However, in the T-3 these forces are small as a result of attenuation of the penetration of the plasma current fields into the OTP region using shields and an insignificant level of the OI and OP scattering fields.

When investigating the problem of the mechanics of the EMS, it is also necessary to consider the ponderomotive forces in the screens. The fact is that the copper screens must have insulating joints in the radial planes of the torus in order to avoid shortcircuiting by the screen of the eddy emf. Thus, the screen must be made of individual sections insulated from each other azimuthally, on the ends of which the eddy currents maintaining plasma equilibrium are closed. The end currents that flow across the powerful toroidal field cause ponderomotive forces which must be considered when developing the structural designs for the screens.

Rigid requirements are imposed on the quality of the toroidal field. The tolerances on the transverse fields at the beginning of the operating cycle in the region of formation of the plasma coil are within the limits $(10^{-4}$ to $10^{-3})B_0$. The sources of the transverse fields are the inaccuracies in the manufacture and installation of the OTP coils, the fields of the intercoil connections, and the scattering fields of the poloidal windings. On the T-3 device the primary source of transverse fields is the remagnetization winding. The calculations and experimental studies demonstrated that for corresponding placement of it in the window of the EMS, these tolerances can be maintained. In order to lower the transverse fields from the OTP, the adjacent sections are wound in opposite directions with the formation of bifilars from the connecting links.

The next step in the tokamak research program was the creation of the T-10 device with large volume, current and duration of the plasma confinement. The T-10 device is among the largest operating tokamaks in the world. In order to optimize the T-10 parameters, a computer program was developed permitting an analysis of a large number of versions considering the physical requirements and the characteristic features of the structural design. On the basis of the performed analysis, a version of the device was selected with the following basic parameters:

Large radius of the torus R_0, meters	1.5
Small radius of the plasma cross section, a, meters	0.35
Plasma current I_{pl}, Mamps	0.8
Duration of the operating pulse t_i, sec	0.8

The general view of the T-10 and transverse section of the EMS are presented in Figures 2, 3. The basic differences in the structural design of the EMS of the T-10 from the T-3 and T-4 consist in the following:

In connection with increasing the duration of the operating pulse for stabilization of the position of the plasma, along with the copper shield, the OU is used;

In order to improve the uniformity of the OU field and decrease the total mass of the device, the magnetic circuit is made four-yoked instead of two-yoked.

The strength problems were complicated significantly on the T-10 device. The total radial force of compression of the central core by the toroidal field winding on the T-10 reaches $1.1 \cdot 10^8$ Newtons. The induction of the toroidal magnetic field inside the OTP varies within the limits of 3.7-7.9 tesla, and the pressure on the winding varies, correspondingly, within the limits of $5.5 \cdot 10^6$ to $25 \cdot 10^6$ Pa. In addition, as a result of interaction of the OTP currents with the OU field, significant tipping moments appear which try to turn the OTP modules around the lines of intersection of their midplanes with the median plane of the device. The magnitudes of these tipping moments reach $(8\text{-}10) \cdot 10^5$ N-meters.

Electromagnetic Systems of Experimental Devices with Superconducting Windings. The estimates show that the economical thermonuclear reactors of the tokamaks must have powers on the order of 10^9 watts per unit and operating pulses with a duration on the order of 10^2-10^3 sec. This requires the construction of EMS with volumes of the toroidal field on the order of 10^3 m^3 and electromechanic energy reserves of tens of gigajoules, or more. The total pulse durations do not permit restriction by the passive screens in order to maintain equilibrium of the plasma column. For this purpose it is necessary to use OU controlled by automated control systems. Reactor EMS with acceptable technical-economic characteristics can be built only on the basis of superconductors. The large scales and harsh operating conditions make the problem of creating superconducting electromagnetic systems (SEMS) for them which are subject to the effect of variable poloidal magnetic fields during operation under enormous mechanical loads extremely complex. Its solution can be obtained only as a result of the construction and the investigation of a number of experimental devices. A number of programs have been planned for this purpose. In our country provision has been made for the creation of tokamaks using superconductivity. In the United States, along with the construction of tokamaks with superconducting windings, a large experimental device is being built with superconducting coils of different types for the OTP (LCP -- large-coil project).

The first experimental installation of a tokamak T-7 with superconducting OTP in the world was developed and built at the IAE imeni I. V. Kurchatov Institute with the participation of the "Kriogenmash" NPO [scientific production association] [see reference 1]. At the end of 1977, the OTP of the T-7 device was installed and tested, confirming the correctness of the basic technical solutions used in its development.

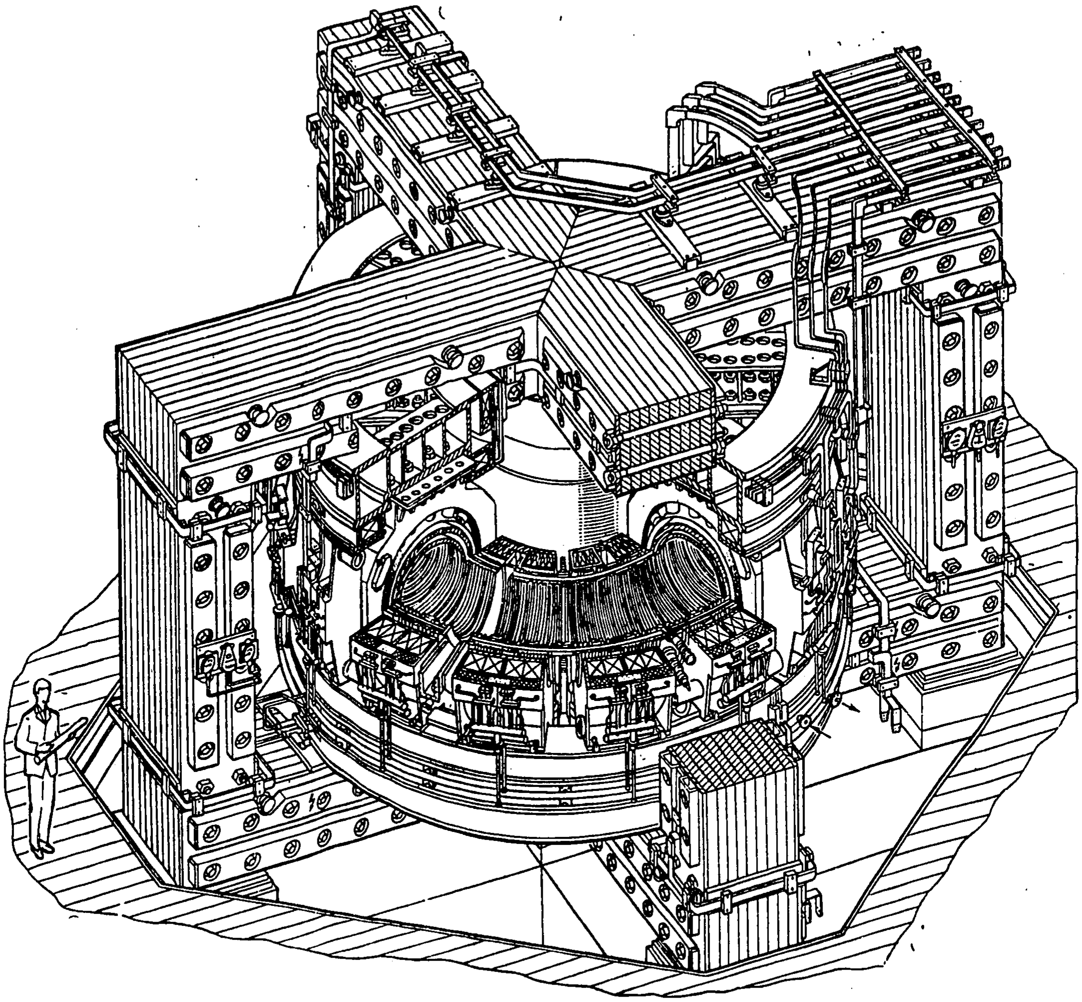


Figure 2. General view of the T-10 tokamak.

Basic specifications of the T-7

Large radius of the torus R_0, meters	1.22
Small inner radius of the chamber a_k, meters	0.35
Toroidal field induction B_0, on the radius R_0, tesla	3
Maximum induction on the OTP B_m, tesla	5
Electromagnetic energy reserve of the OTP, Mjoules	20
Operating pulse duration t_i, sec	1

In order to maintain the plasma equilibrium, a liquid nitrogen-cooled, copper shield was used which is able to greatly reduce the penetration of the plasma current field into the OTP region during the operating pulse, and at the same time, to decrease the heating and the tipping moment of the OTP. At the present time a larger experimental T-15 thermonuclear device was designed with superconducting OTP and liquid nitrogen-cooled OI and OU. It is designed to obtain and study a plasma with parameters approaching thermonuclear and solve a number of engineering problems connected with the creation of power engineering reactors.

In the initial stage of design, provision was made for obtaining a magnetic field of B_0 = 3.5 tesla on the radius R_0 = 2.4 m, with the help of the superconducting winding of the toroidal field (SOTP) on the basis of Nb-Ti [see reference 2]. The magnitude of the plasma current I_{pl} = 1.4 Mamps, and the duration of the operating pulse t_i = 5 seconds.

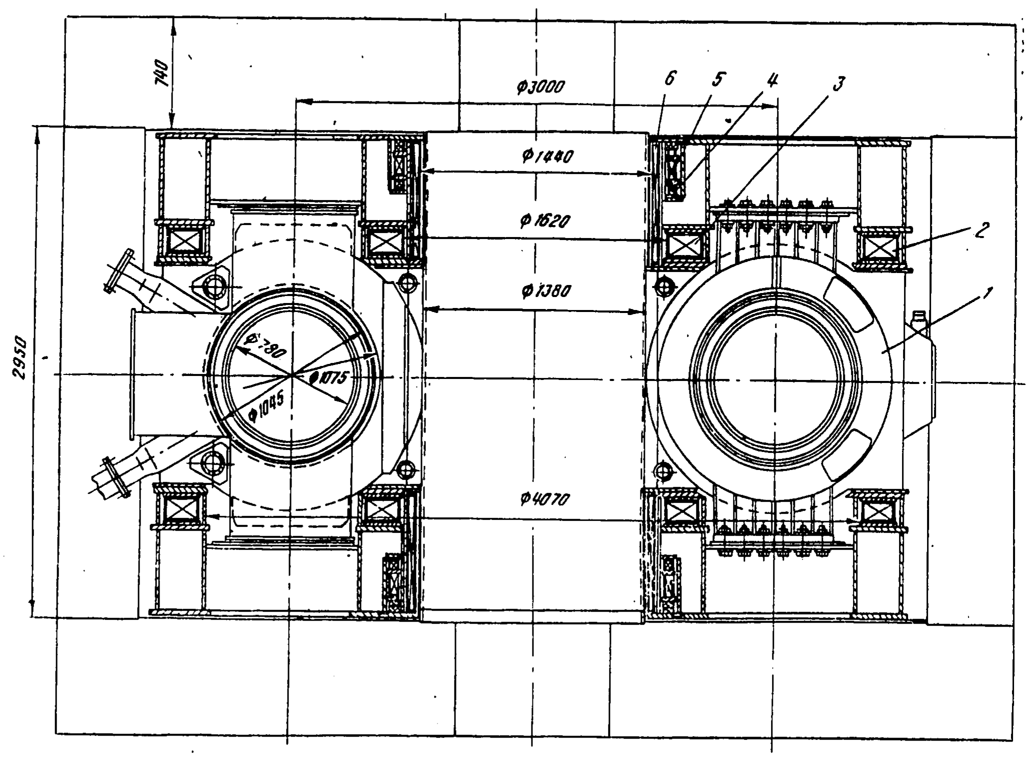


Figure 3. Electromagnetic system of the T-10. 1 -- OTP; 2 -- outer coil of the OI; 3 -- inner coil of the OU; 4 -- induction heating winding; 5 -- remagnetization winding; 6 -- OI.

In order to decrease the probability of the transition of the SOTP coils to the normal state, a shape elongated vertically and approaching the momentless configuration was selected for them, and provision was made for putting the OU inside the OTP. The momentless configuration permits the mutual displacement of the winding elements under the effect of the ponderomotive forces to be diminished, and it permits a reduction in the probability of transition of the SOTP to the normal state on excitation of the toroidal field. The placement of the OU inside the OTP significantly reduces the induction of the pulsating poloidal field in the vicinity of the OTP by comparison with the outside location and the heating of the tilting moments caused by them. It is possible to include the complication of the manufacture of the equipment, assembly and dismantling of the device among the deficiencies of the momentless configuration and placement of the OU inside the OTP.

In connection with the progress in mastering the production of combined multistrand superconductors based on Nb_3Sn and the experimentally demonstrated possibility of manufacturing SEMS from them with magnetic field level and mechanical loads characteristic of large tokamaks [ref. 3], the decision was made to use the Nb_3Sn-based superconductor having lower sensitivity and thermal disturbances as a result of the higher critical temperature for the OTP of the T-15. This made it possible to convert to the circular shape of OTP coil and outside placement of the basic OU instead of the previously adopted momentless shape of the OTP coil and the inside placement of the OU, the manufacture of which causes defined difficulties. Here the theoretical possibility of forcing the operating conditions of the T-15 is manifested, increasing the induction in the center of the plasma cross section to five tesla and the plasma current to 2 Mamps.

The technical specifications of the T-15 device (the rated parameters are presented in the numerator, and the expected parameters under forced operating conditions are indicated in the denominator)

Large radius, meters	2.4
Small radius of the plasma column (with respect to the diaphragm), m	0.7
Toroidal magnetic field induction on the axis, tesla	3.5/5
Maximum nonuniformity of the toroidal field in the vicinity of the plasma	$\pm 1\%$
Stability margin at the column boundary	2.5
Total variation of the magnetic flux of the inductor $\Delta\Phi_i$, volts-sec	15/17
Admissible induction of the poloidal field in the vicinity of the plasma for $I_{pl} = 0$, tesla	10^{-3}
Maximum plasma current I_{pl}, Mamps	1.4/2.0
Buildup time of the plasma current, sec	
to I_{pl} = 0.14 Mamps	0.014
to I_{pl} - 1.4/2.3 Mamps	0.614/1
Duration of the plasma current pulse, sec	5
Pulse repetition frequency under the rated operating conditions	1 pulse in 10 min.
Additional heating power introduced into the plasma using microwaves or injection of the neutrals, Mwatts	10

Figure 4 shows the general view of the T-15. The EMS includes the closed ferromagnetic, 12-yoke magnetic circuit, SOTP, OI and OU, liquid-nitrogen cooled, and the thermal induction heating winding of the OIN chamber installed on the core. The EMS together with the discharge chamber located inside the SOTP is placed in the common vacuum-sealed housing (cryostat). Thus, the devices placed inside the EMS housing in the operating state are maintained on different temperature levels:

For a temperature of T-4.5K -- SOTP with adjacent power structures to it;

At a temperature of $T \approx 80$ K -- OI and OU;

At a temperature of $T \approx 300$ K -- magnetic circuit, OIN, discharge chamber, EMS housing.

In order to decrease the thermal fluxes, the internal space of the EMS housing is evacuated to a pressure of $1.3\cdot(10^{-3}$ to $10^{-4})$ Pa, and radiation shields cooled by liquid nitrogen are installed between the regions with $T \approx 4.5$ K and $T \approx 300$ K. In contrast to the T-3, T-4 and T-10, the T-15 does not have a remagnetization winding. Before the beginning of the operating cycle in order to decrease the variation of the inductor flux $\Delta\Phi_1$ and the duration of the operating pulse, the magnetic circuit is remagnetized using the OI to powerful saturation of the core and in the initial stage of formation of the plasma, it is used as the inductive energy storage element to insure a fast rise of the plasma current. The SOTP consists of 24 large superconducting coils placed in the stainless steel supporting housings, joined in pairs in 12 mounting modules. The positioning of the coils along the radius is fixed by the central supporting column made in the form of a cylinder with two insulating joints vertically. The central cylinder takes radial forces of $1.2\cdot10^7$ Newtons from each coil. The superconducting conductor (Figure 5) is a transposed system of composite superconductors with two copper tubes connected to it for the cooling helium circulation. The structural design and the parameters of the cryogenic system provide for the possibility of cooling both by transcritical and two-phase helium.

The SOTP coils are series connected and have four pairs of current lead-ins which exit through the EMS housing and divide the entire winding into four sections. The sectioning permits an eightfold decrease in the voltage of the winding with respect to ground by comparison with the total voltage acting in the SOTP circuit on output of the energy of the magnetic field to the external discharge resistances, which occurs for protection of the winding in case of transition of it from the superconducting state to normal. The loads from the tipping moments are taken by the central column and special structural elements which provide strong mechanical couplings between the individual elements of the SOTP.

The choice of the number of coils and the inside dimensions of the SOTP coil is made by the structural arguments and the tolerance on the nonuniformity (corrugation) of the magnetic flux at the edge of the plasma. Corrugation is caused by the presence on the outer radius of the toroidal solenoid of large gaps between individual coils. For calculation of the magnetic fields and ponderomotive forces of the SOTP, it was necessary to solve a three-dimensional problem.

The basic OU provided for maintenance of plasma column equilibrium and the calculated shape of its transverse cross section are located outside the SOTP. They consist of three pairs of circular coils made of an aluminum bus with a hole for liquid nitrogen circulation. The coils are fastened to the radiation shields. The spatial pattern of the field and its variations with time are calculated considering the

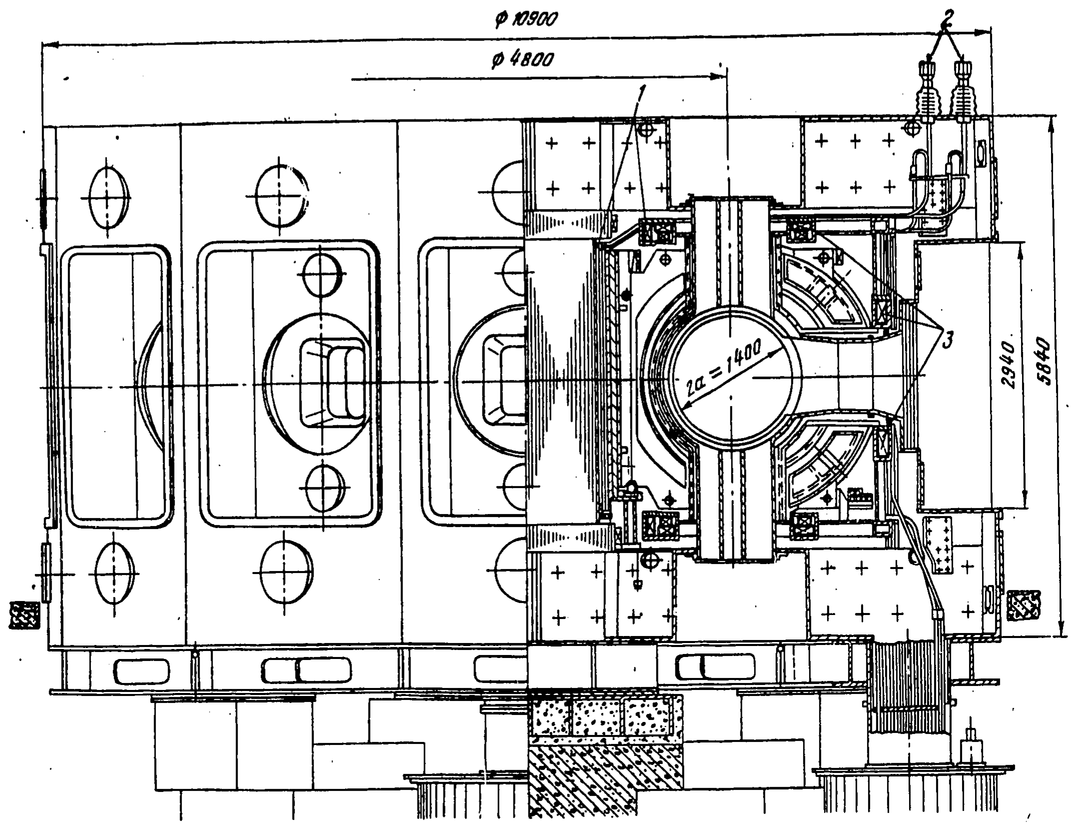


Figure 4. General view of the T-15. 1 -- inductor windings; 2 -- current lead-ins; 3 -- control windings.

MHD of the plasma equilibrium and variations of its active and inductive resistances, gas kinetic pressure and saturation of the magnetic circuit during the operating pulse. The OU currents vary by the program and are corrected by the feedback system. The fast variations of the plasma position are corrected using the high-speed control winding (BOU) placed between the SOTP and the discharge chamber in direct proximity to the plasma. The BOU is designed to generate fields with an amplitude of about 0.015 tesla with maximum variation rate of the field of 5 tesla/sec. The variations of the poloidal magnetic field during normal operations of the device do not lead to dangerous heat releases in the SOTP capable of causing its transition to the normal state.

Harsher operating conditions of the SOTP arise on cutoff of the plasma current. The plasma current cutoff can lead to uncontrolled transition of the SOTP to the normal state as a result of its heating caused by losses of electromagnetic energy and due to fast variations in the induction ΔB in the vicinity of the superconducting conductor. Figure 6 shows the calculated magnetic field patterns before and after cutoff of the plasma current in the rated mode. The solid lines correspond to Φ = const before cutoff, the dotted lines, to Φ = const after cutoff.

From Figure 6 it is obvious that the largest value of ΔB is reached in the maximum induction zone of the toroidal magnetic field, that is, in the region with minimum reserve with respect to kinetic temperature. In the rated mode $\Delta B_m = 0.48$ tesla, and in the forced mode $\Delta B_m = 0.69$ tesla. The specific heat releases q on variation of the induction in the conductor are defined by the expression, joules/m^3

$$q = k\frac{(\Delta B)^2}{2\mu_0},$$

where k is a coefficient which depends on the variation rate of ΔB and the characteristic damping time of the eddy currents in the conductor.

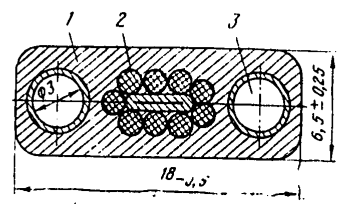


Figure 5. Superconducting conductor of the T-15. 1 -- copper; 2 -- Nb_3Sn in a bronze matrix; 3 -- cooling channels.

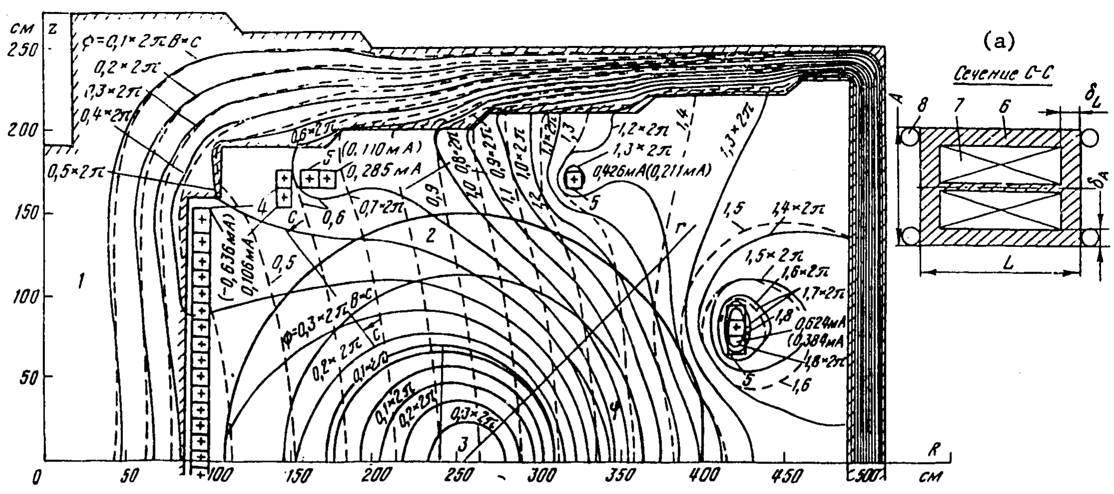


Figure 6. Poloidal field pattern of the D-15 plasma current cutoff in the rated mode.
Key: a. C-C section

For instantaneous variation of the field k = 1. With an increase in the duration of the variation of ΔB by comparison with the characteristic damping time the value of k decreases. The calculations demonstrated [4] that in the rated mode the current cutoff even with the time constant less than $2\cdot10^{-2}$ sec must not lead to transition of the SOTP to the normal state. However, in order to prevent the latter in the forced mode it is expedient artificially to increase the time constants of the SOTP coil housings in order to slow the variation of ΔB.

As a result of the fact that Nb_3Sn is characterized by increased sensitivity to deformations, insurance of high rigidity of the structural elements and development of reliable methods of calculating its stress-strain state are very important. A calculation was performed by the finite element method. The basic assumptions made for the calculation were checked experimentally. In the developed structural design the total deformation of the superconducting conductor taking into account the effect of the ponderomotive forces and production technology is about 0.3%. Figure 7 shows the stress intensity distribution and the displacement of the outer circuit of the SOTP module from the forces operating in the plane of the module in the forced mode.

From Figure 6 it is obvious that on cutoff of the current, induction components occur that are perpendicular to the direction of the current density vectors in the coils of the OTP and cause the appearance of tipping moments. Thus, the maximum tipping moments occur during cutoff of the plasma current.

In the T-15, the tipping moment for cutoff of the plasma current in the forced mode will be $3.6\cdot10^6$ N-meter on the coil.

Basic technical parameters of the EMS of the T-15 device

Toroidal field winding

Number of coils	24
Induction from the radius R_0, tesla	3.5/5
Maximum induction with respect to the winding, tesla	5.8/8.3
Magnetic field energy reserve, Mjoules	380/750
Operating current, amps	3600/5200
Superconducting conductor:	
Nb_3Sn cross section, cm^2	0.1
copper cross section, cm^2	0.8
cooling channel cross section, cm^2	0.14
mass, kg	$90\cdot10^3$
Maximum stress in the SOTP circuit with protected magnetic field energy output, kv	12
Time constant for energy output, sec	20
Radial force on the coil, Newtons	$6\cdot10^6/1.2\cdot10^7$
Tipping moment of the coil, N-m	$1.6\cdot10^6/3.6\cdot10^6$
Weight, tons	300
Cooling system	circulation, trans-critical or two-phase helium for T = 4.5 K
Heat release at the level of about 4.5 K:	
stationary, watts	1250
pulse, joules/pulse	150/270

Inductor

Maximum magnetic flux, W-sec	7.5
Maximum induction in the core/yoke, tesla	3.3/1.25
Total current of the OI, Mamps	4.5
Energy reserve of the OI, Mjoules	7
OI voltage, kv	8
Maximum current of the OI, kiloamps	80
Energy losses in an operating pulse, Mjoules	7.8
Weight of the magentic circuit, tons	750
Weight of aluminum in the OI, tons	4

Control winding

Number of basic OU	3
Number of BOU	1
Total current of the OU, Mamps	1.5
Total current of the BOU, Mamps	0.07
OU voltage, kv	8
BOU voltage, kv	3
Energy losses in the working pulse, Mjoules:	
OU	15.5
BOU	2

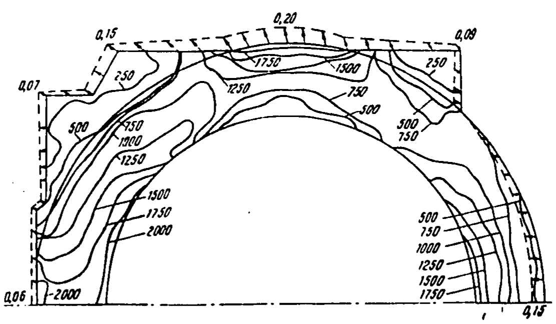


Figure 7. Intensity distribution of the stresses and displacements of the outer circuit of the SOTP module from the forces acting in the plane in the forced mode. ——— -- stress intensity isolines; ----- -- displacements.

Electromagnetic Systems of the Reactors. An idea of the scales and problems of building reactor EMS can be obtained by the materials from the design developments of these devices [see reference 5]. As is known, the final goal of the program with respect to the problem of controlled thermonuclear fusion is the construction of thermonuclear power engineering based on "pure" thermonuclear reactors. However, the creation of hybrid thermonuclear fusion-fission tokamak reactors (GTRT) with a uranium blanket [5] designed for plutonium working and electric power production is of great practical interest. The building of these reactors requires the solution of the same basic problems as the "pure" reactors, but in facilitated form (high plasma parameters and neutron loads on the "first wall" are not required, and the dimensions and thermonuclear power can be reduced significantly). In Figure 8 a diagram of the transverse cross section of a 6900 Mwatts thermal power GTRT is shown from the materials of the very beginning developments. The structure of the EMS is obvious in this diagram. In contrast to the T-15, the plasma has a vertically extended transverse cross section which is more advantageous with respect to the physical parameters. Obtaining high economic indexes and sufficiently positive service life require the use of operating pulses on the order of hundreds or more seconds long (for the GTRT, $t_i \approx 1000$ seconds). For such pulse durations at the present time it does not appear possible to get around the divertor which permits the products of the thermonuclear reaction to be pumped out of the discharge chamber, protection of the wall of the discharge chamber (the first wall) from destructive bombardment of it by particles emitted by the plasma and also a decrease in the flow of impurities from the chamber wall.

In order to obtain a noncircular, vertically extended plasma cross section it is necessary to generate external multipole poloidal fields. Here the separatrix of the poloidal field is formed with one or two zeros, and the most natural is the application of the poloidal diverter. This diverter was provided in the GTRT. Figure 9 shows the calculated pattern of its magnetic field formed by the SOU located both outside and inside the SOTP. The charged particles go from the outer diverter layer of the plasma moving along the magnetic lines of force to the diverter chambers where they collide with its walls, are neutralized and pumped out.

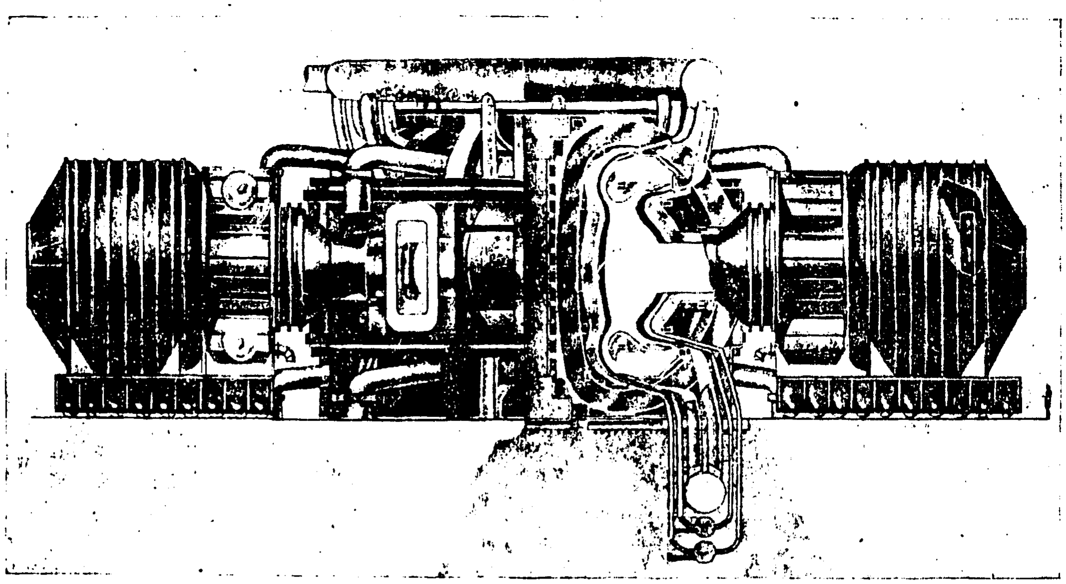


Figure 8. Diagram of the GTRT.

From the presented data the exceptionally high complexity of building the EMS for power reactors is directly obvious. The energy reserve in the SOTP of the GTRT exceeds by two orders of magnitude the energy reserve of the SOTP of the T-15 and the largest superconducting magnetic system in the world of the large BEBC hydrogen chamber (W = 830 Mjoules). In addition, the operating conditions of the SOTP are harsher than for the annular windings of the bubble chambers not subjected to the

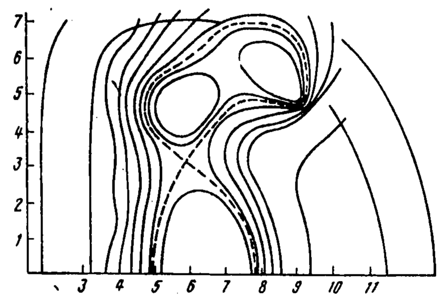


Figure 9. Poloidal field pattern of the GTRT.

Basic parameters of the GTRT electromagnetic system

Toroidal field in the center of the plasma cross section, tesla	6
Maximum field of the SOTP, tesla	12
Energy reserve of the SOTP, gigajoules	70
Type of superconductor	Nb_3Sn
Total current of the OI, Mamps	53
Total current of the OU, Mamps	19
Flux variation of the OI, W-sec	104 ($\pm$52)
Energy reserve of the OI, gigajoules	1.2
Maximum induction in the core, tesla	5.7
Maximum induction on the OI, tesla	3.7
Short term variation rate of the field on the OI, tesla/sec	20-30

effects of variable fields and radiation. The creation of the SOU placed inside the SOTP and insurance of field variation rates in the SOI on the level of 20-30 tesla/sec required at the beginning of the operating cycle to ignite the discharge and for fast rise of the plasma current appeared to be very complicated. The creation of pure reactors requires the construction of larger devices than the GTRT.

At the present time the necessity for building devices that are intermediate between industrial reactors and the T-15 devices built at the present time in our country and similar to it with respect to scales but not using superconductivity, the foreign JET, TFTR and DZhT-60, is generally accepted. The basic purpose of the devices is the solution of the physical and engineering problems and the development of structural designs directly connected with the structure of the power reactors. For the solution of this problem the IAE imeni I. V. Kurchatov and NIIEFA imeni D. V. Yefremov Institutes began the development of a demonstration T-20 thermonuclear reactor, and then the international reactor, the INTOR tokamak.

Basic parameters of the INTOR

Large torus radius R_0, m	5.2
Halfwidth of the plasma cross section a, m	1.3
Elongation of the plasma, v/a	1.6
DT-reaction combustion time, sec	>100
Average ion density $\bar{n}$, m^{-3}	$1.4 \cdot 10^{20}$

Average ion temperture $\bar{T}_i$, kev	10
Plasma current I_{pl}, Mamps	6.4
Thermonuclear DT power P, megawatts	620
Toroidal magnetic field at the center of the plasma crossection B_0, tesla	5.5
Corrugation of the toroidal field on the edge of the plasma, %	± 0.75
Neutron load on the first wall, Mwatts/m^2	1.3
Reserve (number of operating cycles)	$(0.5\text{-}1)\cdot 10^6$
Neutral beam heating power, megawatts	75
Neutral beam energy, kev	175
Fuel impregnation	By gas, tablets
Impurity control	Diverters

On the basis of the presented parameters, a preliminary calculation was performed, and the following basic specifications of the EMS were established:

Number of modules in the OTP	12
Maximum OTP induction, tesla	11.6
Energy reserve of the OTP magnetic field, gigajoules	40
Weight of the OTP module, tons	250
Total current of the OI, Mamps	125
Energy reserve of the OI, gigajoules	3.8
Total current of the OU, Mamps	30
Energy reserve of the OU, gigajoules	2.6
Average power of the OU, megawatts	50
Type of diverter	Poloidal with 10
Weight of the EMS, tons	5000
Power of the cryogenic system on the level of 4.5 K, kilowatts	50
Cool-down time	15 days

Structural Design of the EMS of the INTOR. Considering the experimental nature of the INTOR, the structural design of its EMS must insure the possibility of easy exchange of the models of the blanket elements and also a sufficiently simple method of replacing the individual parts of the chamber and the shielding in the intense radiation zone using robots. The requirement of replacement of sections of the chamber and shielding is determined both by the necessity for testing various versions of the structural elements and replacement and repair of them in case of damage. Diverter plates are subject to regular replacement as a result of their limited service life.

The structural diagram of one version of the EMS is presented in Figure 10. The volume of the EMS is broken down into five regions: a) high-vacuum discharge chamber; b) cryogenic chamber containing the superconducting toroidal field winding (SOTP), induction coil (SOI) and control winding (SOU) are placed; c) the intermediate "thermal" region with efficient shielding by the blanket modules and "thermal" resistive control windings (ROU) located in it; d) central near-axial region with resistive induction coil (ROI) in it; e) diverter region.

Regions a, b, c are separated from each other and from the outside space by vacuum-tight walls, and they have separate vacuum exhaust. The evacuation of the cryogenic region is necessary to insure thermal insulation of the superconducting windings. The evacuation of the intermediate region facilitates protection in the case of tritium leaks. Between the SOTP coils around the perimeter of the EMS provision is made for the "corridors" joining the intermediate region to the outside space permitting the installation modules into which the chamber and the shielding are broken down to be shifted along the radius. Thus, any part of the chamber and the protection can be replaced without heating the superconducting windings.

As a result of complexity of repair, in particular, after radiation contamination of the device, the windings of the electromagnetic system must be made with a margin of reliability such as to reduce the probability of failure during the operating time of the INTOR to a minimum. It appears that this problem can be solved.

Superconducting Toroidal Field Winding of the INTOR. Maximum induction of the toroidal magnetic field exceeds 11 tesla. For such induction, significant ponderomotive forces acting on the winding and variable poloidal magnetic fields, there is a high probability of the appearance of thermal disturbances capable of converting the sections of the SOTP to the normal state. Accordingly, the toroidal field winding must have sufficient reserve with respect to critical current and temperature and a high degree of stabilization such that the short-term disturbances causing the appearance of sections of the normal phase will not lead to transition of the entire winding to the normal state. The indicated requirements can be satisfied by the superconducting conductor (SP) based on Nb_3Sn. It is known that the current-carrying capacity of the composite, thin-strand superconductors based on Nb_3Sn in practice is not reduced for deformations of $\varepsilon < 0.5\%$ and neutron fluxes to on the order of 10^{18} N/cm^2. The industrial manufacturing process for such SP has been developed, and their cost will be reduced with an increase in the scale of the industrial output. It is possible to calculate that the experience in building LCP and the T-15 windings will confirm the expediency of using Nb_3Sn for INTOR and power engineering reactors. For the SOTP on the INTOR, it is expedient to use copper as the stabilizing metal. The application of aluminum, in spite of the fact that there is less of a shortage of it, lower cost and less magnetic resistance, is limited by the low mechanical strength and high variation of the resistance in the presence of radiation. In addition, in practice there is no experience in the manufacture, operation and maintenance of Nb_3Sn superconductors stabilized by aluminum. However, it is necessary to continue the operations of investigating the possibility of creating aluminum-stabilized superconductors from Nb_3Sn for tokamaks.

For the SOTP, a circulating cooling system is proposed which has defined advantages by comparison with the submersible one: during circulation cooling, the structural design of the cryostat is simplified, the problems of insuring electric and mechanical strength are solved more simply.

Both the single-phase and dual-phase helium can be used for cooling. At the present time it is difficult to give preference to any of these versions. The experimental study of both versions is proposed, in particular, on the T-15 device.

In the investigated version it is proposed that the SOTP be made of 12 coils of the modified D-type. The quantity and the dimensions of the coils are selected in such a way that tolerances on the corrugation of the toroidal field will be satisfied, the possibility of input of the neutrals to the discharge chamber and rolling out the chamber and shielding modules through the "corridors" in the gap between the SOTP coils will be insured.

The mass of the toroidal coil of 250 tons will not lead to extraordinary installation difficulties.

The poloidal magnetic field winding system includes inductor winding, the plasma equilibrium and shape control winding and correcting windings (OK). For arguments of economizing on energy losses, these windings are expediently made superconducting. However, this solution is complicated by the necessity for creating quite rapidly varying fields from them defined by the operating pulse parameters.

By the conditions of the physics of plasma formation at the beginning of the operating cycle for ionization of the DT gas in the discharge chamber and rise of the plasma current to approximately 0.1 Mamps, it is necessary briefly to generate an emf of 100 volts on the bypass of the discharge chamber and then reduce it to 25 volts and less in order to realize further buildup of the plasma current. This requires high speed of field variation ($B \approx 20$ tesla/sec) in the SOI region at the start of discharge, which can lead to transition of the SOI to the normal state.

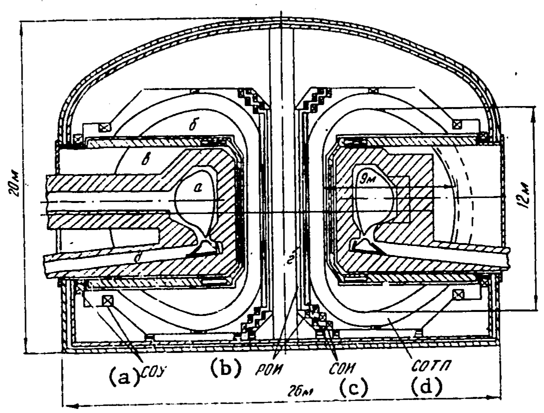


Figure 10. Structural diagram of the INTOR eletromagnetic system.

Key: a. SOU c. SOI
b. ROI d. SOTP

The application of an additional resistive inductor winding installed inside the SOI permits insurance of high voltage at the plasma bypass in the initial discharge stage, at the same time limiting the variation rate of the field in the SOI superconductor on an acceptable level. The resistive winding of the induction coil must have approximately the same number of turns as the superconducting winding, and it is connected parallel to it.

Before the beginning of discharge, the remagnetization current is initially induced in the SOI, and then in the ROI after connection of it parallel to the SOI. After response of the breaker, for leadout of the energy from the OI first the current and the magnetic field of the resistive winding decrease quickly, and the current in the magnetic field in the turns of the superconducting winding remain in practice unchanged as a result of mutual compensation of the emf and voltage applied to the SOI turns. When the voltage on the inductor turns decreases to 25 volts/turn, and the current in the ROI drops to zero, the ROI is disconnected, and further variation of the emf will be created by the SOI. Thus, the ROI insures fast variation of the inductor flux at the start of discharge, and the SOI insures slow variation of the inductor flux during the entire discharge. Along with reducing the variation rate of the field in the vicinity of the SOI, the application of the ROI permits the maximum induction and the amount of SOI superconductor to be decreased.

Maintenance of the plasma equilibrium in the required shape of its transverse cross-section and formation of the diverter field are realized using the OU. The same windings generate part of the eddy emf required to insure current buildup of the plasma. The magnetic field calculations demonstrated that for placement of the OU inside the SOTP the total current, the OU energy reserve and the tipping moment decrease by several times. The variation rates of the fields in the vicinity of the OTP conductors are reduced significantly.

However, the creation of reliable superconducting control windings located inside the SOTP appears to be a very real problem. Obviously, sufficiently reliable EMS with OU inside the SOTP can be constructed only when using ordinary copper resistive conductors for the OU; however, there will be significantly active energy losses here.

BIBLIOGRAPHY

1. D. P. Ivanov, V. Ye. Keylin, B. A. Stavisskiy, N. A. Chernoplekov, "Superconducting Toroidal Solenoid for the 'Tokamak-7'," ATOMNAYA ENERGIYA (Atomic Power), Vol 45, 1978, p 171.

2. V. A. Glukhikh, L. B. Dinaburg, N. I. Doynikov, et al., "Engineering Problems of Rebuilding the 'Tokamak-10' Device," DOKLADY VSESOYUZNOY KONFERENTSII PO INZHENERNYM PROBLEMAM TERMOYADERNYKH REAKTOROV (Reports of the All-Union Conference on Engineering Problems of Thermonuclear Reactors), Leningrad, NIIEFA, Vol 1, pp 26-41.

3. V. Ye. Keylin, Ye. Yu. Klimenko, I. A. Kovalev, et al., "Stabilized, High-Current Niobium-Tin Solenoid," DOKLADY VSESOYUZNOY KONFERENTSII PO INZHENERNYM PROBLEMAM TERMOYADERNYKH REAKTOROV, Leningrad, NIIEFA, Vol 1, 1977, pp 179-187.

4. E. N. Bondarchuk, N. I. Doynikov, A. I. Kostenko, et al, "Effect of Plasma Current Cutoffs on the Operating Stability of a Superconducting Toroidal Magnetic Field Winding of the T-10M Device," Preprint P-B-0416, Leningrad, NIIEFA, 1979.

5. Ye. P. Velikhov, V. A. Glukhikh, V. V. Gur'yev, et al., "Hybrid Thermonuclear Reactor of a Tokamak for Producing Fissionable Fuel and Electric Power," DOKLADY VSESOYUZNOY KONFERENTSII PO INZHENERNYM PROBLEMAM TERMOYADERNYKH REAKTOROV, Leningrad, NIIEFA, Vol 1, 1977, pp 5-25.

[161-10845]

10845
CSO: 1860

UDC 621.311.6:621.039.6

POWER SUPPLY SYSTEM FOR THE TOKAMAK TYPE THERMONUCLEAR DEVICES

Moscow ELEKTROTEKHNIKA in Russian No 1, Jan 81 pp 16-20

[Article by Ye. V. Kornakov, engineer, F. M. Spevakova, candidate of technical sciences, A. M. Stolov, doctor of technical sciences]

[Text] One of the most important problems occurring when building the tokamak type devices is creation of power supplies for the electromagnetic system characterized by very high powers and stored energies. The complex tokamak power supply system consists of a number of devices designed to create a toroidal stabilizing field and poloidal field insuring the occurrence of a plasma column, resistance heating of the plasma and also maintaining equilibrium of the plasma column. Each of these power supplies is a device that provides for generation of pulses of a defined shape and characterized by different powers and required energies.

Toroidal Field Winding Feed Systems. The toroidal field windings require power supplies with energy reserves much higher than the other windings of the electromagnetic system. In the operating part of the pulse (the plasma heating period), the toroidal field must be kept constant. The energy required of the power supply is defined both by the winding parameters and the duration of the working part of the pulse which can vary within broad limits.

The basic parameters of the toroidal field power supply systems of tokamaks developed at the NIIEFA imeni D. V. Yefremov Institute are presented in the table.

The required energy reserve of the toroidal field power supply determines the choice of the technical solution.

For devices with comparatively small intake powers (to several megajoules), the pulsed sources with capacitor banks are the most widespread (see Figure 1). The current rise in the toroidal field winding L takes place using a previously charged converter П of the capacitor bank C on inclusion of the commutator K. When the capacitor bank discharges, and its voltage begins to change polarity, the diode D that shunts the winding is included. Then the winding current decreases by an exponential law, and the commutator K disconnects the capacitor bank. In the case where the time constant of the winding essentially exceeds the duration of the operating part of the pulse, the toroidal field in this interval is in practice constant. This system, distinguished by comparative simplicity and reliability, was used on the TM-4A device.

With an increase in the intake power to values exceeding 10 Mjoules, it appears to be more expedient to use valve converters as the power supplies. Here the ratio of the total power released in the winding w_Σ to the energy released in the winding during the operating part of the pulse w_{pl} is defined by the ratio of the time constant of the winding T to the duration of the working part of the pulse t_0 and the forcing coefficient k, that is,

$$\frac{w_\Sigma}{w_{\text{пл}}} = 1 + \frac{T}{t_0} k^2 \left[\ln \frac{k+1}{k-1} - \frac{2}{k}\right].$$
(a)

Key: a. w_{pl}

Name of device	Plasma confinement time, sec	Energy reserve in the toroidal field winding, Mjoules	Maximum power of the power supply, Mwatts
TM-4A tokamak	0.015	5	500.00
T-3 tokamak	0.050	60	77.00
T-10 tokamak	1.000	400	160.00
T-15 tokamak*	5.000	750	0.45

*In the construction phase.

By the forcing coefficient k we mean the ratio of the converter power during rise of the winding current to the power in the working part of the pulse. With an increase in the forcing coefficient, the total energy consumption decreases, but the converter power increases. Usually the forcing coefficient is defined by the admissible magnitude of the thermal losses released in the winding of the toroidal field. In the power supply systems with converters, the winding current builds up with maximum voltage of the converters; the current area is shaped with reduced voltage, and the current drop is realized in the inverter mode.

Depending on the possibilities of the electric power supply system of a thermonuclear device, the converters can be fed directly from the network or from the electric motor units with flywheels if the feed network does not permit power surges. For example, the toroidal field of the T-3[1] tokamak was created using ignitron converters fed by a synchronous generator with peak power of 77 Mwatts (Figure 2). The maximum winding current L was 7000 amps; the no-load rectified voltage of the ignitron converters IP was 11 kv. The drive of the unit was from an asynchronous motor D with slip regulator PC. During the shaping of the pulse the slip of the unit varied from 1 to 18%.

On the T-10 tokamak, in connection with increased power of the feed network, it turned out to be possible to directly feed the converters through anode transformers from the network.

[1] M. A. Gashev, et al., "Basic Technical Specifications of an Experimental 'Tokamak-3' Thermonuclear Device," ATOMNAYA ENERGIYA (Nuclear Power), No 4, 1964.

The converters developed and manufactured by the KhEMZ plant with maximum current of 20 kiloamps and total no-load voltage of 8 kv were made from thyristors. One of the problems arising when building systems with converters is the choice of the method of adding their powers. The most expedient appears to be the use of a 12-pulse system of the converter unit. This system is formed by two three-phase bridge circuits joined in parallel or in series.

With parallel connection of the converter units, the currents under emergency conditions increase . With series connection of the converters, the winding voltage of the converters relative to the ground increases. Some of the methods of lowering the winding voltage with respect to ground are breaking it down into sections and series-alternate inclusion of the sections of the winding and the converters. In this case the winding voltage with respect to ground can be reduced a number of times equal to the number of sections. Figure 3 shows the power system for the toroidal field winding of the T-10 tokamak. The winding consists of four sections L1-L4. In this system with nonsimultaneous opening of the converters П1-П8, the winding potentials with respect to ground increase, for the elimination of which a special high-speed protection is required.

During operation of the converters with significant forcing coefficients, the decrease in winding voltage in the operating part of the pulse as a result of an increase in the angle of regulation of the converters leads to significant growth of he reactive power intake from the network.

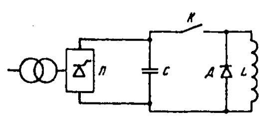


Figure 1. Power supply for the TM-4 tokamak toroidal field winding.

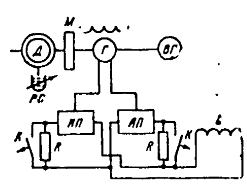


Figure 2. Power supply of the toroidal field winding of the T-3 tokamak. Г -- generator; M -- flywheel; BГ -- auxiliary generator.

In the system with series-alternate connection of the converters and winding sections, the possibility arises for decreasing the winding voltage by excluding part of the converters from the circuit with the help of commutation equipment. As an example Figure 4 shows a diagram of the series-alternate connection of two converters and two sections of a winding. For exclusion of the converter П1 from the circuit, the latter is converted to the inverter mode, it is shunted by the commutator K, and after deexcitation, disconnected by the P1 and P2 disconnects. The disconnected converter can be used to power other windings of the thermonuclear device in the operating part of the cycle.

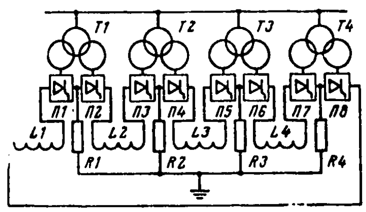


Figure 3. Power supply of the toroidal field winding of the T-10 tokamak. T1-T4 -- anode transformer; R1-R4 -- ground resistors.

A decrease in the reactive power intake from the network, when it is necessary to increase the angle of adjustment of the converters, can be achieved by application of an asymmetric control circuit. If in the two series-connected bridge circuits fed by cophasal voltage, the ignition angle of the cathode group of the first bridge and the anode group of the second bridge is increased simultaneously by the same amount, the resultant voltage will be six-pulse, and the reactive power intake from the network, with an increase in the adjustment angle by more than 30%, begins to decrease by comparison with the circuit with symmetric control, and this decrease is greater, the greater the angle of adjustment. In the system with a multiple of four converters, with asymmetric control circuit, the 12-pulse converter can be maintained. With parallel connection of the power supply converters, an asymmetric control can also be used, but in this case it is necessary to connect the two bridges fed by the cophasal voltages, in one of which the cathode group of valves is adjusted and the other, the anode group, in parallel through a disconnect reactor. For creation of a 12-pulse circuit with parallel connection of the converters it is also necessary to have a multiple of four valve groups. Three separating reactors are required in this case.

In cases where the power required to shape the pulses in the toroidal field winding reaches such large amounts that the direct feed from the network or from the electrode of mechanical units with flywheels is connected with engineering problems that are difficult to resolve and with high cost of equipment, the circuits with the application of inductive storage elements with an energy reserve that is no less than four times the reserve of the electromagnetic energy of the load turn out to be more expedient. As the source of charge of the storage elements, homopolar generators or valve converters can be used.

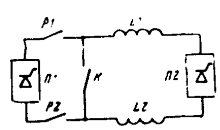


Figure 4. Diagram of the power supply with a decrease in the reactive power consumption.

When building feed systems with inductive storage elements, one of the basic problems is the creation of the high-power commutation equipment (disconnects). In a number of cases, for matching the parameters of the feed systems, the commutation equipment and the requirements advanced by the effort to realize optimal structural design of the device, it is expedient to use two winding inductive storage elements.

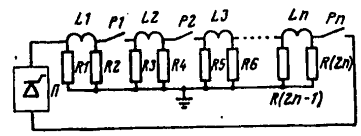


Figure 5. Diagram of the power supply of a superconducting winding. L1-Ln -- winding sections; П — feed converter; P1-Pn — disconnects.

In order to reduce the voltage on the inductive storage element and the toroidal field winding fed by it with respect to ground, both the storage element and the winding can be made sectional with series-alternate inclusion of the storage element sections and the winding.

A significant reduction in power of the power supplies of toroidal field windings can be achieved on application of a superconducting magnetic system. In this case a constant toroidal field is created, and the poloidal field and correction windings operate in the cyclic mode. Since the energy accumulation in a superconducting winding can take place over a prolonged time period, the power of the converter feeding the winding can be comparatively small. For example, in a toroidal field winding of the T-15 tokamak built at the present time, the current buildup takes place in two hours.

When creating the feed system of a superconducting winding, one of the serious problems is insurance of fast energy output from the winding on the occurrence of a normal phase of the conductor. A fast drop in the current can be achieved on introduction of an active resistance into the winding circuit. Here, the smaller the time constant of the circuit on output of the energy, the higher the voltage occurring on the winding. In order to reduce the winding voltage with respect to ground it is expedient to section the winding and insure energy output by the introduction of active resistances between the sections of the windings as a result of response of the breakers shunting the resistances.

One of the possible versions of such a system is illustrated in Figure 5. However, in this system, on inducing a current in the winding, imbalance occurs between the currents of the individual sections. The magnitude of this imbalance turns out to be comparatively small, for the excitation of the superconducting winding takes place for a voltage of quite small magnitude. After completion of induction of the current and a decrease in the voltage to zero in the sections, the imbalance decreases and reaches zero. The system in Figure 5 with execution of a winding from four sections was used to feed the toroidal field winding of the T-15 tokamak.

Obviously, hereafter when building sufficiently large-scale devices of the tokamak type, the application of the superconducting toroidal field windings will be the most expedient technical solution.

Feed Systems of Poloidal Field Windings. As is known, the creation of the plasma current in the tokamak type devices is insured by the induction method using the winding called an inductor. As a result of the peculiarities of the structural designs of the tokamaks, the inductor is located at comparatively large distances from the plasma column, the coefficient of magnetic coupling of the inductor to the plasma column is comparatively small, and the pulse power required from the power supply is determined to a significant degree by the reserves of electromagnetic energy and also the active losses in the plasma. The poloidal field is formed both by the inductor winding and the control windings designed to insure the condition of equilibrium of the plasma turn. The number of control windings is determined by the specific structural design of the electromagnetic system.

In spite of the fact that the feed system of the inductor cannot be considered insulated, without connecting the power supplies for the control windings, in a number of cases it is possible to create independent feed systems.

The inductor feed systems can be based on different principles: using the inductor of the primary winding of the transformer, the secondary winding of which is a plasma coil, and with the application of an inductor as an inductive energy storage element.

In each of these versions, in order to increase the range of variation of the inductive flux it is expedient to use demagnetization of the core, which when using an inductor as a storage element permits simultaneous decrease in power of the feed equipment and the commutation unit.

The shape of the plasma current pulse can be close to trapezoidal with a duration of the plane peak exceeding the rise and fall time of the current. A characteristic feature of the operation of the inductor power supplies is nonlinear nature of the load. The conductivity of the plasma varies by several orders, and the self-induction coefficient of the plasma coil also varies during heating and variation in size of cross section of the plasma column.

A comparatively large pulse power is required of the power supplies for fast rise of the plasma current, and appreciably less, for maintaining constancy of the plasma coil current. In systems with comparatively small energy reserves required to generate the plasma current pulses, artificial lines can be used as the power supplies. In order to decrease the effect of the variation of the load parameters on the processes in the official line, a ballast resistor is included in series with the inductor winding. This system was used to feed the TM-4A tokamak inductor for shaping the plasma current pulse with front and decline duration of two milliseconds and an area of 15 milliseconds. The current amplitude of the inductor winding was 9000 amps, the energy reserve in the capacitors of the artificial line, 0.4 Mjoules.

For a duration of the shaped pulse on the order of tens of milliseconds and required energy reserve of the inductor winding on the order of several megajoules, a feed system with capacitance pulse that is variable in time (see Figure 6) can be used as one possible version. The initial rise of the load current takes place as a result of discharge of the capacitor bank C1. Then the commutation of the capacitor banks charged to different voltages is realized by means of diodes. In this system the capacitance of the circuit varies automatically. This system was used on the T-3 device with four groups of capacitor banks with total energy reserve of 2M-joules.[1]

---

[1]Ibid.

In cases where the duration of the plasma current pulse exceeds tens of milliseconds, and significant energies of the power supplies are required, it is expedient to use combined circuits in which the rise in current is realized by a high voltage source, and maintenance of constancy of the current at the peak, by a low-voltage source included in series with the high voltage source. This system was used in the power supply for the inductor of the T-10 device (see Figure 7). A two-stage capacitor bank with total energy reserve of 5 Mjoules was used as the high-voltage source, and the П2 thyristor converter with a power of 40 megawatts, as the low-voltage source. In order to eliminate overvoltages on the anode transformer AT, which can occur at the beginning of discharge of the bank for defined ratios of the load inductance and the scattering inductance of the anode transformer, the converter П2 is shunted by the diode D1. The same result can be achieved for simultaneous ignition of two opposite arms of the bridge П2 and absence of the control pulses on the other valves of the converter in the time interval from the beginning of the discharge of the capacitor bank to the time the bank reaches a voltage equal to the voltage of the converter П2. As the high voltage source providing for fast rise of the plasma current, an inductive energy storage element can be used. The inductive storage element previously charged with the help of a converter transmits part of the stored energy to the inductor on response of the breaker that shunts the resistor R. After the current rises to the given value the resistor is shunted by a switch, and the inductor current is maintained by using a second converter.

In the investigated inductor winding feed systems, the induction coil was used as the primary winding of the transformer. With an increase in the inductor energy reserve and the required power, the systems using an inductor as an inductive storage element turned out to be more expedient. In such systems the power intake for initiation and the beginning of the rise of the plasma current was provided for by the inductor itself with release of the energy stored in it during the core demagnetization process. A further rise in the plasma current and maintenance of its given value can be insured by the converter. The power supply system based on these principles (see Figure 8) was used to power the T-15 tokamak inductor.

The demagnetization of the core is realized by the converter П with the commutators K1, K3 included. On completion of demagnetization, the converter П is converted to the inverter mode and the disconnect P responds simultaneously, introducing the resistor R into the circuit. A voltage will come up in the inductor winding in this case that will provide for breakdown in the discharge chamber and fast buildup of the plasma current. The inductor current decreases, and when it reaches zero, the switch 3 closes, the commutators K1, K3 open, and the commutators K2, K4 close. The inductor current begins to build up in the opposite direction, and the required law of variation of the inductor current is provided by the converter П. In the T-15 tokamak inductor feed system, an 80,000 amp, 1000 volt thyristor converter is used. The breaker provides a voltage of 8000 volts in the inductor.

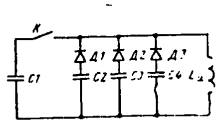


Figure 6. Circuit diagram with variable capacitance (L_i -- inductor winding).

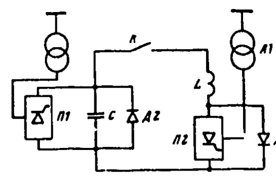


Figure 7. Power supply of the inductor with capacitor bank and dc power supply.

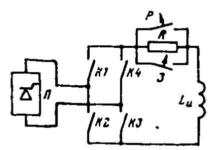


Figure 8. Inductor power system with mechanical reverser (K1-K4 — mechanical reverser commutators).

In connection with the development of the tokamak type devices, improvement of their parameters and an effort to achieve higher plasma parameters, the functions of the power supply systems have become more complicated. Whereas in the initial phase of development of the tokamaks on the T-3 device the poloidal field was determined by the inductor winding and currents induced in the massive housing, hereafter on the TM-4A and T-10 devices, it was necessary to install an additional control winding each to insure plasma equilibrium. The power supply system of the control winding of the T-10 tokamak provided for the creation of a pulse of special shape and was a 10 Mwatt thyristor converter which shaped the pulse as a result of variation of the adjustment angle using a programmed regulator.

In the developments of the devices of the next generation it was necessary to insure the exact equilibrium conditions of the plasma coil taking into account the ratio of the control field and the plasma current and also the influence of the gas dynamic pressure of the plasma column on the equilibrium condition. Therefore it turned out to be expedient to build inductor and control winding power supply systems by a united principle. For example, on the TM-4A device, both the inductor winding and the control winding are powered by identical devices -- artificial lines.

On the T-15 tokamak the control field is created by three windings, each of the power supply systems of which, just as the feed system of the inductor winding is a combination of a high voltage source and controlled thyristor converter for comparatively low voltage. In order to improve the equilibrium conditions of the plasma, these converters operate by the program corrected from pulse to pulse using regulators in the plasma column position function.

Further improvement of the conditions of equilibrium of the plasma is achieved by using, in addition to the control windings, auxiliary systems that provide for high-speed adjustment of the position of the plasma column using feedback. One of the versions of such a system is the device based on the principle of pulse-width regulation which it is proposed will be used on the T-15 device.

As was demonstrated, with the development of experimental thermonuclear devices, the energies and powers of the feed system increased and the functions of such systems also became more complicated. Since in the near future the transition from experimental to power engineering thermonuclear devices is expected, the requirements on the power supply systems will be altered. In addition to the necessity for creating devices characterized by energies on the order of megajoules and powers on the order of many hundreds of megawatts, feed systems with high operating reliability and high efficiency are required which are economical, completely automated with long operating reserve of each assembly and simple to maintain.

[161-10845]

10845
CSO: 1860

UDC 621.311.6.025

POWERFUL AC UNITS WITH INERTIAL ENERGY STORAGE ELEMENTS FOR FEEDING ELECTROPHYSICAL DEVICES

Moscow ELEKTROTEKHNIKA in Russian No 1, Jan 81 pp 20-22

[Article by I. A. Glebov, academician of the USSR Academy of Sciences, E. G. Kasharskiy, doctor of technical sciences, F. G. Rutberg, candidate of technical sciences, G. M. Khutoretskiy, doctor of technical sciences]

[Text] Autonomous power supplies are being used to feed some of the electrophysical loads having a short-term nature. If the required power levels are in the range of 10^8 to 10^9 watts with an energy of 10^8 to 10^{10} joules, the electromechanical unit operating with variable rpm is the preferred power supply. In this case, the energy of rotating masses is used. This energy is converted to the energy of a magnetic field or arc discharge on deceleration.

The electromechanical unit usually consists of a generator, flywheel and drive motor. In addition, auxiliary machines -- the control system sensors -- can be put on the shaft. Both turbogenerators and salient-pole synchronous motors are used for the short-term electromechanical units. The latter can be in both the horizontal and vertical positions. The role of the flywheel can be performed by a weighted generator rotor.

Such a storage unit has three characteristic operating conditions corresponding to the storage of power (acceleration), conservation of energy in an inertial storage element (idle without excitation or with excitation) and energy release (braking).

At the present time in Soviet practice definite experience has been accumulated in the use of standard synchronous generators in the braking mode on an active load. There is also foreign and Soviet experience in the design of special units for feeding electrophysical loads [1, 2, 5].

The purpose of this paper is to analyze the basic characteristics connected with the design and the operating conditions of such units.

The data on the largest units are presented in the table. Units with inertial storage elements are accelerated, as a rule, as a result of the application of asynchronous motors with phase rotor. In some devices with rpm close to synchronous, a thyristor frequency converter is connected to the circuit of the rotor winding of the motor, which permits smoother regulation of the rpm and also raising of it above synchronous. The application of the frequency starting method also appears to be prospective.

The primary problem which is solved when designing an energy storage element with a flywheel is insurance of the required level of storage power.

In the structural execution of the flywheels it is possible to isolate several basic areas (see Figure 1). The most important criterion for estimating the structural design of a flywheel is the specific energy capacity -- the ratio of the energy accumulated in it to its mass. The maximum achieved value of the specific energy capacity for isotropic titanium flywheels is approximately 100 joules/g; for steel flywheels it is approximately 60 joules/g, and for flywheels made of beryllium bronze, about 65 joules/g. However, for the isotropic flywheel with high specific energy capacity with respect to Figure 1,a, b there is a restriction on its energy capacity as a whole. The transverse (axial) size of such flywheels must not exceed 200-300 mm, which makes it possible to forge the flywheel from the lateral surfaces and also to realize effective ultrasonic and physical monitoring of the presence of microcracks and disturbances of the internal structure. Increased values of the admissible stresses are established by the strength conditions, respectively.

The diameter of the forging, in addition to the strength conditions, is also limited by the possibilities of the process equipment. Therefore for isotropic flywheels, according to Figure 1, a, b the stored energy is limited in the future to a value on the order to 10^8 joules for steel flywheels and $2 \cdot 10^8$ joules for titanium alloy flywheels.

A further increase in the amount of stored energy can be realized as a result of increasing the length with transition to cylindrical shape of the flywheel. Here the forging conditions are improved, the admissible stresses are decreased and, consequently the specific energy consumption is reduced. The modern technology for obtaining large cylindrical flywheels is based on the experience in manufacturing all-forged rotors for large turbogenerators. The specific energy capacity of such flywheels is 10-18 joules/g. According to [3] it is possible to assume that the manufacture of an all-forged steel cylindrical flywheel weighing about 300 tons is realistic. Such a flywheel obviously could store energy on the order of $4 \cdot 10^9$ joules.

Another area of manufacture of heavy flywheels is assembled rotors. Thus, the magnitude of the specific energy consumption of the flywheel built by the "Siemens" Company is 16 joules/g with a stored energy of $3.5 \cdot 10^9$ joules. The growth in the diameter of the assembled flywheels is also limited by strength conditions, and increasing the length is limited by the vibration resistance requirements.

Further increase in the amount of stored energy is possible by installing units with two or more flywheels each [2].

In the future nonmetallic composites formed by glass, quartz or similar fiber will have definite advantages for flywheel manufacture. Such materials have a high ratio of admissible voltage to specific weight (to $5 \cdot 10^6$ cm and higher). According to [4], in the near future the technical possibilities will permit the manufacture of flywheels with a specific energy capacity of 240-314 joules/g with an energy capacity of one flywheel to $0.7 \cdot 10^9$ joules. However, it is necessary to note that at the present time the manufacturing technology for large-scale flywheels made of nonmetallic materials has been insufficiently developed.

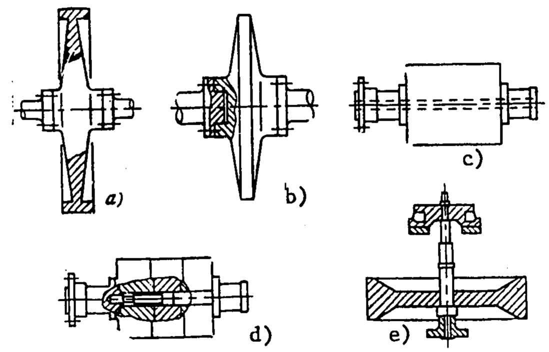


Figure 1. Structural forms of flywheels used for storage units.
a -- equal-strength; b -- conical; c -- cylindrical all-forged;
d -- cylindrical compositional; e -- with vertical shaft.

Another method of improving the general energy capacity of the unit is the transition to a structural design with vertical shaft. In this case the salient-pole generator approaches the hydrogenerator with respect to type. It is most expedient to match the flywheel to the generator rotor. The specific energy capacity of this rotor-flywheel does not exceed 1-5 joules/g, but on the basis of the increased load capacity of the thrust bearings by comparison with other bearings, and also as a result of the absence of vibrational restrictions in the future a total energy capacity on the order of 10^{10} joules and even higher can be reached here.

The most typical for the units with inertial storage elements are the feed conditions of either the magnet through the rectifier or the electric arc load. These operating conditions have been described in sufficient detail in [1]. Their basic difference consists in the fact that with arc loading it is desirable to output power as uniformly as possible, and on charging of the electromagnetic storage element (magnet) the largest current is reached at the end of the regime when there is a noticeable reduction in the rpm. This part of the regime is the harshest with respect to electromagnetic and thermal loads both with electric arc discharge and especially in the inductive storage element charging mode. At the same time the initial part of the braking mode when feeding the magnet is characterized by poor use of the generator with respect to power, inasmuch as the stator current increases on charging from 0 to the maximum value permitted by the thermal and thermomechanical restrictions. The choice of the law of regulation of the excitation during the process of braking of the unit has great significance. When feeding an active load, it is usually desirable to have the voltage invariant. Inasmuch as, as a result of the reduction in frequency during braking the generator emf decreases proportionally, the voltage level maintained using the excitation regulator must be taken as somewhat lower than rated (Figure 2, curves 1 and 2). The line 1 corresponds to more complete use of the energy capabilities of the flywheel. The saturation level with respect to the magnetic flux at the points of completion of the regime lies within the limits of 1.1-1.2, and in some cases, even higher.

When feeding the inductive storage element through the rectifier, it is efficient before the beginning of the regime to assume that the voltage is rated or even higher than rated by 5-10%. During the course of the feed regime, proportional reduction in the voltage can be permitted (Figure 2, curve 3). However, from the

Parameter	Manufacturing Company (country)					
	Siemens (FRG)		Toshiba (Japan)	General Electric* (USA)**	General Electric* (England)**	Prospectus** of General Atomics Co. for installation of Doublet III
Shaft position	Horizontal	Horizontal	Horizontal	Vertical	Vertical	Vertical
Structural design of generator	Salient-pole	Salient-pole rotor matched to flywheel	Nonsalient-pole	Salient-pole rotor matched to flywheel	Salient-pole rotor matched to flywheel	Salient-pole rotor matched to flywheel
Peak generator power, megavolt-amperes	167	95	125	475	--	260
Cos ϕ corresponding to peak power	0.9	0.9	0.8	0.7	--	--
Rated generator voltage, kv	2×2.75	6.6	3(phase)	13.8	--	--
Rated rpm	1500	1000	3600	--	225	--
Current frequency, hertz	110-85	51.5-48.5	120-96	90-63	90	--
No. of poles	8	6	--	--	--	--
Limits of variation of the rpm in the operating mode, rpm	1650-1250	1030-970	3600-2880	--	225-112	448-340
Rated power of the drive motor, megawatts	5.7	6	2.5	12.5	--	6.25
Weight of flywheel, tons	223	--	50	--	760	--
Total weight of unit, tons	400	225	130	--	--	270
Energy obtained from the flywheel masses in 1 cycle, megajoules	1450	26	210	2250	--	800
Acceleration time of the unit from 0 to operating rpm, minutes	20	--	20	--	--	--
Pulse duration of current in the machine, sec	24	1.25	3	6.7	To 30	6
Duration of 1 cycle, sec	360	2.6	243*	306	630	--

*By the presented oscillograms. **By the advertising data.

point of view of optimizing the regime it is desirable that the voltage be reduced more slowly than reduction of the rpm (for example, curve 4 in Figure 2). The indicated law must be supported by a special excitation regulator.

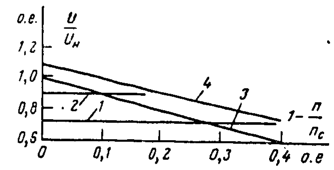


Figure 2. Variation of the voltage during braking for a load of various types. 1, 2 -- active arc load; 3, 4 -- load through the rectifier on the inductive storage element (magnet).

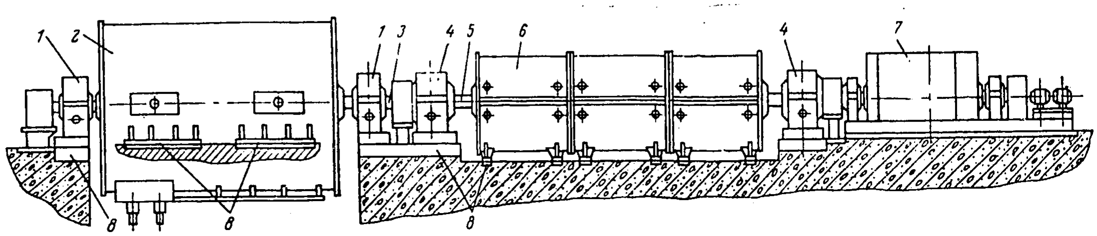


Figure 3. General view of the unit. 1, 2, 3 -- bearing, stator and rotor of the generator, respectively; 4, 5, 6 -- bearing, shaft and flywheel housing respectively; 7 -- induction motor; 8 -- base plates.

The necessity for feeding the storage element through a rectifier requires consideration of the inductance of the ac circuit when determining the commutation angle of the laws of the thyristor device. In turn, the commutation and adjustment angles influence the power factor of the device.

An analysis of the development of the power units for large electrophysical devices performed by the VNIIelektromash, made it possible to discover the necessity for developing a unit for short-term operation and substantiation of the level of the requirements imposed on it with respect to power and stored energy.

The unit with inertial energy storage element in the LPEO Association "Elektrosila" imeni S. M. Kirov was designed and put into production. It consists of a three-phase ac generator, flywheel and accelerating induction motor (Figure 3).

The unit accelerates to a rated rpm, it is excited and outputs a pulsed active load as a result of the energy of the rotating flywheels. Braking of the entire device takes place in this case.

Unit of the following technical specifications

Specific power, MV·A	242
cos ϕ	0.9
Rated current frequency, hertz	50
Rated voltage, kv	10.5

Rated rpm	3000
Limits of frequency variation in the operating mode, rpm	3000-2100
Flywheel moment, $kN \cdot m^2$	765
Annular velocity of the flywheel, m/sec	205
Pulse duration, sec	5

The generator is made in the form of a synchronous two-pole turbogenerator with all-forged rotor, with indirect air cooling of the rotor and stator windings. The frontal sections of the stator winding were also attached using glass textolite rings, brackets and inserts. The generator has a closed ventilation system, air coolers are built into the welded housing of the stator in order to remove the losses in the gaps between the pulse modes. The air circulation inside the machine is realized by means of fans seated on the rotor shaft. The rotor rests on two standing bearings with forced oil lubrication. At rated rpm the generator rotor stores energy of about $0.16 \cdot 10^9$ joules. The specific energy capacity of it is 5 joules/g.

A flywheel made in the form of an all-forged cylinder of a steel forging with high mechanical properties is directly coupled to the generator rotor through a half-coupling. The flywheel rotates in two characteristic standing slip bearings. The basic body of the flywheel is located inside the protected sectional housing equipped with air coolers. The energy stored by the flywheel at the rated rpm is $0.8 \cdot 10^9$ joules, and its specific energy capacity is about 10 joules/g.

On the side of the flywheel there is an accelerating induction motor with phase rotor of the radial power 4 megawatts. When starting, a rheostat is connected to the rotor winding. The engine with the bearings is located on a separate plate, on which the reference-voltage generator is also installed.

The unit can operate on an individual load and in parallel with other light generators. The calculated loading pulse reaches 3-5 sec. The braking of the unit with a reduction in the rpm by 20-30% will take place with automatic excitation control for maintenance of the voltage at the outputs of the generator within the given limits.

The excitation of the generator is provided independently of the thyristor stationary system, which also has the function of deexcitation on discharge of the load and during emergency shut downs of the unit.

Conclusions

1. The technical possibilities of heavy machine building permit provision for the creation of power supplies with short-term power to hundreds of megawatts with a stored energy on the order of 10^9 joules, and higher.

2. Further progress in the field of improving power and energy consumption of the units is connected with improving the structural designs of the generators and the flywheels, and the introduction of new materials and application of vertical structural elements.

BIBLIOGRAPHY

1. I. A. Glebov, E. G. Kasharskiy, F. G. Rutberg, SINKHRONNYYE GENERATORY V ELEKTROFIZICHESKIKH USTANOVKAKH (Synchronous Generators in Electrophysical Devices), Leningrad, Nauka, 1977.

2. E. G. Kasharskiy, A. V. Shabarova, "Inertial Storage Elements with High-Power Synchronous Generators," ELEKTROTEKHNICHESKAYA PROMYSHLENNOST' SER. ELEKTRICHESKIYE MASHINY (Electrotechnical Industry, Electrical Machine Series), Moscow, Informelektro, No 1, 1979.

3. I. A. Glebov, Ya. B. Danilevich, NAUCHNYYE PROBLEMY TURBOGENERATOROSTROYENIYA (Scientific Problems of Turbogenerator Building), Leningrad, Nauka, 1974.

4. C. E. Caveness, "Energy Storage through Long Term Flywheels," APPLICATION IEEE, 1976, Region Six (Western USA), conf. Tucson, Ariz., 7-9 Apr. 1976, N. Y., 1976, pp 119-124.

5. ATOMNAYA TEKHNIKA ZA RUBEZHOM (Nuclear Engineering Abroad), No 1, 1979, p 48.

[161-10845]

10845
CSO: 1860

UDC 621.313.291:621.039.9

PROSPECTS FOR THE APPLICATION OF SHOCK HOMOPOLAR GENERATORS FOR SUPPLYING POWER TO THERMONUCLEAR DEVICES

Moscow ELEKTROTEKHNIKA in Russian No 1, Jan 81 pp 23-25

[Article by G. A.Baranov, candidate of technical sciences, V. A. Glukhikh, doctor of technical sciences, B. G. Karasev, V. V. Kharitnov, candidates of technical sciences]

[Text] The development of plasma physics research and controlled thermonumclear fusion is accompanied by a constant increase in level of peak power released to load and the intake power. This is initiating further improvement of the new, prospective electric power supplies that are in wide use and mastery of them. This paper contains a discussion of the actual technical possibilities and the prospects for the application of shock homopolar generators (UUG) -- unipolar dc machines that generate current pulses in the dynamic braking mode of the rotor -- in thermonuclear research.

The power supply for the experimental thermonuclear devices from the UUG was realized in the first stages of research in this area. Attention is being given to the UUG also in modern nuclear physics. In the United States power supply systems are being developed for the theta-pinch thermonuclear reactors where UUG with kinetic energy reserves of 10^8 to 10^{10} joules and discharge currents of 10^6 to 10^7 amps have been selected as the power supplies. In a number of papers the expediency of using UUG to power the windings of the tokamak type devices also in plasmaphysics experiments is noted.

The prospectiveness of the UUG as a powerful energy-consuming electromechanical storage element and energy converter is based on an entire series of advantages of unipolar machines especially valuable when using it in the shock operating modes. First of all, it is necessary to note the absence in the UUG of special multiturn windings and a collector which usually greatly reduce the overload capacity of the machine with respect to current and limit the linear velocity of rotation of the rotor.

Good use of the active volume of the UUG defines the high values of the specific indexes of these power supplies. For illustration, the values of the specific energy capacity Q and the density of the stored energy q of the quadrupolar cylindrical UUG with steel magnetic circuit and massive smooth rotor are presented in Table 1. They are defined beginning with the volume and the mass of the entire UUG without considering the drive which, by the way, is unnecessary inasmuch as the rotor can accelerate to the required linear velocity in the motor mode of operation of the machine.

The maximum values of the specific indexes corresponding to the linear velocity of the rotation of the rotor at the periphery presented in Table 1 V = 300 m/sec are, in our opinion, entirely acceptable both from the point of view of the mechanical strength of the rotor and with respect to the current pickup conditions. When necessary, the value of q and Q can be increased by eliminating the steel magnetic circuit. In the range of stored energies and time for release of it under load characteristic of modern thermonuclear research (to 10^9 joules in a time on the order of 1 sec), sources of other types hardly have such specific indexes. Thus, in the impact synchronous generator with rectifier (USV) closest to the UUG with respect to its technical capabilities and capable in the dynamic braking mode of the rotor of conversion of an energy to 5000 megajoules in one cycle, the specific energy capacity $Q \approx 1.3$ kjoules/kg [1].

With respect to conversion and transmission of the stored energy to load, the UUG are also characterized by high indexes. For constancy of the excitation flux the discharge of the UUG is with respect to physical essence of the transient processes in the generator-load circuit, analogous, as is known, to the discharge of a capacitor bank having an equivalent capacitance $C_e = 2A_0/e_0^2$, where A_0 is the stored energy; e_0 is the no-load emf. With an active load in practice all of the stored energy is converted to electric power inasmuch as the mechanical losses in the UUG are incommensurably small by comparison with the peak generator power. Here the energy distribution and the discharge circuit depends on the ratio between the active resistances of the load and the UUG. The internal resistance of the UUG is small so that the greater part of the converted energy can be released in the active load.

For active-inductive load, which is the most characteristic for thermonuclear studies, all of the discharge characteristics of the UUG can be defined in terms of one dimensionless parameter -- the similarity criterion [2]

$$k = T_a/T_M,$$

where T_a is the electromagnetic time constant of the generator-load circuit; $T_M = 2A_0r/e_0^2$ is the electromechanical time constant.

For $k \leq 0.25$, the UUG discharge is of an aperiodic nature; for $k > 0.25$, it is also oscillatory damping. The efficiency of using the UUG for the active-inductive load can be estimated by the value of the coefficients: $A_{k*} = A_0 - A_k/A_0$; $W_* = W_H k_L/A_0 = W_{H*} k_L$; $A_{r*} = A_{H*} - W_*$; $\eta_H = W_H k_L/A_H$; $\eta_r = A_{rH} k_r/A_H$, where A_k is the kinetic energy of the rotating masses for maximum discharge current; W_H is the maximum magnetic field energy of the load; A_{rH} is the energy dissipated in the active load resistance; $k_L = L/L_H$ and $k_r = r/r_H$ are the load coefficients (L, r are the inductance and the active resistance of the generator circuit -- the load); L_H, r_H are the inductance and the active resistance of the load.

The relations for the indicated coefficients as a function of the similarity criterion k calculated in the most realistic range for large UUG with large energy reserve $0 < k \leq 3$, are presented in the form of graphs in Figure 1. As is obvious from Figure 1, for $k \leq 3$, up to 85% of the stored kinetic energy is converted to electromagnetic power, where up to 46% of the stored energy is converted to the magnetic field energy. Here, in the majority of cases in practice $W_* \approx W_{H*}$, inasmuch as the natural inductance UUG can be brought to very low values, on the order of 10^{-7} henries, executing its current-carrying elements by the bifilar type. Obviously, the actual values of the energy conversion factors of the UUG are better than the corresponding indexes of the high-energy storage elements of other types. For example, the USV can convert up to 75% of the kinetic energy of the rotor during one pulse [1]. However, it has more energy losses than the UUG from the energy dissipated in the generator windings, the matching transformer and the rectifier.

Table 1

v, m/sec	q, Mj/m^3	Q, kj/kg
150	10,1	1,29
200	18	2,31
250	28	3,62
300	40,5	6,15

Finally, it is necessary to note the simplicity and the variety of the structural diagrams of the UUG opening up the possibilities for broad variation of its parameters, the effective application of superconducting materials [3] and also improvement of the mass-size characteristics of the power system as a whole as a result of matching with the possible intermediate elements of the discharge circuit in one structural mode of the UUG: a matching pulse transformer [4], commutator [5], inductive storage element [6]. As an example, Figure 2 shows the structural diagram of the cylindrical type UUG that we developed matched with an inductive storage element. For efficient choice of the basic geometric dimensions of the device, this matching can be very useful. In Table 2 its parameters are presented which are calculated for the cases of transfer of 10 and 100 megajoules to the active load.

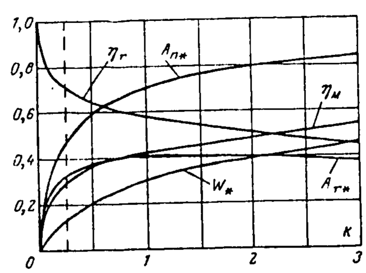


Figure 1. Graphical relations for the kinetic energy conversion factors of the rotor as a function of the similarity criterion k.

Along with the enumerated advantages, the UUG also have a number of disadvantages which limit the range of their application. Thus, the UUG is a high-current machine with comparatively low voltage, the level of which per unit, for example, for generators with ferromagnetic circuit, in practice does not exceed 800 volts.

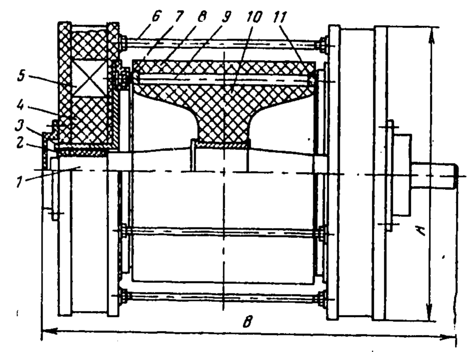


Figure 2. Structural diagram of the UUG matched with an inductive energy storage element. 1 -- rotor shaft; 2 -- bearing; 3 -- current conductor; 4 -- nonconducting insert; 5 -- excitation winding -- storage element; 6 -- fastening pins; 7 -- current pickup with hard brushes; 8 -- rotor band; 9 -- current carrying element of the rotor; 10 -- nonconducting part of the rotor (fiberglass); 11 -- contact rings.

Table 2

Parameter	Released power, megajoules	
	10	100
Maximum current, megamps	1	1
Energy release time, milliseconds	1	10
Maximum voltage on the load for current commutation, kV	100	100
Overall dimensions (without drive and commutator), meters	A=2.8; B=3.5	A=3.6; B'=6.5
Mass (without drive and commutator), tons	20	80
Specific indices:		
released power density, Mjoules/m^3	1	1.5
specific energy capacity, joules/kg	500	1250

Accordingly, it is not always possible to obtain optimal matching of the UUG parameters and the load. In modern UUG, the pickup of large currents from the motor in the majority of cases is carried out using liquid metal sodium-potassium alloy, the presence of which requires organizational and technical measures with respect to insuring safe operation of the device.

In connection with the prospectiveness of the application of the UUG in thermonuclear research at the Scientific Research Institute of Electrophysical Equipment imeni D. V. Yefremov, work is being done which is aimed at improving the efficiency of the use of these machines. The primary engineering problems are directly or indirectly connected with the necessity for increasing the no-load voltage of the UUG. Here, along with such general technical problems of machine building as improving the induction of the excitation magnetic field on the basis of using superconducting materials, increasing the linear rotation rate of the rotor in the active zone, the application of effective gas rotor bearings, it is also necessary to solve specific problems, among which the primary one is the creation of a high-speed, high-current, current-pickup, far from operating at linear velocities to 300-400 m/sec and current densities to 10^8 amps/m^2 in the sliding contact.

In order to accumulate experience in the development, operation and maintenance of superconducting UUG, a disc type generator was made and tested with liquid-metal current pickup and superconducting excitation winding made of composite aluminum bus [7]. The basic specifications for this generator are as follows: armature diameter 0.32 meter; linear velocity in the sliding contact 50 m/sec; no-load emf 17 volts; maximum discharge current 110 kamps; peak power 770 kilowatts; maximum induction of the magnetic excitation field 3.4 tesla.

Work is being done on the application of gas rotor bearings in such UUG located directly in the active zone of the machine; the bearing surface is the side surface of the rotor disc. Their use simplifies the structural design in the operation and maintenance of the generator, it insures cleanness of the inside cavity of rotor assembly. The flow of gas escaping from the bearing is used to prevent leakage of the liquid metal of the current pickup devices into the structural gaps. The experienced UUG of the disc type with flat gas dynamic bearing confirms the high efficiency of such machines [8].

A number of experimental models of high-speed current pickups of different types have been built and studied. Satisfactory results were obtained on the models in which sodium-potassium liquid metal alloy is used for the current pickup. The primary difficulty in building a reliable liquid metal pickup arises, as is known, from instability of the liquid metal flow in the narrow annular gaps between the rotating and stationary elements of the sliding contact. In order to keep the liquid metal in the contact zone, various types of steels of the labyrinth type were used in a number of models and experimental UUG permitting a current of up to 700 kiloamps to be picked up at velocities to 150 m/sec in the sliding contact [9]. At higher velocities, the investigated steels turns out to be insufficiently effective. In this case, continuous pumping of the liquid metal through the contact zone was provided for with exit of it from the cavity of the current pickup. In a number of models and experimental UUG, this procedure is used for the current to be picked up with linear velocity in the sliding contact on the order of 200 m/sec [10]. Obviously, there are no theoretical restrictions on picking up currents on the basis of pumping the metal through the contact zone even at higher velocities.

In the models of the current pickups with hard brushes, a study was made of the possibility of applying standard brushes in the UUG used in the high-current electric machines. When testing models of the MG, MGSO, EG2AF, 6110M and other brushes with a cross section of 1.5 cm^2, the following results were obtained: linear velocity in the sliding contact 200 m/sec; specific pressure on the brush required to insure stable sliding contact, $3.8 \cdot 10^3$ Pa; time of pressing the brush againstthe rotor 5 sec; maximum admissible current density with respect to the operating reliability conditions in the sliding contact 1500-1800 amps/cm^2; the contact voltage drop was 2.2-2.5 volts; the brush wear during operation for 5 seconds for the indicated current densities to 0.5 mm [11]. The presented data agree with the results of the experimental studies of other authors [12]. The characteristics of the investigated brushes obviously would be somewhat better with less operating time under load.

Nevertheless, from the point of view of the application of such brushes in a large UUG with high discharge current, they do not satisfy the imposed requirements, inasmuch as the brush assembly based on them would be very awkward (several hundreds of brushes per current pickup), complex and insufficiently reliable. A search for new brush materials, for example, carbon fiber [6] permitting the level of admissible current density in the contact to be raised, is needed.

On the basis of the experimental studies of current pickups the NIIEFA has built two large UUG. The two-disc generator with loop type magnetic circuit having a no-load emf of 80 volts and a stored energy of 4 megajoules was used to test the high-current commutating equipment with currents to 700 kiloamps [13]. The four-pole cylindrical UUG with annular magnetic circuit (80 volts, 40 metajoules) is designed to test an inductive storage element [10]. Both machines have an outside rotor diameter of about 1 meter and liquid metal annular current pickups operating with linear velocities in the sliding contact on the order of 150 m/sec.

Conclusions

1. The prospects for using UUG in thermonuclear research are determined by the theoretical possibility of simple and effective storage and conversion of large energies on a level of 10^8 to 10^9 joules with a peak power per unit on the order of 10^9 watts and discharge currents of 10^6 to 10^7 amps. In this case, the UUG are advantageously distinguished from the other pulse sources with approximately the same parameters by high specific indexes, simplicity of the structural designs, and minimum auxiliary equipment.

2. The experimental studies and operation and maintenance of individual models of the UUG confirm the actual possibility of creating reliable and effective large broad-application power systems based on them already at the present time.

BIBLIOGRAPHY

1. L. P. Gnedin, E. G. Kasharskiy, F. G. Rutberg, "Prospects for the Application of Turbogenerators to Obtain Large Pulse Powers when Feeding Powerful Plasmatrons," ELEKTROTEKHNIKA (Electrical Engineering), No 3, 1971, pp 3-7.

2. B. G. Karasev, I. V. Lavrent'yev, V. V. Kharitonov, "Discharge of a Shock Homopolar Generator with Constancy of the Excitation Flux," ELEKTROFIZICHESKAYA APPARATURA (Electrophysical Equipment), Moscow, Atomizdat, No 5, 1966, pp 3-6.

3. V. V. Kharitonov, A. Yu. Koretskiy, "Unipolar Machines with Superconducting Excitation Winding," Preprint of the OAB -- 11, Leningrad, NIIEFA, 1976, 60 pp.

4. V. V. Kharitonov, "Discharge of a Shock Homopolar Generator Using Pulse Transformers," Preprint A-0210, Leningrad, NIIEFA, 1974, 14 pp.

5. V. N. Artemov, B. G. Karasev, V. V. Kharitonov, "Study of a Liquid-Metal Sliding Contact of Unipolar Machines," UNIPOLYARNYYE ELEKTRICHESKIYE MASHINY: DOKLADY KONFERENTSII (MOSKVA, MART, 1969) (Unipolar Electrical Machines: Conference Reports (Moscow, March 1969)), Moscow, Informelektro, 1969, pp 150-154.

6. A. E. Robson, et al., "An Inductive Energy Storage System based on a Self-excited Homopolar Generator," PROC. 6TH SYMP. ENG. PROBL. FUSION RES., SAN DIEGO, CALIFORNIA, 1975, New York, N. Y., 1976, pp 298-302.

7. V. N. Artemov, et al., "Development and Study of a Homopolar Generator with Superconducting Excitation Winding," Preprint A-B-0262, Leningrad, NIIEFA, 1976, 13 pp.

8. G. A. Baranov, et al., "Shock Homopolar Generators with Gas Rotor Bearing," DOKLADY VSESOYUZNOY KONFERENTSII PO INZHENERNYM PROBLEMAM TERMOYADERNYKH REAKTOROV (LENINGRAD, 28-30 IYUNYA 1977) (Reports of the All-Union Conference on Engineering Problems of Thermonuclear Reactors (Leningrad, 28-30 June 1977)), Leningrad, NIIEFA, Vol 3, 1977, pp 28-35.

9. V. N. Artemov, et al., "Liquid Metal Current Pickup of a Shock, Disc-Type Thermopolar Generator," ELEKTROFIZICHESKAYA APPARATURA, Moscow, Atomizdat, No 14, 1976, pp 102-107.

10. V. A. Glukhikh, et al., "Development of a Shock Homopolar Generator for Feeding a High-Current Electron Accelerator," Preprint A-0294, Leningrad, NIIEFA, 1976, 17 pp.

11. V. V. Kharitonov, B. G. Karasev, "Current Pickups with Solid Brushes in Shock Homopolar Generators," ELEKTROTEKHNICHESKAYA PROMYSHLENNOST'. SER. ELEKTRICHESKIYE MASHINY (Electrotechnical Industry. Electric Machines Series), Moscow, Informelektro, No 12, 1972, pp 6-7.

12. R. A. Marshall, "Design of Brush Gear for High Current Pulses and High Rubbing Velocities," IEEE TRANS. POWER APPAR. AND SYSTEMS, Vol 85, No 11, 1966, pp 1177-1187.

13. Ye. A. Bezgachev, et al., "Disc-Type Shock Homopolar Generator," Preprint A-0222, Leningrad, NIIEFA, 1974, 14 pp.

[161-10845]

10845
CSO: 1860

UDC 621.313.17.001.3

DISC TYPE SHOCK HOMOPOLAR GENERATOR WITH GAS ROTOR BEARING

Moscow ELEKTROTEKHNIKA in Russian No 1, Jan 81 pp 25-28

[Article by G. A. Baranov, candidate of technical sciences, V. N. Skripunov, engineer, V. V. Kharitonov, candidate of technical sciences]

[Text] The realization of a number of designs of large thermonuclear and electrophysical devices is connected with the development of pulse electric power supply systems capable of storing energy on the order of 10^8 to 10^9 joules and transmission of it to load in a comparatively short time measured in milliseconds, tenths of a second and seconds depending on the type of user.

The electromechanical systems based on shock homopolar generators (UUG) are prospective in this area. The massive rotors of these generators are used as effective mechanical storage devices which convert the kinetic energy stored over a quite long period of time into electromagnetic energy of a single high-current pulse in the dynamic braking mode. In this case the UUG is connected either directly to the load or to an intermediate inductive storage element.

The pulse power supply for the indicated parameters, as is known, is a large system, the overall dimensions, occupied areas and the cost of which frequently significantly exceed the corresponding indexes pertaining to the load itself. Accordingly, the advantages of the UUG as a storage element and energy converter are manifested more completely, and the area of its application expands if the machine is characterized by high values of the specific indexes: energy capacity, energy density, relative mass, specific loads, relative cost, and so on.

One important factor, if not the main factor, in increasing the efficiency of the UUG is increasing the admissible angular velocity of the rotor and bringing it to 300 m/sec or more. Here, the development of the UUG is connected with the known current pickup problem, in the solution of which definite progress has been made in recent years. However, the problems of suspension and locking the rotor in the bearings and also the composition of the rotor assembly are requiring important significance.

In this paper a discussion is presented of the problems of creating UUG with gas rotor bearing having a number of advantages by comparison with roller and slide bearings. The application of gas in a slide bearing as the lubricant makes it possible to reduce the friction losses in it and increase the admissible annular velocity of the sliding element, to simplify the structural design and the operation and maintenance of the UUG and insure planeness of the inside cavity of the rotor

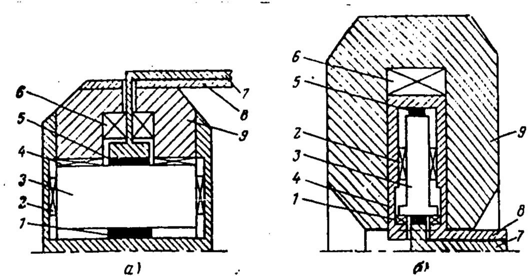


Figure 1. Structural diagrams of the UUG of the cylindrical (a) and disc (b) types with gas bearings. 1, 5 -- current pickups; 2, 4 -- gas bearings; 3 -- rotor; 6 -- excitation winding; 7, 8 -- current conductors; 9 -- magnetic circuit.

assembly. The last fact is especially important for UUG in which liquid metals are widely used for current pickup from the rotor. The flow of gas escaping from the bearing can be used also to prevent the liquid metal from getting into the working gaps of the generator [1]. The gas bearings differ advantageously from the roller bearings by greater efficiency and operating reliability in powerful magnetic fields (for example, in the excitation field of the UUG without ferromagnetic circuit) disturbing the normal functioning of the standard roller bearings as a result of the conduction or induction effect on the conducting elements.

The structural design of the UUG with gas rotor bearing is found to be the most efficient if the bearings are placed directly in the active zone of the machine, using the side or end surface of the rotor as the bearing surface (Figure 1). This permits the creation of a highly compact UUG without a traditional shaft with the bearing assemblies for the electrical machine. The acceleration of the rotor in this case is carried out in the motor operating mode of the device. The compact two-pole UUG shown in Figure 1 or their rotor assemblies can be successfully used as base modules when developing multirotor structural designs of UUG [2]. There are other advantages of the presented structural diagrams. As is obvious from Figure 1, the current-carrying elements of the generator, as a result of the application of gas bearings, can be executed in such a way that the electrodynamic forces applied to the rotor and the current pickups mutually compensate for each other. This solution or the realization of it opens up broad prospects for the creation of UUG for high currents, the magnitude of which in practice is not limited by the electrodynamic stability of the sliding contacts [3].

For accumulation of experience in the development, operation and maintenance of UUG with gas rotor bearings the NIIEFA Institute imeni D. V. Yefremov has built and tested an experimental disc-type generator with flat gas bearing and liquid metal current pickup based on sodium-potassium alloy.

The generator is a disc unipolar machine of vertical execution without ferromagnetic circuit. As the drive, a high-speed dc motor is used which is connected to the generator by means of a throw-out coupling. For testing the UUG in the shortcircuit mode, a special liquid metal switch was used which is connected directly to the output buses of the generator.

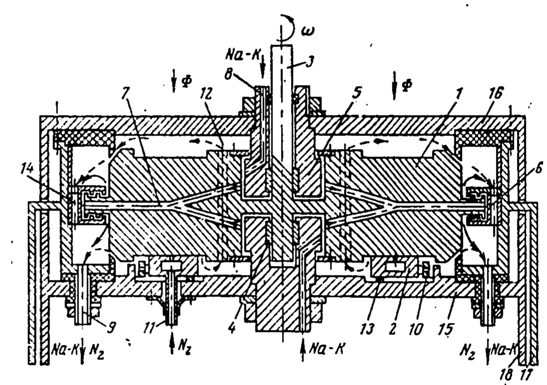


Figure 2. Rotor assembly of the experimental UUG. 3 -- rotor shaft; 17 -- output bus.

The structural design of the rotor assembly is shown in Figure 2. The rotor 1 of the generator about 0.3 mm in diameter is fixed by means of a gas bearing 2 which takes its weight (24 kg) and the radial slip bearing 4, the inserts of which are made of copper-graphite materials. In the center of the rotor and on the periphery there are annular liquid-metal current pickups 5 and 6. The central and peripheral devices are connected to each other by radial channels 7, through which the liquid metal goes to the periphery after feeding it to the central part through the channels 8.

For mutual compensation of the electrodynamic forces acting on the rotor during discharge of the generator, the current tapping buses 15 and 16 are located on both sides of the rotor disc, outside of which they are joined and connected by the current conductor 18 to one of the power electrodes of the switch.

The gas fed to the bearing through the connecting pipe 11, leaking out of it, flows not only around the lower, but also the upper end surfaces of the rotor. For this purpose, in it there are axial openings 12, and between the gas bearing and the surface of the bus 15 there is an elastic annular baffle 13. The gas flow goes out of the cavity of the rotor assembly through the channels 9 and 14 which are also used to take off the liquid metal. The path traveled by the liquid metal is shown by the arrows made up of a solid line. The gas flows have been noted by a dotted line.

The gas bearing of the rotor is a hollow ring with outside diameter of 0.19 m and inside diameter of 0.12 m fastened in the suspension 10 of the Cardan type. In the ring, 48 holes 0.5 mm in diameter were made, from which the inert gas (nitrogen) escapes under pressure $(1\text{-}4)\cdot 10^5$ Pa.

With respect to type, this bearing is a gas static annular bearing with one-sided lubricating layer. In order to feed the gas to the lubricating layer on the order of 40 microns thick from the feed openings, a choke with an annular diaphragm is used. The choice of the annular diaphragm arises from the high stability of the bearing with vibration of the "jackhammer" type [4]. The basic characteristics of the bearing -- the number and diameter of the feed openings, thickness of the lubricating layer, gas flow rate, pressurization pressure -- were determined beginning with the condition of maximum rigidity of the gas layer according to the data of [4].

The structural diagram of the liquid-metal switch [5] is presented in Figure 3. It is made in the form of coaxially arranged contacts 1 and 2 separated by the insulator 3. An elastic diaphragm 4 separates the inside cavity of the electrode 1

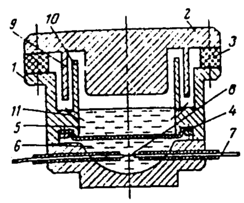


Figure 3. Structural diagram of a liquid-metal switch.

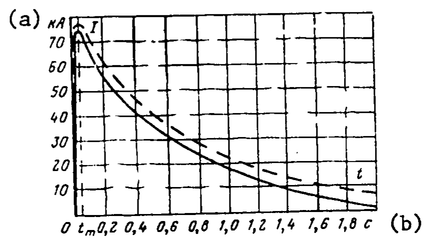


Figure 4. Oscillogram of the generator discharge current.

Key: a. kiloamps b. seconds

into two parts. In the upper part there is liquid metal 5 (a sodium-potassium alloy), between the free surface of which and the contact 2 there is an intercontact gap. A dielectric liquid 6 (transformer oil) in which the discharge electrodes 7 have been installed which are connected by an exploding conductor 8, is poured into the lower part under the diaphragm. In the upper cavity of the switch there are cylindrical baffles 9 and 10 which protect the surface of the insulator 3 from contamination by its liquid metal. Poles 11 are made in contact 1 through which the metal getting into the screen zone leaks back.

The operating principle of the switch is based on displacement of the liquid metal using the energy of the electrical explosion of the wire 8 in the liquid. The duration of the closed state of the contacts 1, 2 is determined in the given case by the time the liquid metal 5 is in contact with the contact 2. The volume of liquid metal poured into the cavity of the switch was about 1 liter. The closing time of the contacts did not exceed 0.2 milliseconds. The energy of the capacitor used to explode the copper wire 8, 0.5 mm in diameter and 20 mm long, is 1.7 kjoules. The parameters of the exploding wire were calculated by [6].

The generator was discharged in the following sequence. Nitrogen was fed to the intake chamber of the bearing from a special tank under a defined pressure. The rotor "floated" with a clearance of 30-40 microns. Then it was accelerated by the drive motor to a speed of 12,000 rpm, and the excitation winding was connected to the power supply. Then liquid metal was fed to the central current pickups, the drive motor was disconnected, and the switch contacts were closed. After stopping the rotor as a result of its dynamic braking, the liquid metal feed to the current pickups and the gas feed to the bearing stopped.

Figure 4 shows the oscillogram (solid line) of a characteristic discharge current pulse obtained for the following values of the parameters: initial linear velocity of rotation of the rotor in the peripheral zone of the sliding contact v = 135 m/sec, no-load emf E = 3.5 volts, kinetic energy stored in the rotor A = 100 kilojoules, the excitation field induction on the axis of rotation at the center of the inductor B = 0.28 tesla. The maximum discharge current I = 75 kiloamps, the current buildup time to a maximum t = 0.04 sec, the current pulse duration 2 seconds, the peak electromagnetic power 250 kilowatts.

In Figure 4 the dotted line indicates the calculated function i = f(t) obtained on the basis of integration of the emf equation and the voltage drops in the discharge loop and the equation of motion of the rotor. The parameters L and R of the discharge circuit were determined experimentally from experience in including the circuit under dc voltage.

The presented studies demonstrated that the gas bearing operate stably in the entire range of linear velocities of rotation of the rotor which could be obtained during the course of the experiments, beginning with the possibilities of the drive (to 180 m/sec on the periphery of the rotor).

Figure 5 shows the load capacity of the bearing statically as a function of the pressure P_H in the pressurization chamber for different gaps h between the bearing and the rotor. For the rotor to rise above the surface of the bearing by a distance h = 10 microns a pressure of $p_H = 10^5$ Pa is needed. With an increase in the pressure to $p_H = 3.2 \cdot 10^5$ Pa for h = 10 microns, the load capacity of the bearing increased to 243 kg. The gas flow rate with lift of the rotor by a distance h = 10 microns was 5 m^3/hr; for h = 30 to 40 microns, about 20 m^3/hr. The rigidity of the lubricating layer was about 10^7 N/m.

The experimental studies also demonstrated that the liquid metal switch insures reliable arcless commutation of large pulsed currents. The electrical explosion of the wire is realized in a dielectric liquid which is selected from the condition of exclusion of the active interaction of it with the liquid metal (especially with highly aggressive alloys based on alkali metals) in the case of rupture of a rubber diaphragm. In the given design, replacement of the exploding wire when preparing the switch for operation is not connected with unsealing the cavity with the liquid metal, which eliminates the possibility of oxidation of it and simplifies introduction of the new wire into the electrode gap.

The generator tests confirm the reliability and effectiveness of the developed structural diagram on the basis of which it is possible to create compact storage devices. For example, placing a defined number of rotor assemblies executed by the given system and connected electrically in series, in one superconducting solenoid, it is possible to obtain a quite high-voltage UUG. On rotation of the rotors in mutually opposite directions, the effect on the solenoid and the foundation of the braking moment are eliminated, which significantly facilitates the development of the structural design of this system. The rotor assemblies can be located either beside each other or one above the other, that is, arguing by the requirements of composition, the development of the structure in length or height. According to the estimates, this device containing, for example, 10 series-connected rotors 2 meters in diameter and 0.3 meters thick can have very high tecnical indices: the total length is 5 meters; the average operating induction is 4 tesla; the linear velocity of rotation of the rotor at the periphery is 300 m/sec; the maximum current

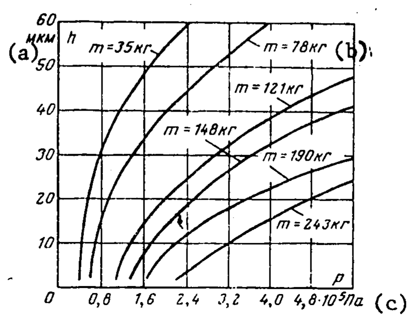


Figure 5. Load characteristics of a gas bearing

Key: a. microns b. kg c. Pa

density in the sliding liquid-metal contacts is $50 \cdot 10^6$ amps/m^2; the storage kinetic energy is 1500 megajoules; the no-load emf is 6000 volts; the maximum discharge current is 10^7 amps; the total mass of the rotor assembly is $100 \cdot 10^3$ kg; the gas pressure in the pressurization chamber of the bearing is $2.5 \cdot 10^5$ Pa; the total gas flow rate in the bearings is 0.15 m^3/sec; the mass of the superconducting inductor $20 \cdot 10^3$ kg; amount of helium for cooling the inductor 15 m^3; helium flow rate for maintaining the superconducting state of the inductor 0.1 m^3/hr; ratio of the energy stored by the generator to its total mass $12.5 \cdot 10^3$ joules/kg.

BIBLIOGRAPHY

1. G. A. Baranov, V. N. Skripunov, V. V. Kharitonov, USSR Author's Certificate No 584402, Unipolar Machine, Published in V. I. [Inventions Bulletin], No 46, 1977.

2. G. A. Baranov, V. N. Skripunov, V. V. Kharitonov, USSR Author's Certificate No 582555, Multidisc Homopolar Generator, Published in V. I., No 44, 1977.

3. G. A. Baranov, B. G. Karasev, V. N. Skripunov, V. V. Kharitonov, USSR Author's Certificate No 584401, "Rotor Assembly of a Shock Homopolar Generator," Published in V. I., No 46, 1977.

4. S. A. Sheynberg, V. P. Zhel'- M. D. Shishenev, OPORY SKOL'ZHENIYA S GAZOVOY SMAZKOY (Slide Bearings with Gas Lubrication), Moscow, Mashinostroyeniye, 1969.

5. B. G. Karasev, V. N. Skripunov, "Pulse Liquid Metal Switch for Strong-Current Circuits," ELEKTROFIZICHESKAYA APPARATURA (Electrophysical Equipment), Moscow, Atomizdat, No 14, 1976, pp 99-101.

6. V. K. Rakhuba, N. K. Stolovich, "Optimization of the Process of Energy Conversion in the Case of Electric Explosion of Wires in a Liquid," ZHTF (Technical Physics Journal), Vol XIII, No 6, 1973, pp 1222-1227.

[161-10845]

10845
CSO: 1860

UDC 621.313.17.001.5

GAS BEARINGS OF THE ROTORS OF HIGH-SPEED UNIPOLAR MACHINES

Moscow ELEKTROTEKHNIKA in Russian No 1, Jan 81 pp 28-31

[Article by G. A. Baranov, candidate of technical sciences, N. D. Zablotskiy, doctor of technical sciences, V. S. Karpov, candidate of technical sciences, I. Ye. Sipenkov, candidate of physical and mathematical sciences, V. N. Skripunov, engineer, V. V. Kharitonov, candidate of technical sciences]

[Text] Gas bearings are a tested means of solving a number of problems in modern machine building connected primarily with increasing the rotor rpm. In particular, in electric machine building, this type of bearing permits a significant increase in the operating efficiency of high-speed unipolar machines, especially shock homopolar generators (UUG). The application of gas bearings in UUG not only decreases the power losses, but also insures high purity of the inside cavity of the rotor assembly, simplifies the structural design and the operation and maintenance of the UUG [1].

The UUG used at the present time are, as a rule, large electric machines having high power and energy capacity. Therefore the bearing capacity and diameter of the gas bearings of such machines must be quite large. For example, for thermonuclear studies UUG are needed with a rotor mass to 50 tons and with linear velocities on the periphery of the rotor on the order of 300 m/sec. The diameter of the thrust bearing of such a rotor can reach 0.5-1 meter, and the radial bearing, 0.2-0.4 meters.

The NIIEFA Institute imeni D. V. Yefremov has developed, manufactured and tested two experimental UUG with vertical rotor supported by gas bearings. First a disc UUG was built (Figure 1, a) with a rotor mass of 24 kg, in which a gas bearing was used -- an annular bearing with forced pressurization of the gas -- and two radial bearings which are ordinary self-lubricating slide bearings made of graphite. As a result of the development and testing of this version of the UUG, the conclusion was drawn of the expediency of continuing operations in this direction. Later, a UUG was built and tested with a larger rotor (110 kg) in which not only a thrust bearing but also radial bearings were gas bearings with pressurization (Figure 1,b). In addition, the rotor of the second UUG, in contrast to the first, was made of ferromagnetic material.

In both experimental generators, all of the external static load (rotor weight) was taken by the thrust bearing to which the gas lubricant (nitrogen) was fed through one series of feeders with flow rate limiters of the annular diaphragm type [2] uniformly arranged around the periphery of the thrust bearing at the same distance from its inside and outside circuits. The radial gas bearings of the second generator had two rows of analog feeders each removed from the ends of the bushing by a distance equal to a quarter of its length. The schematic diagram of the bearing assembly of the rotor with gas lubrication of the bearings is shown in Figure 2. The advantages of bearings with this pressurization system are relative simplicity of manufacture and sufficient reliability.

The gas dynamic theory of lubrication establishes the basic criterion of the optimal design of gas bearings with pressurization -- "the regime parameter" [3], which for bearings with annular diaphragms has the following structure:

$$m = BnN\delta / h_0^2 p_s, \qquad (1)$$

where p_s is the pressure in the pressurization chamber, h_0 is the characteristic thickness of the lubricating layer of the bearing; δ is the feeder diameter; n is the number of series of feeders; N is the number of feeders in a row; B is the coefficient which depends on the physical properties of the gas and its temperature; for nitrogen when T = 288 K, B = 0.042 kg/sec^2.

The nature of the effect of the regime parameter on one of the basic operating characteristics of the bearing -- the specific static rigidity K -- is illustrated in Figure 3 [2], where $p_{a*} = p_a/p_s$ is the ratio of the outside pressure to the pressurization pressure. The curves were calculated for a collar bearing.

As is obvious from Figure 3, with an increase in the number of feeders the rigidity increases asymptotically, approaching a finite limit which can be interpreted as the rigidity of the bearing with linear source ($N \to \infty$). The theoretical model of the "pressurization lines" is based on this [3], which provides for approximation of the series of discrete feeders by a linear source and permits significant simplification of the calculation of the gas bearings. As the criterion of applicability of this model for engineering estimates it is possible to recommend the condition

$$l_1/l_2 \gtrsim 1, \qquad (2)$$

where ℓ_1 is the distance of the feeder to the nearest exit cross section of the lubricating layer; ℓ_2 is the distance between adjacent feeders. As applied to the bearings used in the UUG with rotor mass of 110 kg, this condition gives N > 20 for the thrust bearing and N > 12 for the radial bearing; in reality, these bearings had 36 and 18 feeders in a row, respectively.

On the basis of the model of "pressurization lines," the following calculation formulas are obtained for the basic static characteristics of a thrust bearing with annular diaphragms -- bearing capacity W, axial rigidity W_h and volumetric flow rate of the lubricant Q (reduced to atmospheric pressure p_a):

$$\left.\begin{aligned}
&W = Ap_s w; \quad w = \frac{1}{3}\frac{(p_{d*} - p_{a*})(2p_{d*} + p_{a*})}{p_{d*} + p_{a*}};\\
&W_h = -\left(\frac{\partial W}{\partial h}\right)_{h=h_0} = \frac{Ap_s}{h_0}K;\\
&K = \frac{4p_{d*}(p_{d*} - p_{a*})(p_{d*} + 2p_{a*})\,\vartheta(p_{d*})}{3(p_{d*} + p_{a*})\{2p_{d*}\vartheta(p_{d*}) - (p^2_{d*} - p^2_{a*})|d\vartheta(p_{d*})|/|dp_{d*}|\}};\\
&Q = \beta Nh\delta\,[p_s/p_a]\,\vartheta(p_{d*}).
\end{aligned}\right\} \qquad (3)$$

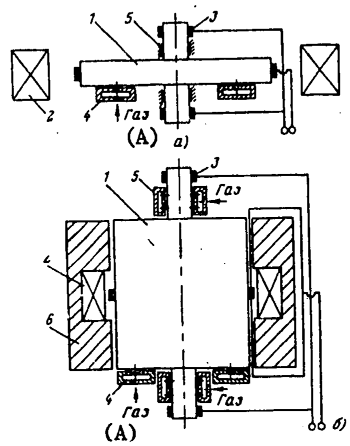


Figure 1. Structural diagrams of homopolar generators. a -- disc type; b -- cylindrical type. 1 -- rotor; 2 -- excitation winding; 3 -- current pickup; 4, 5 -- gas bearings; 6 -- magnetic circuit.

Key: A. gas

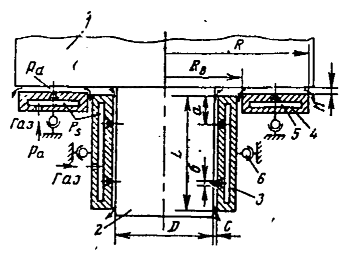


Figure 2. Bearing assembly of the rotor with gas-lubricated bearings. 1 -- rotor; 2 -- journal; 3 -- radial bearing; 4 -- thrust bearing; 5 -- pressurization chamber.

where w is the specific bearing capacity; K is the specific rigidity; $A = \pi(R^2 - R_B^2)$ is the area of the bearing surface of the thrust bearing; R, R_B is its outside and inside radii; h is the thickness of the lubricating layer; $p_{d*} = p_d/p_s$ is the ratio of the pressure over the pressurization line to the pressure in the pressurization chamber.

The function $\theta(p_{d*})$ expressing the law of escape of the flow through the limiter is described by the approximate Prandtl formula for limiters of the diaphragm type [3]

$$\theta(p_{d*}) \approx \begin{cases} 1, & p_{d*} \leq 0,5; \\ 2\sqrt{p_{d*}(1-p_{d*})}, & p_{d*} \geq 0,5. \end{cases} \qquad (4)$$

The coefficient β in the last formula (3) depends on the physical properties of the gas and its temperature; for nitrogen when T = 288 K, $\beta = 6.3 \cdot 10^2$ m/sec.

The value of p_{d*} is defined as the solution of the algebraic equation

$$\frac{p^2_{d*} - p^2_{a*}}{\theta(p_{d*})} = m\xi; \quad \xi = \frac{\ln r_0}{\ln r_e} \ln \frac{r_0}{r_B}, \tag{5}$$

where r_B, r_0 are the inside radius and the radius of the pressurization line reduced to the outside radius of the thrust bearing.

This equation is also valid for an unloaded radial bearing with two pressurization lines if we set $\xi = a/D$, a is the distance of the pressurization line from the end of the bushing; D is the bushing diameter.

In Figure 3 the dotted line indicates the sections of the curves corresponding to the critical regimes accompanied by the occurrence of inertial effects disturbing the normal operation of the bearing [2]. From equations (4) and (5) it follows that the critical pressurization occurs for

$$m \leqslant m_{\text{кр}} = \frac{0,25 - p^2_a}{\xi}. \tag{6}$$

In the one-way thrust bearing which is used in the developed UUG, instead of the characteristic thickness of the lubricating layer h_0, the self-setting working clearance h, previously unknown, is introduced into the expressions (1) and (3). In this case, by the initial data and using the condition of static equilibrium of the rotor G = W (G is the external axial load, in the given case the weight of the rotor) and expressions (3) for the reaction of the lubricating layer W, the absolute pressure above the pressurization line p_d is calculated directly. It can be considered also as the lower limit of the admissible pressures in the pressurization chamber

$$p_{s\,\min} \approx p_d = 2\tau(1 + \sqrt{1 + \tau^{-1}})\, p_a, \tag{7}$$

where

$$\tau = \frac{1}{8}\left(1 + \frac{3G}{Ap_a}\right).$$

As the upper limit, beginning with condition (6) it is expedient to take the value of $p_{smax} \approx 2p_d$. The range of $p_d < p_s < 2p_d$ corresponds to the range $\infty > m > m_{cr}$ in which, according to Figure 3, the maximum specific rigidity is reached. Therefore it is possible to give p_s in such a way that for the corresponding values of p_{d*} and p_{a*} the parameter m uniquely related to them (for the given ξ) by equation (5) will satisfy the condition $m = m_{opt}$ for which the specific rigidity is maximal.

After the calculated value of the parameter m is found from expression (5), it is necessary to use expression (1), replacing h_0 in it by h for determination of the self-adjusting value of the operating gap h, by which, using expression (3), it is possible to calculate the axial rigidity and the flow rate. Here it is necessary to be convinced of satisfaction of the conditions

$$h < \frac{\delta}{4}; \; h > h_{\min}, \tag{8}$$

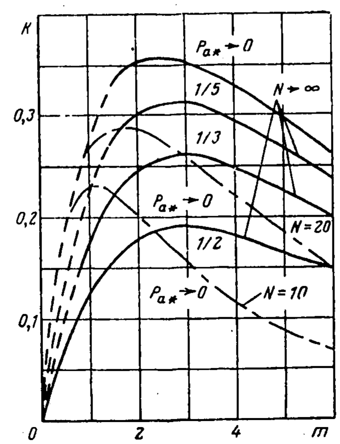


Figure 3. Specific static rigidity K as a function of the regime parameter m. - - - - - — critical pressurization regime.

the first of which indicates that the annular diaphragm functions as a flow rate limiter, and the second, which reflects the level of manufacturing technology and precision of the assembly, indicates absence of dry friction. Usually $h_{min} \geq (1$ to $2)\cdot 10^{-4} L_0$, where $L_0 = R - R_B$ for the collar bearing. If the conditions (8) are not satisfied, it is necessary to vary the initial data or the pressurization pressure and perform the calculation again.

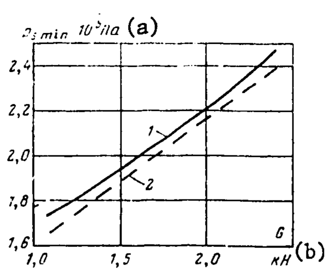


Figure 4. Minimum pressurization pressure $p_{s\ min}$ as a function of the load G. 1 -- experiment; 2 -- calculation.

Key: a. Pa b. kN

On the basis of the expressed procedure, the thrust bearing of a homopolar generator with rotor weighing 110 kg was calculated for the following initial data defined by the structural, technological and operating arguments: the outside radius R = 0.23 m, the inside radius R_B = 0.12 m, feeder diameter δ = 0.6 mm, outside pressure p_a = $1\cdot 10^5$ Pa, nitrogen is the lubricant. The calculated value of the pressure on the pressurization line turned out to be $p_d = 1.66 \cdot 10^5$ Pa, which approximately corresponds to the experimental data presented in Figure 4. The maximum specific rigidity is reached for a pressure in the pressurization chamber $p_s = 2.2 \cdot 10^5$ Pa. The corresponding value of the parameter m is about 2.5; in this case the working gap h = 40 microns, that is, the conditions (8) were satisfied. As a result, the absolute axial rigidity of the thrust bearing $W_h = 35 \cdot 10^6$ N/m, and the lubricant consumption reduced to atmospheric pressure, $Q = 3.6\ m^3$/hr.

The radial loads occuring as a result of residual unbalance Δ, under the effect of which the rotor axis completes rotation by a circular trajectory on rotation of it, were taken by radial gas bearings with a diameter of 0.09 m.

The length of the bearingsL = 0.11 mm, the number of pressurization openings M = 18, the hole diameter δ = 0.6 mm were selected on the basis of recommendations made in [4] for radial bearings with ideally balanced rotor. The magnitude of the clearance C was determined beginning with the requirement of insurance of a radius of trajectory ε_r acceptable with respect to the operating conditions and stable operation of the rotor in the entire range of given velocities.

In order to decrease ε_r, it is necessary to lower the residual unbalance of the rotor or increase the lubricating clearance C; the latter, however, leads to a decrease in the threshold rpm of the rotor. Therefore the clearance C must be selected in some range, the lower bound of which is determined by the condition $\varepsilon_r \leq 0.5$ C, which is satisfied if $\Delta_* \leq 0.1$ [5], and the upper bound, by the condition $\omega_{max} \leq \omega_0$, where ω_{max} is the maximum rotor rpm; ω_0 is the threshold rpm; $\Delta_* = \Delta/C$ is the relative unbalance of the rotor.

The threshold rpm of the rotor was defined by the formula [5]

$$\omega_0 = 2\left[-\frac{1}{M}\left(\frac{\partial W}{\partial \varepsilon}\right)_{\varepsilon=0}\right]^{0.5},$$

where $\left(\frac{\partial W}{\partial \varepsilon}\right)_{\varepsilon=0}$ is the rigidity of the lubricating layer of the bearings without rotation of the rotor for zero eccentricity ε.

The rigidity of the bearings was determined experimentally by the expression:

$$\left(\frac{\partial W}{\partial \varepsilon}\right)_{\varepsilon=0} = \frac{Mg}{\varepsilon},$$

where $\varepsilon = C - h_{min}$; h_{min} is the minimum thickness of the lubricating layer; M is the mass of the rotor; g is the gravitational acceleration.

The rotor of the homopolar generator had a residual unbalance Δ = 1 micron, C = 33 microns, which exceeded the lower bound C > 10 microns.

The calculated value of the threshold velocity using the procedure of [4] for this clearance was $\omega_0 = 2200$ 1/sec, and considering the experimentally defined rigidity (61 MN/m) $\omega_0 = 1470$ 1/sec (for a pressure $p_{a*} = 0.17$). The maximum rotor rpm reached at idle and limited by the possibilities of the drive, ω = 1250 1/sec. Here the gas flow rate through the radial bearings Q = 17.5 m^3/hr.

It must be noted that the radial magnetic attraction of the rotor caused by asymmetry of the excitation winding field had significant influence on the admissible rotor rpm of the UUG with gas bearings. Depending on the field magnitude, the admissible rpm was reduced to 600-800 1/sec. In subsequent operations more detailed study of this phenomenon is proposed.

The electrodynamic forces of interaction of the current conducting rotor and stator elements for discharge currents on the order of 20-40 kiloamps had no noticeable influence on the operation of the bearings, as a result of the in practice complete mutual compensation of these forces in the rotor.

A shock homopolar generator of the cylindrical type with magnetic circuit and gas bearings of the rotor, the diameter of which was 0.23 m with a length of 0.57 m, was tested. As the current pickups, liquid metal was used (indium-gallium-tin alloy). The generator was tested in the repetitive-short term modes.

The tests of the generators with vertical axis of rotation of the rotor demonstrated their reliable operation even without the upper gas thrust bearing provided for in the design, which greatly simplified both the adjustment of the gas bearings and the process of assembling the rotor assembly. The gas radial bearings and the thrust bearings were placed in self-adjusting Cardan devices, and they were made of nonmagnetic materials, and this, in turn, excluded the influence on them of magnetic scattering fields of the inductor and facilitated the assembly of the generator as a whole.

Conclusions

1. The gas bearings of a shock homopolar generator are set for operation in the required rotor rpm range.

2. The procedure for calculating the gas rotor bearings is suitable for engineering practice.

3. In the subsequent developments of shock homopolar generators it is expedient to recommend the application of gas bearings in machines without ferromagnetic circuit. In such machines in practice there is no radial magnetic attraction of the rotor complicating the reliable operation of the gas bearings.

BIBLIOGRAPHY

1. G. A. Baranov, et al., "Shock Homopolar Generators with Gas Rotor Bearings," DOKLADY VSESOYUZNOY KONFERENTSII PO INZHENERNYM PROBLEMAM TERMOYADERNYKH REAKTOROV (LENINGRAD, 28-30 IYUNYA 1977) (Reports of the All-Union Conference on Engineering Problems of Thermonuclear Reactors (Leningrad, 28-30 June 1977)), Leningrad, NIIEFA, Vol III, 1977, pp 28-35.

2. N. D. Zablotskiy, V. S. Karpov, I. Ye. Sipenkov, D. K. Zaytsev, "Study and Calculation of Gas Bearings with Pressurization for Large, High-Speed Rotors: Report of the Leningrad Polytechnical Institute imeni M. I. Kalinin," Deposited at the VINITI, No B803342, 1979.

3. L. G. Stepanyants, "Some Methods of Gas Dynamic Lubrication Theory," TRUDY LPI IM. M. I. KALININA (Works of Leningrad Polytechnical Institute imeni M. I. Kalinin), No 280, 1967, pp 27-43.

4. Ye. G. Grudskaya, N. D. Zablotskiy, "Characteristics of a Flexible, Gas-Lubricated Radial Bearing," MASHINOVEDENIYE (Mechanical Engineering), No 5, 1976, pp 65-69.

5. V. S. Karpov, "Effect of the Shaft Unbalance on the Resonance Frequency and Stability of a Hybrid Gas Bearing," MASHINOVEDENIYE, No 6, 1979, pp 87-93.

[161-10845]

10845
CSO: 1860

UDC 621.039.637

CAPACITIVE STORAGE ELEMENTS AS A SOURCE OF POWER FOR CONTROLLED THERMONUCLEAR FUSION

Moscow ELEKTROTEKHNIKA in Russian No 1, Jan 81 pp 31-37

[Article by B. V. Yefimov, S. L. Zayyents, candidates of technical sciences, G. S. Kichayeva, engineer, M. V. Kostenko, corresponding member of the USSR Academy of Sciences, G. S. Kuchinskiy, doctor of technical sciences, professor, V. A. Popova, O. V. Shilin, P. I. Shkuropat, candidates of technical sciences, G. A. Shneyerson, doctor of technical sciences, V. L. Shutov, engineer]

[Text] The performance of physical research connected with the solution of the problem of controlled thermonuclear fusion (UTS) requires the study of the required values of the current, voltage and energy in the given mode. The choice of one energy storage element or another (see Table 1) is determined by the requirements of the performed experiment. Thus, the capacitive storage elements (YeN) which are considered in this paper, inferior to other types of storage elements with respect to specific energy capacity, have an indisputable advantage in cases where it is necessary to provide fast energy input to load. The YeN have small internal resistance (to 10^{-3} ohm) and permit the use of high voltage (to 10^{7} volts). Therefore YeN is the only type of energy source insuring a power of up to 10^{13} watts and a current buildup rate to 10^{14} amps/sec under laboratory conditions in the low-inductive load. If the criteria of suitability of the storage element for the research program on UTS are its technical characteristics, then in the case of thermonuclear power plants (TYaES), the cost of the produced electric power acquires important significance. This requires provision of a service life of the basic elements of the YeN corresponding to the service life of the standard electrical equipment.

The schematic diagram of the capacitive storage element is presented in Figure 1 where its basic functional systems are indicated. Let us consider the significance of the individual systems and their component elements.

The capacitor bank KB is designed for storing the required energy. The charge unit ZU provides for raising the voltages on the capacitor to the given value. The commutation system CK is designed to isolate the load from the KB in the charging mode and connect the load to the KB in the discharge mode. The basic elements of the CK are commutators (controlled dischargers) and the control systems for them. The connecting elements of the storage element SE are used to transmit energy from the capacitor bank to the CK and the collector K to the load H. The control, blocking and signal system UBS insures normal safe operation of the storage element.

Table 1. Basic parameters of the storage elements

Type of storage element	Energy per unit volume W', megajoules/m^3	Maximum power P, watts	Power per unit volume P', watt/m^3	Characteristic energy transmission time τ, sec
Capacitive	0.1-0.5	10^{12}-10^{13}	10^{11}	10^{-4}-10^{-8}
Inductive	10-40	10^8-10^9	10^9	10^{-8}
Mechanical	100	10^7-10^8	10^8	0.1-10
Storage element	200-500	10^6-10^7	10^7	1-10
Explosives	10,000	--	--	10^{-6}

The largest technical difficulties when developing the storage elements occur in connection with insurance of the following requirements:

Achievement of maximum energy density (more than 0.1 megajoules/m^3);

Effective energy transmission to the low-inductive load;

Maximum high current buildup rate in the load (above 10^{13} amps/sec);

Obtaining large currents (more than 10^7 amps);

Accumulation of high energy (more than 10^7 joules).

Basic parameters characterizing the capacitive storage element are the following: rated voltage U_0, stored energy W_0, current in the load I_0, natural induction L_0, discharge period or current buildup rate on the load T, dI/dt. They can vary for different storage elements within broad limits, depending on each other; therefore it is inexpedient to classify the YeN with respect to any one attribute. In [1] the classification of the storage elements was proposed by the following attributes:

The charge voltage -- low voltage storage elements (to 10 kv), medium voltage (10-100 kv) and high voltage (above 100 kv);

Stored energy -- low-energy storage element (to 100 kjoules), medium (to 1000 kjoules) and high-energy (above 1000 kjoules);

Current pulse duration -- millisecond, microsecond and nanosecond storage elements.

The value of the stored energy to a significant degree determines the requirements on the reliability of the individual elements of the storage element and also its cost.

The current pulse duration first of all determines the requirements on the structural design of the YeN from the point of view of the magnitude of its natural inductance. In addition, the time range imposes restrictions on the admissible magnitude of electric field intensity in the capacitor insulation and, consequently, the specific energy capacity of the YeN. Thus, in the storage elements in the nanosecond range, in which distilled water is used as the dielectric, it is possible to obtain an energy density to 1 millijoule/m^3.

The capacitive storage elements are distinguished with respect to the method of connecting the capacitors in the discharge mode. When it is necessary to insure a high current in the load, the capacitors of the YeN are connected to the load in parallel so that the currents of the individual capacitors are added [the pulse current generator system (GIT)]. If necessary to obtain a high-voltage pulse on

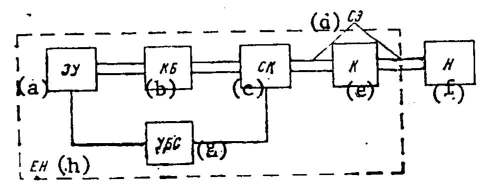


Figure 1. Schematic diagram of the capacitive storage element.

Key:
a. ZU = charging device
b. KB = capacitor bank
c. CK = commutation system
d. SE = connecting elements
e. K = collector
f. H = load
g. UBS = control, blocking and signal system
h. YeN = capacitive storage elements

the load, the YeN capacitors are connected in the discharge mode in series [the pulse voltage generator circuit (GIN)]. When using series capacitors in the YeN connected to each other and to the load by means of special connecting elements with relatively large characteristic inductance, the characteristic discharge time of the YeN, t turns out to be much larger than the traveling time of the wave along the discharge circuit τ. In this case the discharge conditions are quasistationary. Excluding the inductance of the internal connections, the capacitor can be converted to a line with distributed parameters. The discharge mode in this case is defined by the parameters of the external circuit and the capacitor output, and it will be wave if $L_H + L_B \tilde{<} L_\ell$ and $R_H \tilde{<} Z_0$, gd L_H, L_B are the inductances of the external circuit and the lead-outs of the capacitor, respectively; R_H is the active load resistance; Z_0 is the wave impedance of the line; $L_\ell = C_k Z_0^2 = L'\ell$, where L' is the inductance per unit length of the uniform line; L is the line length; C_k is the capacitance of the capacitor. Such lines permit us to obtain current and voltage pulses when operating on a low impedance load with a duration on the order of 10^{-7} seconds and less [2] and insurance of the highest current buildup rates -- to 10^{14} amps/sec and a power to 10^{13} watts [3]. At the present time, along with the traditional storage elements executed by the GIN or GIT system, a large number of nanosecond shaping lines (NFL) are in operation with output voltage to 10 MV and stored energy to 10^6 joules. Such shaping lines and the GIN's are described, for example, in [3].

Table 2. Characteristics of the capacitive storage elements for medium voltage level.

Device	W_0, megajoules	U_0, kilovolts	L_0, nanohenries	τ_1, microseconds	I_0, megaamps	Type of discharger
"Seyllac"(USA) [4]	10	60	0.44	--	180	Stage
"Isar-1" (FRG) [5]	2.7	40	4.1	9.5	21.3	--
"Shiva" (USA) [6]	25	20	--	500	--	Ignitron
GIT-50 (USSR) [7]	0.05	50	5	1	5	Solid state
GIT-2700 (USSR) [8]	4.7	30	3	9.5	20	Vacuum
GIT-1000 (USSR) [9]	1.0	150	40	2.5	8.0	Trigatron

Note. τ_1 -- current pulse buildup time.

Table 3. Characteristics of certain types of high voltage pulsed capacitors

Type of capacitor (manufacturer)	Voltage kv	Capacitance, microfarads	Inductance, nanohenries	Reserve, pulse	Reliability	Specific energy, joules/dm^3	Maximum current, kiloamps
IK-6-150 TSCh ("Kondensator" PO**)	6	150	60	10^4	--	98	50
PK-40-594 ("Kondensator" PO)	40	5	40	10^3	--	60	200
IK-50-ZU4 ("Kondensator" PO)	50	3	40	10^3	0.99*	57	200
IK-100-04 ("Kondensator" PO)	100	0.4	150	$5\cdot10^2$	0.99*	90	50
KMK-30-10 (LPI)	30	10	10	10^4	--	65	400
KMK-60-2 (LPI)	60	2	20	10^3	0.95*	160	300
KMK-100-0.5 (LPI)	100	0.5	20	10^3	--	110	150
ESC-248A (Cornell Dubille Electric, USA)	20	15	5	--	--	75	--
CD-11148 (BICC, England)	100	0.625	204	$2\cdot10^4$	--	55	--

*These data, in contrast to all of the previously presented data, were obtained when testing real capacitors.

**Production association.

***Leningrad Polytechnic Institute.

In this article a study is made of the capacitive storage elements made by the circuit for parallel connection of capacitors (GIT) which have become the most widespread as a source of large pulsed currents (to 10^8 amps) with high buildup rate (to 10^{13} amps/sec). The parameters of some of the storage elements are presented in Table 2. The high-energy GIT contains 10^2-10^4 like elements. Therefore from the point of view of reliability this GIT is a complex system.

The effort to simplify the installation and servicing of the storage element has led to the fact that the GIT with large energy reserve is assembled from relatively large standardized modules -- cells. However, there is an energy limit which can be stored in an individual cell. The indicated limit is connected with the danger of explosion on breakdown of one of the capacitors as a result of discharge in it of individual cell capacitors. As the special experiments and operating practice of the GIT have demonstrated, the cell energy, depending on the type of capacitors used, must not exceed 10-50 kilojoules. When using special protection measures, for example, electroexplosion fuses, the cell energy can reach 100-200 kilojoules.

When developing the GIT, the following problems arise which follow from the general requirements on the capacitive storage elements;

The creation of capacitors with increased specific energy;

Insurance of low natural inductance of the GIT;

Development of a commutation system with high carrying capacity;

Insurance of the required reliabilities and service lives of the capacitive storage elements.

Creation of Capacitors with Increased Specific Energy. At the present time, the specific energy for the majority of types of pulse capacitors will be about 0.1 megajoules/m^3 (Table 3). The primary ways of increasing the specific energy include the use of new polymer film materials having increased strength with large electrode areas and high dielectric constants. Good results are achieved as a result of the application of combined film-paper and film insulation based on polyethyleneterephthalate (lavsan) film with castor oil impregnation or impregnation with synthetic liquid dielectrics (phenoxylylethane) in which the paper is used as the wick to improve the insulation impregnation process.

The operating intensities of the film-paper insulation are expediently selected so that the paper impregnation will work for intensities corresponding to operation of the insulation of the pulse capacitors with paper insulation. Here the average operating intensity of the combined dielectric E_{comb} depends on the relative paper content in it χ (with respect to the thickness of the combined dielectric), that is,

$$E_{комб} = E_б[(1-\varkappa)\varepsilon_б + \varkappa\varepsilon_п]/\varepsilon_п,$$
(a)

Key: a. comb

where ε_b and ε_π are the dielectric constant of the paper and the film, respectively.

For $\varepsilon_b > \varepsilon_\pi$, $E_{comb} > E_b$.

The specific energy of the capacity with combined dielectric having a dielectric constant ε_{comb},

$$W_{уд.комб} = \frac{\varepsilon_{комб} E^2_{комб}}{2} = \frac{\varepsilon_б E^2_б}{2\varepsilon_п} [(1-x)\varepsilon_б + x\varepsilon_п] = W_{уд.б}[(1-x)\varepsilon_б + x\varepsilon_п],$$

Key: a. spec.comb b. comb c. spec.b

where $W_{spec.b} = \varepsilon_b E_b^2/2$ is the specific energy of the capacitor with paper dielectric.

As follows from the last expression, with an increase in the film content in the combined dielectric $W_{spec.comb}$ will increase more the higher the ratio $\varepsilon_b/\varepsilon_\pi$. However, on making the transition to purely film insulation in order to increase the specific energy of the capacitor it is necessary to be oriented toward the application of films with increased dielectric constant.

At the present time the application of paper-film and film insulation will permit the creation of individual types of capacitors designed for limited service life in the aperiodic discharge mode with reduced reliability, but with specific energy to 0.5 Mjoule/m^3.

Insurance of Low Natural Inductance of the GIT. The natural inductance of the GIT L_0 must be much less than the load inductance L_H in cases where it is necessary to convert the energy of the storage element W_0 with maximum efficiency to the energy of the magnetic field of the load $W_M = i_m^2 L_H/2$, where i_m is the current amplitude. This follows from the expression for the use coefficient of the storage element

$$\eta = \frac{W_м}{W_0} = \frac{L_н}{L_0 + L_н},$$

which is closer to 1 the smaller the ratio L_0/L_H.

In a number of cases the problem arises of obtaining a current with high initial buildup rate in the inductive load $(di/dt)_0 = U_0/(L_0 + L_H)$. Then for the given voltage of the storage element U_0, the total inductance of the discharge circuit $L_0 + L_H$ must be minimized.

The inductance of the GIT on the order of units and fractions of a nanohenry can be insured using parallel inclusion of a large number of elements (cables, buses, commutators, capacitors). Here the requirements on the parameters of the individual elements are more rigid, the smaller the number of them.

The inductance of a system of two parallel conductors with direct and return currents separated by an insulating gap can be reduced by decreasing the gap and the length of the conductors or by increasing their width. The conductors can be brought closer together as a result of using insulation with high electric strength.

As applied to the connecting elements, a small inductance is achieved as a result of using flat buses with solid insulation or coaxial cables. Sometimes it is structurally more convenient to use closed conducting screens forcing the flux out of the region between them instead of bringing the forward and return wires directly closer together. The procedure for calculating the electromagnetic field is discussed, for example, in [9-12].

The effort to decrease the natural inductance of the GIT poses the problem of optimizing its structural design. The experience in developing the GIT indicates that the structural design in which the inductances of the basic systems (the capacitor bank, commutators, connecting elements) are commensurate is optimal.

An optimization example is presented in [13] for GIT in which the connecting elements are cables connected over the entire plane to the collecting mains -- collector in the form of two sheets separated by a layer of insulation with a thickness h. The load is connected to the edge of the capacitor. A similar method of connecting the cable is used in the "Seyllac" device [4]. If the buses have the shape of a rectangle of length ℓ_1 and fixed width ℓ_2, then with invariant number of current conductors connected in the bus section with an area equal to one, the inductance of the GIT, with an increase in ℓ_1, first decreases as a result of an increase in the number of parallel-connected elements, and then it increases as a result of buildup of the inductance of the plane buses. Figure 2 shows the use factor of the GIT as a function of the ratio of the collector inductance $L_k = \mu_0 h\ell_1/\ell_2$ to the equivalent inductance of the remaining systems of the GIT $L' = L_c + L_T + L_p$ for different values of the load inductance. Here L_c, L_T, L_p are the inductances of the capacitors, the current conducting cables and commutators calculated for one current lead to the buses. As is obvious from Figure 2, η increases sharply on variation of the ratio L_k/L' from 0 to 1; then it changes smoothly in the range of $1 \leq L_k/L' \leq 10$, after which it decreases. The maximum value of the use factor $\eta_{max} \approx L_H/(L_k + \sqrt{L'L_k})$.

The effort to increase the number of cables without changing the collector inductance led to the use of the spatial structures of the latter. In these structures it is possible to increase the effective width of the buses with invariant dimensions of them in plan (the latter are determined by the required magnitude of the energy density on the load). As an example we have the "Isar" box buses [14]. Inclusion of them in parallel (Figure 3) permits solution of the problem of insuring small equivalence induction of the cables and collectors simultaneously for given dimensions of the current pickup.

The requirements on the parameters of the GIT which is designed to feed the load with inductance close to zero will become especially rigid. Here the voltage between the buses decreases on approaching the load, and it approaches a minimum at the exit for $L_H \to 0$. This permits us to use interbus insulation of variable thickness, which gives no noticeable gain in the magnitude of the collector inductance [13].

Large Current Commutation. In modern YeN both single and multiple-action commutators are used. In the first case the system of dischargers must insure multiple commutation of the currents reaching tens of millions of amperes in some of the storage elements without damaging the electrodes and the bearing structures.

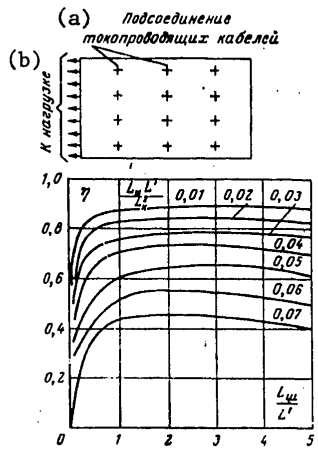


Figure 2. Use coefficient of the GIT as a function of the ratio of the GIT element inductances and load.

Key: a. connection of the current conducting cables
b. to the load

Table 4. Characteristics of powerful GIT commutators

Type of discharger	U_0-U_m, kv	I_M, M·amps	q, coulombs/pulse	N	τ, nanoseconds	σ, nanoseconds	L, nanohenries	ψ
IRT-4 ignitron [23]	50-1	0.2	23	10^2	1000	300	85	--
Vacuum discharger [16]	30-1	2.0	20	10^2	200	20	5	--
Vacuum discharger, LPI*[17]	40-1	1.5	70	10^4	150	20	7	10^{-4}
Vacuum discharger, LPI [18]	100-1	1.5	70	10^4	200	20	10	10^{-4}
Commutator on sliding discharger of LPI [19]	50-1	1.0	20	10^3	50	(5)	1-5	--
Solid-state, two-channel discharger [21]	50-10	1.0	--	10^3	1000	100	5	--
LPI multichannel solid state discharger [22]	50-25	1.5	10	--	50	5	1	--

Note. U_m-U_0 is the range of controllability with respect to voltage; I_M is the maximum multiply switched current; q is the carrying capacity per pulse; N is the service life (the number of inclusions without noticeable variation of the characteristics); ψ is the probability of voluntary response.

*Leningrad Polytechnic Institute.

The choice of the GIT commutator, the development of the schematic diagram and the structural design of the commutation system (SK) are determined on the whole primarily by the rated voltage of the capacitor bank U_0, the given range of operating voltages from U_m to U_0 (usually $U_m \leq 0.2U_0$), the amplitude and the characteristic current pulse time which must be insured in the load, the admissible magnitude of the inductance and also the operating reliability requirement.

For fast inclusion of the YeN to the load at a given point in time, commutators are used in which controlled pulse breakdown of gas, liquid or solid insulation is realized. It is necessary to note that commutators with liquid dielectric are not used in the GIT as a result of the very small stability of the electrical characteristics.

The u·ed commutators are distinguished by variety of structural versions and control methods [9]. The use of controlled semiconductor commutators (thyristors) which comparatively recently began to be used in pulse engineering and are still used only for commutation of low-voltage YeN in the millisecond range operating at small currents appears to be highly prospective.

The commutation of the currents of 10^7 to 10^8 amps requires the creation of a SK consisting of a large number of dischargers operating in parallel, as a result of which the required carrying capacity and low equivalent inductance of the SK are insured. Here problems arise in insuring synchronous inclusion of a large number of commutators and high operating reliability of each commutator, difficulty in the solution of which increases with an increase in the number of commutators [15]. Since the number of parallel-included elements in the SK is determined by the parameters of each of them, the effort to decrease the number of commutators in the YeN requires the creation of commutators with large carrying capacity with respect to current and small natural inductance.

Insurance of the high carrying capacity of the commutator requires primarily a reduction in the current density in the commutator. This can be achieved in the commutators with diffuse and multichannel shape of the discharge as occurs in vacuum dischargers [16-18], dischargers based on sliding discharge with respect to the surface of the dielectric [19] and also in the multichannel gas [20] and solid-state dischargers [21, 22]. In addition, in order to reduce the erosion of the electrodes in the dischargers, special inserts are used made of tungsten-containing composites, and forced displacement of the discharge channel over the surface of the electrodes as a result of electrodynamic forces is also used, which decreases the operating time of the channel influencing individual sections of the electrodes [17].

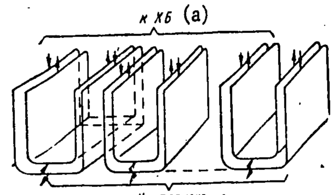


Figure 3. Box collector.

Key: a. to the KV b. to the load

The limiting values of the currents switched by one discharger reached at the present time are several megaamperes (Table 4). Therefore in some cases (for currents on the order of 10^6 amps) the commutation system of the storage element can be made quite simple, in the form of a discharger with the corresponding control system.

For large values of the current, the use of several commutators operating in parallel is unavoidable. The synchronous operation of these commutators is important both from the point of view of effective use of the energy of the storage element and from the point of view of emergency-free operation of it.

Reliable parallel operation of the dischargers can be insured in the GIT by decoupling of them in time, using collecting elements -- cables. The parallel operation of the dischargers with sharply expressed dependence of the response delay time τ and its mean square deviation signal on the voltage (for example, for dischargers in compressed gases of the trigatron type, and so on) can be realized under the condition of $2\ell/v > 2t_{\alpha}\sigma$, where ℓ is the cable length; v is the propagation rate of the electromagnetic wave in the cable; t_{α} is the two-way confidence interval corresponding to the reliability of response of the discharger α in the delay interval $2\ell/v$. The value of α is determined from arguments of admissible probability of nonresponse of any of the GIT dischargers, $p = 1 - \alpha^n$, where n is the number of parallel-included dischargers. Thus, the required decoupling in time is determined by the statistical characteristic of the dischargers $F(\sigma)$, their number and the required reliability of parallel operation of them. As the estimates show, in order to insure parallel operation of 100 dischargers for $\sigma = 20$ nanoseconds, a delay of about 150 nanoseconds (15 meters of cable) is required with a probability of nonresponse of the discharger of 0.05.

For dischargers with weak dependence of σ on voltage (for example, for vacuum dischargers) the indicated decoupling condition is not strict. As studies of the parallel operation of the vacuum dischargers developed at the Leningrad Polytechnic Institute imeni M. I. Kalinin have demonstrated [17, 18], synchronous inclusion of them is insured with high reliability for $\sigma \approx 100$ nanoseconds.

When performing some of the experiments, the response frequency of the YeN must be very high. The admissible response frequency of the commutators is limited by an entire series of factors, above all, the rate of recovery of its electric strength. At the present time, dischargers have been developed which are capable of switching currents to 50 kiloamps in the frequency mode (with a frequency to 30 hertz). It must be noted that the problem of the operation of the SK in the frequency mode can be solved not only by increasing the admissible response frequency of the individual commutators, but also by using several commutators instead of one.

Operating Reliability of the Storage Element. Depending on the structural design of the bank, the equipment of it with diagnostic means, the condition of the insulation and protection, two approaches to determination of the required reliability of individual elements are possible.

1. Breakdown of one of the storage elements leads to automated disconnection of part of the storage element -- the cell -- and the operation of the entire device is not interrupted. In this case a limited reduction in the stored energy of the storage element is given for the entire service life for which the required current parameters in the load are still insured. The requirement on the reliability of the elements in this case depends on the number of elements in the cell and does not depend on the total energy of the storage element. However, very rigid requirements are imposed on the protection systems, the systems for automatic disconnection of a damaged cell and the fire and explosion safety systems.

2. Each breakdown of any of the storage elements leads to an emergency -- cessation of operation of the entire storage unit. In this case, more rigid requirements are imposed on the operating reliability of the individual storage elements than in the first case, and with an increase in the storage element energy (the number of elements) the required reliability of the individual elements increases.

For normal operation of large storage elements, the reliability of the individual elements must be on the level of 0.99-0.999.

The studies of the processes of aging of the insulation of the capacitors and cables demonstrated that the distribution of the service lives of the capacitors in the region of small probabilities is subordinate to Weibull distribution $F = 1 - e^{-\lambda N \alpha}$ for $\alpha \leq 1$, and the distribution of the cable service lives is the composition of logarithmic normal and Weibull distributions. The experiments on real capacitors and cables confirm the correctness of the selected distributions and made it possible more precisely to define the reliability of the capacitors and cables. As is obvious from Tables 3, 5, for the required reliability of 0.99 or more, the individual elements of the storage units have service lives on the order of 10^3-10^5 pulses. In a number of cases the necessity arises for increasing the service lives. This is possible by using special measures.

Application of High-Quality Insulation and Improvement of Capacitor and Cable Manufacturing Technology. The tests demonstrated that the failure of capacitors and cables arises both from technological defects and from insufficient electric strength of the materials used. In order to increase the service life of the pulse capacitors, the application of capacitor paper with increased density KON-3M and synthetic films (polyethyleneterephthalate and polypropylene) having increased electric strength and uniformity, is prospective. The studies of samples of combined paper-film insulation demonstrated that the service life of the capacitors with such insulation can be increased by at least an order. The improvement of the existing technology for winding, drying and impregnation will lead to an increase in the service life of the high-voltage pulse capacitors. For cables it is expedient to use high-purity polyethylene, for example, P-107-01 or PE-153-01K, or combined insulation made of extruded polyethylene and polytetrafluoroethylene tape with smearing with organosilicon liquid. When making cables, special attention must be given to the measures to improve the surface of the cable conductor, shielding the locations with increased electric field intensity and elimination of other inclusions in the polyethylene.

Performance of Improved Acceptance Testing. As experience shows, in spite of careful observation of the technology, random production defects are possible, the discovery of which is the goal of the acceptance tests. The production defects can lead to increased intensity of failures at the beginning of operation, and emergencies with the elements can exceed the admissible values for which operation and maintenance of the storage element is possible.

The acceptance testing program for all of the insulating structural elements includes multiple effects of the damping voltage pulses of oscillatory shape with an amplitude somewhat exceeding the amplitude of the pulses in the operating mode. Thus, the acceptance testing mode developed at the LPI [Leningrad Polytechical Institute] for the IK-50-3U4 capacitors (dc voltage effect 1.5 U_{rated} 5 minutes and 100 oscillatory damping pulses with $\Delta = 1.5$ for 1.3U_{rated}) permits the percentage failure of capacitors at the beginning of operation to be reduced by 2 or 3 times.

Transition from Oscillatory to Aperiodic Discharge. As experience shows, in large storage elements the capacitors operate in the damping oscillatory discharge mode with a decrement significantly greater than 1.5. The studies performed on samples of the insulation and tests run on real capacitors and cables demonstrated that improvement of the oscillation decrement increases the service life of the insulation. Thus, the transition from oscillatory discharge with $\Delta = 1.5$ to aperiodic increases the service life of the capacitor insulation by approximately 100 times.

The transition to aperiodic discharge can be achieved, for example, by using highly nonlinear resistances based on zinc oxide.

Limitation of the Overvoltage in the Storage Elements. For each normal discharge of the storage element where the discharges respond synchronously or with insignificant scattering, overvoltages develop in the cables which are caused by propagation of waves with steep fronts, their refraction and reflection from the cells and the load. The magnitude of the overvoltage depends on the ratio of the inductances included in front of the cables, and their wave impedance on the commutation time, the scattering of the response delay time of the dischargers, cable length and nature of the load. The theoretically limiting values of the multiplicities of such overvoltages can reach 1.7-2.4 in the cables, and 1.1-1.2 in the inductance of the capacitor leads (in the capacitor sections, the wave processes in the cables do not cause overvoltages).

The more precise calculations in the developed circuit diagram indicate that these estimates are noticeably higher for the majority of structural elements. However, the overvoltages remain significant, and even for GIT with relatively slowly responding dischargers, under normal conditions the multiplicities can exceed 1.7-1.8.

Higher multiplicities occurred in the anomalous modes with significant response delays of one or several dischargers. On the cable plugs of the nonresponding commutators the multiplicities of the overvoltages can reach 3.5 and more.

As the operating practice of the GIT shows, this phenomenon can have significant influence on the operating reliability of the banks. Therefore in recent years, both in the USSR and abroad, various devices have been developed to decrease overvoltages. The primary method is connection of linear or nonlinear resistors on the dischargers and on the load or in one of these places. For the slow GIT capacitors can be connected in series with the resistors. The number of resistors is selected so that for the waves propagated over the cables, they represent a matched load. The application of these devices lowers the maximum multiplicities to 1.1 to 1.2.

Reduction of the Operating Intensity of the Electric Field of the Capacitors and Cables. If the enumerated methods do not permit us to obtain the required reliability of the storage elements, it is necessary to lower the operating intensity of the electric field of the capacitors and cables. The deficiency of this method consists in the fact that the specific energy capacity of the storage element decreases in this case, and its dimensions and natural inductance increase. The tests of the IK-50-3UCh capacitors and the calculations demonstrated that for achievement of reliability on the order of 0.99 with a service life of 10^4 pulses, it is necessary to lower its operating intensity by 1.3 times, which leads to a decrease in the energy capacity of the capacitors by 1.7 times. Thus, in order to create a storage element of the same energy, it is necessary to increase the number of capacitors by 1.7 times. In order to increase the operating reliability of the cables it is possible to use cables for a larger rated voltage than the storage element. For example, in storage elements for 50 kV, the type AKPVM-1/60 and KPV-1/75 cables (Table 5) will have sufficient reliability reserve, but the cable inductance will be 1.5 times higher than that of the cables designed for 50 kV.

The reliability of the commutators can be increased analogously. The admissible probability of voluntary response of the commutator is determined by the admissible probability of interruption of the experiment, which can be taken equal to 10^{-2} to 10^{-1} for the estimate, and the number of commutators. For a large number of commutators (on the order of 100), this will lead to rigid requirements of low probability of voluntary response of the discharger $\psi = 10^{-3}$ to 10^{-4}. When developing the discharger, the initial magnitude of the breakdown voltage of its insulation $U_{breakdown}$ must be selected considering the given values of the rated voltage of the storage element U_0 and the admissible probability ψ. If the breakdown voltages of the discharger are approximated by a normal distribution law (for example, for vacuum dischargers), it is possible to write

$$U_{пр} - t_\alpha S \leqslant U_{пр} \leqslant U_{пр} + t\ S,$$
(a)

Key: a. breakdown

where t_α is a two-way normal distribution quantile for $\alpha = 1 - \psi$; S is the mean square deviation; $U_{breakdown}$ is the general mean distribution.

From the condition of equality of U_0 to the lower limit when $S=0.15U_{breakdown}$, we obtain: $U_{breakdown} \geq U_0/(1-0.15t_\alpha)$ for $\psi = 10^{-3}$ and $\alpha = 0.999$ $U_{breakdown} \approx 2U_0$, that is the discharger must have a double margin of strength.

Prospects for Use of Capacitive Storage Elements in the Designs of Thermonuclear Power Plants. The developments of thermonuclear reactor designs permits discovery of an entire series of engineering problems, the solution of which is needed to build reactors. The type of storage element is different for different types of reactors. Thus, for confinement of a plasma in stationary and slow reactors (tokamaks, theta pinches with relatively weak magnetic field), it is proposed that superconducting magnets be used. To feed fast reactors with inertial and magnetic plasma confinement, the basic type of storage element appears to be capacitors.

The criterion for the selection and the possibility for the use of one type of storage element or another for the TYaES, in addition to technical aspects, includes economic indexes of the station, in particular, the cost of an installed kilowatt of electric power K which must correspond to the indexes of modern electric power plants. The basic cost index of the storage element -- admissible cost of stored energy x_0 for capacitive storage elements -- is determined first of all by the cost of the capacitors [7], that is,

$$x_0 = K'Q\eta\varepsilon\nu f(\tau),$$

where K' are the expenditures on creating the storage element; $Q = W_p/(W_\pi + W_M)$ is the energy multiplication factor in the reactor; W_p is the energy produced by the reactor; W_π is the plasma energy; W_M is the magnetic field energy; η is the

Table 5. Characteristics of high-voltage pulse cables

Type of cable (manufacturer)	Voltage, kv	Reserve, pulse	Reliability	Outside diameter, mm	Inductance, nanohenries/m	Current with a duration of 100 microseconds, kiloamps
FKP-1/50 (OKB KP)	30	10^4	0.999	15	80	40
KVN-35/100(OKB KP)	35	10^4	--	22	--	100
AKPVM-1/50 (Sevkabel')	50	10^4	0.990	18	110	60
KVIM (OKB KP)	160	10^4	0.999	18	100	40
KVI-120 (OKB KP)	100	10^5	0.999	35	220	40
AKPVM-1/60 (Sevkabel')	100	10^4	0.996	22	150	60
KPV-1/75 (Sevkabel')	150	10^4	0.996	45	160	100
17/14 (France)	60	10^5	--	22	118	--
20P.2 (England)	20	10^6	--	20	100	--
X98 (France)	30	$3\cdot10^5$	--	10.6	245	--
40P.2 (England)	40	10^6	--	36	80	--

equivalent use coefficient of the storage element; ε is the efficiency of the thermal cycle; ν is the combustion pulse repetition frequency; $f(\tau)$ is a coefficient which takes into account the admissible value of x_0 as a function of the service life of the capacitors.

In this expression the values of K', η and ε vary within narrow limits; therefore they can be taken as constant and equal to K' = 250 rubles/kilowatt; $\eta \approx 0.5$; $\varepsilon = 0.4$. The value of $f(\tau)$ in the case where the service life of the capacitors τ_0 for the rated operating intensity E_0 is less than the service life of the electric power plant $N\nu$, takes into account the necessity for replacing the capacitors $N\nu/\tau_0$ times during the service life of the electric power plant $f(\tau) = \tau_0/N\nu$. The value of $f(\tau)$ can be increased significantly as a result of reduction of the operating intensity of the capacitor so that the service life will be equal to the service life of the electric power plant. In this case the cost of the capacitors, as was stated, increases, but appreciably more slowly than their service life increases. Therefore, as was demonstrated in [1], in the case of optimized capacitive storage element $f(\tau) = \sqrt[3]{\tau_0/N\nu}$. The pulse repetition frequency ν is limited by the preparation time of all of the reactor systems for the operating mode, including for the storage element -- the charge rate of the capacitor bank and the possibilities of the commutation system, so that it is difficult to expect $\nu > 1$. The value of Q is determined by the specific type of TYaES, just as the technical parameters of the YeN.

Conclusion

The performed analysis indicates that the equipment and the process for creating capacitive storage elements are at the present time on a sufficiently high level, which permits insurance of the performance of experimental studies by the UTS program and use of the YeN as the demonstration reactor power supply.

BIBLIOGRAPHY

1. S. L. Zayyents, G. S. Kichayeva, G. S. Kuchinskiy, et al., "Problem of Creating Capacitive Storage Elements with Increased Service Life," IZV. AN SSSR. SER. ENERGETIKA I TRANSPORT (News of the USSR Academy of Sciences, Power Engineering and Transport Series), No 6, 1978, pp 3-8.

2. G. A. Mesyats, GENERIROVANIYE MOSHCHNYKH NANOSEKUNDNYKH IMPUL'SOV (Generation of Powerful Nanosecond Pulses), Moscow, Sov radio, 1974.

3. V. P. Smirnov, "Obtaining High-Current Bunches of Electrons: A Survey," PTE, No 2, 1977, pp 7-31.

4. E. L. Kemp, "The Design of Seyllac a 15-Meter Theta-Pinch Machine," 5TH SYMPOSIUM OF FUSION TECHNOLOGY, Oxford, England, 2-5 July 1965.

5. C. Angelfinger, G. Decker, F. Fünfer, et al., "Isar-1-Fast Megajoule Theta-Pinch Experiment," SECOND IAEA CONFERENCE ON PLASMA PHYSICS AND CONTROLLED NUCLEAR FUSION RESEARCH, Culham, England, Sept. 1965.

6. G. R. Allen, W. L. Gagnon, P. R. Rupert, J. B. Tvenholme, "Engineering Storage and Power Conditioning System for the Shiva Laser," SIXTH SYMPOSIUM ON ENGINEERING PROBLEMS OF FUSION RESEARCH, IEEE Pub. 75CH 1097-5-NPS, 1974.

7. P. N. Dashuk, S. L. Zayyents, G. S. Kichayeva, et al., "Capacitive Storage Elements of Maximum Parameters for Electrophysical Devices," IZV. AN SSSR. SER. ENERGETIKA I TRANSPORT, No 6, 1977, pp 32-42.

8. A. I. Pavlovskiy, Ye. N. Smirnov, V. Ya. Latysh, et al., "Powerful Capacitor Banks with an Energy Capacity of 1.35 and 2.7 Megajoules," PTE, No 1, 1974, pp 122-126.

9. TEKHNIKA BOL'SHIKH IMPUL'SNYKH TOKOV I MAGNITNYKH POLEY (Large Pulse Current and Magnetic Field Equipment), Edited by V. S. Komel'kov, Moscow, Atomizdat, 1970.

10. G. A. Shneyerson, "Transient Regimes and Limiting Parameters of Pulse Current Generators with Plane Buses," IZV. AN SSSR, SER. ENERGETIKA I TRANSPORT, No 1, 1972, pp 146-153.

11. V. A. Popova, Yu. A. Chubanova, "Calculations and Measurements of Inductances of Plane Buses," VYSOKOVOL'TNAYA IMPUL'SNAYA TEKHNIKA (High Voltage Pulse Engineering), Cheboksary, No 2, 1975, pp 32-39.

12. P. L. Kalantarov, L. A. Tseytlin, RASCHET INDUKTIVNOSTEY (Calculation of Inductances), Leningrad, Energiya, Leningr. otd-niye, 1970 115 pp.

13. G. A. Shneyerson, "Minimizing the Inductances of the Buses of Capacitive Storage Elements," ZHTF (Technical Physics Journal), Vol 47, 1977, pp 2231-2433.

14. A. Schlütter, Federal Republic of Germany Patent No 1285614, Collector, 1964.

15. P. I. Shkuropat, "Problems of the Commutation of Large Pulse Currents," ELEKTROFIZICHESKIYE KHARAKTERISTIKI KANAL'NOY STADII RAZRYADA PRIMENITEL'NO K PROBLEME KOMMUTATSII (Electrophysical Characteristics of the Channel Discharge Stage as applied to the Problem of Commutation), Karaganda, 1976, pp 31-32.

16. W. R. Baker, "High Voltage Low Inductance Switch for Megampere Pulse Currents," RSI, No 30, 1959, pp 70-702.

17. P. N. Dashuk, G. S. Kichayeva, "Controlled 50 kV Vacuum Dischargers for Multiple Commutation of Megampere Currents," PTE, No 2, 1975, pp 113-115.

18. V. B. Ikonnikov, G. S. Kichayeva, P. I. Shkuropat, "Low-Inductive Controlled 100 kV, $1.5 \cdot 10^6$ amp Vacuum Discharger," PTE, No 6, 1975, pp 114-116.

19. A. V. Grigor'yev, P. N. Dashuk, S. N. Markov, et al., "Low-Inductive Megampere Current Commutator Using Sliding Discharge," PTE, No 4, 1976, pp 151-153.

20. T. E. Games, FAST HIGH CURRENTS SWITCHING SYSTEMS FOR MEGAJOULE CAPACITOR BANKS, Culham Laboratory, Abingdon, 1973, CLM-123.

21. A. B. Andrezen, V. A. Burtsev, A. B. Produvnov, "Study of the Time Characteristics of the Breakdown of a Discharger with Solid Dielectric," ZHTF, No 2, 1975, pp 294-296.

22. Yu. N. Bocharov, S. L. Zayyents, A. I. Kruchinin, et al., "Use of Solid State Dischargers in a Capacitive Storage Element with Maximum Low Inductance," ELEKTROFIZICHESKIYE KHARAKTERISTIKI KANAL'NOY STADII RAZRYADA PRIMENITEL'NO K PROBLEME KOMMUTATSII (Electrophysical Characteristics of the Channel Stage of Discharge as Applied to Commutation Problems), Karaganda, 1976, pp 82-83.

23. Yu. D. Khromoy, V. P. Andronova, R. G. Antokhin, et al., "High-Voltage IRT-4 Pulse Discharger," PTE, No 2, 1978, pp 195-197.

[161-10845]

10845
CSO: 1860

UDC 621.039.6;621.311.62;621.382.233.026

THYRISTOR FEED SYSTEMSFOR EXPERIMENTAL THERMONUCLEAR REACTORS

Moscow ELEKTROTEKHNIKA in Russian No 1, Jan 81 pp 37-39

[Article by G. G. Zhemerov, candidate of technical sciences, A. K. Ginzburg, engineer]

[Text] The experimental thermonuclear reactors, the creation of which is connected with the cardinal solution of the problem of power supplies are complex engineering structures requiring a powerful feed system to function. The pulse power intake by the research thermonuclear device is hundreds of megawatts for a pulse duration of several tens of seconds. As a rule, the load is equivalent to a series-connected resistor and inductance with large time constant. The necessity for shaping the current buildup and the decay front in the load gives rise to the application of thyristor rectifiers providing for operation both in the rectifying and in the inverter modes. The thyristor rectifier feed can be realized by two basic systems (Figures 1, 2): from the ac industrial network or from the synchronous short-term operating generator. The second system (Figure 2) is expedient in cases where the industrial network does not have sufficient power or the required quality of voltage with respect to admissible deviations, oscillations and distortions cannot be insured on its terminals.

The operating conditions of the pulse synchronous generator equipped with a flywheel are such that for several minutes or tens of minutes the shaft rpm increases to rated, then during the time of the current pulse to the load it decreases by 30-50%.

As is obvious from Figures 1, 2, the thyristor rectifiers feeding the inductive storage element or the magnet, can be made by various schemes with a different number of pulsations in the output voltage curve. The choice of one system or another is determined by the load power, the level of output voltage and load current, the structure of the protection system , the parameters of the basic elements of the power system.

One of the possible means of optimizing the thyristor feed system is multipurpose use of a thyristor converter. In some cases, in the energy storage mode it can turn out to be expedient to feed the synchronous generator from a special rectifier B4 through the rectifier B1 by the so-called barrier-layer motor system, which permits exclusion of the accelerating induction motor AD. As is obvious from Figure 2, in order to implement this synchronous generator control method, switches are needed in the rectifier and load circuits.

Considering what has been discussed, it is possible to formulate the following basic scientific and technical problems connected with the creation of thyristor feed systems for thermonuclear reactors:

The study of the electromagnetic processes in the thyristor converters operating in the cyclic mode and with variable frequency of the feed network, the develoment of methods of calculating the elements of such thyristor converters;

Optimization of the power systems, the control system and the structural design of superpowerful controlled rectifiers;

Optimization of the thyristor feed systems of the thermonuclear devices;

The creation of new elements for superpowerful pulsed controlled rectifiers, thyristors, cutouts, transformers, protective units, reactors, and so on.

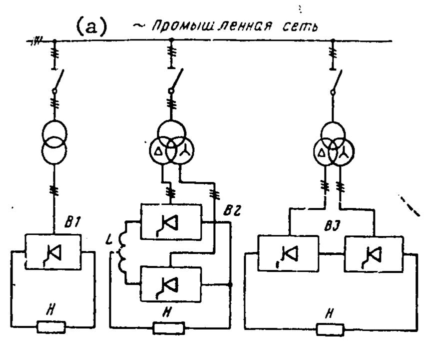


Figure 1. Thyristor feed system from the industrial ac network (B -- controlled rectifier; H -- load).

Key: a. ~industrial network

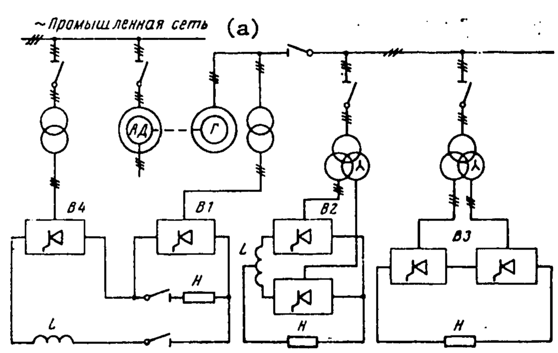


Figure 2. Thyristor feed system with pulsed synchronous generator (AD -- induction motor; Г -- synchronous generator; L -- limiting reactor).

Key: a. ~ industrial network

APPROVED FOR RELEASE: 2007/02/08: CIA-RDP82-00850R000400010021-3

Let us briefly discuss the enumerated problems, which are interrelated.

The analysis of the quasisteady state electromagnetic processes in a controlled rectifier performed on the basis of the assumption of constancy of the operating conditions does not permit sufficiently exact calculation of the elements of the rectifier operating in the cyclic mode or determination of the operating peculiarities of the rectifier and the feed network. At the same time, in connection with the high power of the converters, more precise determination of the loads and operating conditions of its elements even by 1% will lead to a significant reduction in the material expenditures. In [1], which is an effort at a new approach to the analysis of electromagnetic processes in the rectifier it is demonstrated that for cyclic operating conditions, phenomena occur which are absent in the stationary mode: magnetizing of the feed transformer by direct current, asymmetry of the effective values of the primary currents, asymmetry of the powers, the appearance of noncanonical harmonics, nonuniform loading of the valves with respect to the current. All of these phenomena must be taken into account when designing the feed systems.

A number of specific problems arise when analyzing electromagnetic processes and calculating the controlled rectifiers fed from the network, the frequency of which varies within broad limits. The frequency variation has a significant influence on the processes and the characteristics of the rectifier. These problems must be solved and brought to the engineering methods of calculation.

Problems of decreasing the influence on the power network of the powerful controlled rectifiers also require further development, although in [2, 3, and so on] results were obtained which are suitable for practical design work.

The number of thyristor converters produced for the feed systems of thermonuclear reactors is still small by comparison with the thyristor converters for other purposes. Therefore, an attempt at structural standardization of the thyristor converters for feed systems with thyristor converters for electronic instruments is justified. The effort to limit the level of the rated output voltage of 1000-1200 volts is connected with the convenience of servicing, operating and maintaining low-voltage converters. As a rule, by sectioning the load and applying special inclusion of the thyristor converters it is possible to solve the circuitry problems connected with the application of low-voltage converters. When using electromechanical units, the voltage levels from the generator windings amount to several kilovolts, which makes it expedient to use transformerless converter systems in which the valve sections are fed directly from several three-phase generator windings, to decrease the installed power. However, this complicates the structural design of the pulse generator and significantly complicates the design of the thyristor converters, inasmuch as the required elements are not available for a voltage of several kilovolts: the high-speed cutouts, the protection and signalling equipment, structural elements, and so on. In case of feeding a thyristor converter from a short-term generator, a theoretically new solution of the pulse-phase regulation system is required on the part of its operation during variation of the frequency within broad limits and with deep distortions of the shape of the feed voltage.

As an example let us consider the thyristor feed system of the experimental "Tokamak-10" device started up in 1975 and operating successfully at the present time. The total installed capacity of the feed system will be 260 megawatts. The converter parameters are presented in Table 1.

Table 1

Type	Rated rectified voltage, volts	Rated rectified current, amps	Voltage of valve windings, of transformer, volts	Load parameters	
				Resistance, ohms	Inductance, henries
P	1050	20	830	0.0375	0.0775
R	1050	5.0	830	0.01	0.022
U	400	20	465	0.019	0.01

The type P converters aredesigned to feed longitudinal field windings; type R converters are designed to feed demagnetization windings; type U converters are designed to feed control windings.

The feed system for longitudinal field windings with a power of 168 megawatts for a voltage of 8400 volts (Figure 3) is of the greatest interest. As is obvious from Figure 3, the load is divided into four parts, including in series with 8 thyristor converters, type P, executed by the six-pulse bridge rectification circuit. This connection insures identical current through the winding sections, and the use of thyristor converters with grounding of the midpoint lowers the required level of insulation of the thyristor converters.

As a result of using transformers, the voltages of the valve windings of which are shifted by the angle $\pi/6$, the equivalent diagram of the feed system is a twelve-pulse system, which permits reduction of the influence of the converters on the feed network. The operating conditions of the device are such that the maximum values of the active and reactive powers required by the converters correspond to the maximum value of the load current. Numerical values of the active and reactive powers are presented in Table 2.

During operation of the controlled rectifier in the inverter mode, the current in the load is extinguished. The effective values of the higher harmonics of the feed network current, the order of which $N = 12n \pm 1$, were $n = 1, 2, 3, \ldots$, can be calculated by the following formula:

$$I_N = \frac{\sqrt{6}}{\pi N k_{\text{тр}}} I_d, \qquad (1)$$

(a)

Key: a. tr

where k_{tr} is the transformation coefficient.

Considering that

$$k_{\text{тр}} = \frac{110!}{0{,}83} = 132{,}53, \qquad (2)$$

let us define harmonics 11 and 13 of the 110 kv network current:

$$I_{11} = 85.6 \text{ amps}; \; I_{13} = 72.8 \text{ amps}.$$

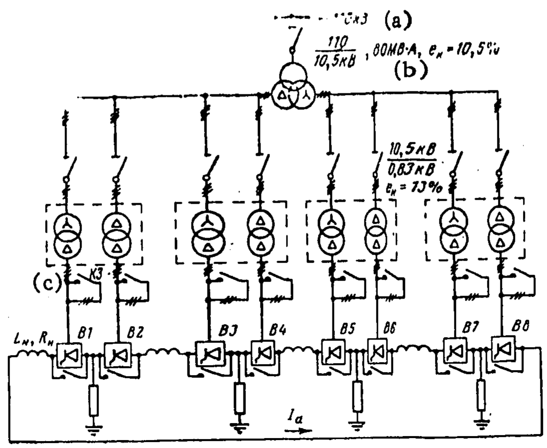


Figure 3. Thyristor feed system of the longitudinal field winding of a "Tokamak-10" device (B -- controlled rectifier; L_H, R_H -- inductance and resistance of one load section; KZ -- short circuiting device).

Key: a. kilovolts b. 80 megavolt-amperes c. KZ = shortcircuiting device

Table 2

Operating conditions	Load current I_d, kiloamps	Control angle α, degrees	Total apparent power, S_Σ, megavolt-amperes	Total active power P_Σ mw	Total reactive power Q_Σ, megavolt-amperes
Rectifier	20	27	180	160	81.7
Inverter	20	103	180	−40.5	175

The relative magnitude of the higher harmonics in the voltage of the feed network in fractions of the existing value of the voltage is defined by the expression [2]

$$\Delta V_B = \frac{1}{\sqrt{2}} \frac{P_\Sigma}{P_{K.3}} \sqrt{\frac{2\pi}{m\gamma} - 1}, \quad (3)$$

(a)

Key: a. short circuit

where m is the pulse nature of the rectification circuit; γ is the minimum value of the commutation angle; for the current I_d = 20 kiloamps, γ = 13°; P_Σ is the active power of 8 converters operating simultaneously (from Table 2); $P_{\text{short circuit}}$ is the power of the short-circuited 110 kV feed network.

From (3), ΔV_B = 3.4%.

The magnitude of the fluctuations of the effective value of the network voltage will be defined by the approximate formula

$$\Delta V_{\text{эф}} = \frac{\pi}{3} \frac{P_\Sigma}{P_{\text{к.з}}} \frac{I_d}{I_{d\text{н}}}. \qquad (4)$$

(a) (b)

Key: a. eff b. short circuit

For $I_d/I_{dH} = 1$, from (4) we obtain: $\Delta V_{eff} = 4.4\%$.

Here a simplified calculation of the basic energy characteristics of the thyristor feed system is presented as an illustration. It is understandable that during the design work, exact calculations must be made of the power engineering indexes, taking into account the operating conditions of all of the converters and their mutual influence.

The thyristor converters are protected by using shortcircuiters included at the entrance and exit of the valve bridges (see Figure 3). The individual protection of the thyristors is accomplished using high-speed fuses. The protection system has selectivity.

The experience in operating and maintaining thyristor converters on the "Tokamak-10" device confirmed the correctness of the technical and structural solutions adopted when designing the feed system for the device.

BIBLIOGRAPHY

1. G. G. Zhemerov, "Calculating a Controlled Rectifier that Operates in the Cyclic Mode," ELEKTRICHESTVO (Electricity), No 11, 1978, pp 30-36.

2. V. P. Shipillo, "Effect of a Thyristor Electric Drive for a Feed Network," ELEKTROTEKHNICHESKAYA PROMYSHLENNOST'. SER. ELEKTROPRIVOD (Electrotechnical Industry. Electric Drive Series), Moscow, Informelektro, No 1, 1970, pp 5-10.

3. E. M. Apter, G. G. Zhemerov, I. I. Levitan, A. G. El'kin, MOSHCHNYYE UPRAVLYAYEMYYE VYPRYAMITELI DLYA ELEKTROPRIVODOV POSTOYANNOGO TOKA (Powerful Controlled Rectifiers for DC Electric Drives), Moscow, Energiya, 1975.

[161-10845]

10845
CSO: 1860

UDC 621.311.6:621.039.6.038.613

CREATING THE ELECTRIC FEED SYSTEMS OF INJECTORS FOR THERMONUCLEAR DEVICES

Moscow ELEKTROTEKHNIKA in Russian No 1, Jan 81 pp 39-43

[Article by A. N. Vladimirov, engineer, N. N. Semashko, doctor of physical and mathematical sciences]

[Text] High-current beams of ions and hydrogen atoms (deuterium) are used to create high-temperature plasma in open magnetic traps and for heating a plasma to thermonuclear temperatures in closed magnetic systems of the tokamak type. The development of methods of creating powerful particle fluxes has been stimulated primarily by the work under the controlled thermonuclear fusion program. In the first tokamaks the powers of the injection systems did not exceed tens of kilowatts; at the present time they are units of megawatts, and in the designs for future devices, injection systems have been substantiated with powers of tens and hundreds of megawatts (see the table) [1].

Three basic factors have provided for the growth of the injector power. First of all, the development of physics, engineering and technology of high-current ion sources: the current of the beams created by them has increased by three orders. Secondly, progress in the creation of vacuum pumping means with high velocities. Finally, the third factor is creation of the electric feed systems for the injectors corresponding to the modern requirements of obtaining high-current beams.

The injection systems of the next generation of thermonuclear devices will provide for the creation of a so-called two-component plasma, the introduction of fuel (deuterium and tritium) into the reactors and ignition of the reaction.

The parameters of the injection system are determined by its functions and also the type, the parameters and the purpose of the device itself (research, demonstration reactor or industrial thermonuclear electric power plant). The basic parameters of the injection system are the following:

The power of the input particle flux P_0 determined by the type of device and the volume of the plasma; P_0 = 10 to 400 megawatts;

The energy of the injected particles E_0, which depends on the type and size of the device, the purpose of injection; for tokamaks E_0 = 40 to 600 kev, for open traps, from 20 kev to 1-1.5 Mev;

The injection time T; for tokamaks from several seconds to quasicontinuous mode and completely continuous for open traps;

Basic characteristics of powerful injection systems of large devices

Name of device	Power, megawatts	Energy, kev	No of injectors	No of ion sources in injector	Current (ion) of a single source, amps	Pulse duration, sec	Typ of ion source
TFTR	20	120	4-6	3	70	0.5	IBM
MFTF	24	20	--	24	80	0.01	IBM
MFTF	18	80	--	24	80	0.5	IBM
D-III	20	80	6	2	70	0.5	IBM
PLT	4	40	4	1	60	0.3	DP
PDX	10	40	6	1	80	0.3	DP
DITE	1	30	2	2	30	0.1	IPM
T-10M	4.5	40/80	2	3	35	1.5	IBM
JT-60	20	75	14	2	35	To 10	DP
TFR	4	30	2	5	14	0.05	PP
JET	25	80/100	--	--	--	--	--

Note. IBM -- source without external magnetic field; DP -- duopigatron; IPM -- source with peripheral magnetic field; PP -- periplasmatron.

The efficiency of the injection system with respect to power (the ratio of P_0 to the power intake by the injection system from the network); for reactors with injection, that is, without ignition of a self-sustaining reaction it has defining significance, and its value must be no less than 0.7.

The operating principle of an injector consists in obtaining hydrogen ions, acceleration and formation of a beam of these ions and subsequent neutralization of them. The requirement of the highest possible efficiency with respect to power in the atom energy range, which is of interest for thermonuclear applications (20-1500 kev), leads to the construction of injectors of two different designs [2]. For exit energies of the deuterium atoms to 200 kev the principle of constructing the injectors is based on obtaining a beam of positive ions with the required energy and subsequent recharging of them to atoms. Here the injector (see curve 1) contains one or several ion sources, each of which contains and shapes a primary ion flux with rated energy. On passing through the neutralizer (the recharged target), a defined part of the primary ion beam is neutralized. The formed flux of atoms is directed at the thermonuclear device, and the remaining ions are deflected most frequently by the magnetic field. The cross section of the recharging process decreases with an increase in the energy E_0; therefore for high energies in order to increase the efficiency of the injectors it is expedient to use devices for recovery of the energy of the nonrechargable ions.

However, for energies above 200 kev the recharging coefficient of the positive ions becomes so small that from the point of view of efficiency the system based on obtaining, forming and accelerating a flux of negative ions and subsequent neutralization of them turns out to be more advantageous. In this case (see Figure 2) the source creates and forms a flux of negative low-energy ions E_1. In the acceleration system the negative ions acquire a rated energy E_0. Then conversion of a defined part of

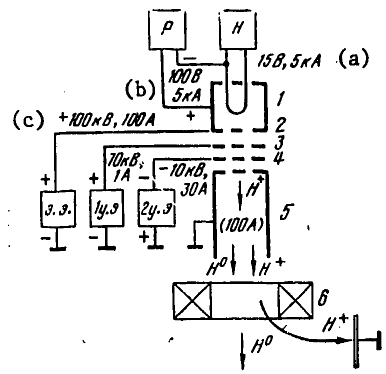


Figure 1. Diagram of an injector using positive ions. 1 -- gas discharge chamber; 2 -- emission electrode; 3 -- first accelerating electrode; 4 -- second accelerating electrode; 5 -- neutralizer; 6 -- deflecting magnet.

Key:
a. 15 volts, 5 kiloamps
b. 100 volts, 5 kiloamps
c. +100 kilovolts, 100 amps

the negative ions to atoms with an energy of E_0 which are input to the thermonuclear device takes place on the metal vapor or plasma target. The remaining ions (positive and negative) are deflected by the magnetic field. Here recovery of the energy of these ions is also possible.

The sources of low-energy E_1 negative ions can be based on the following two principles: extraction of negative ions directly from the gas discharge plasma, acceleration to an energy E_1 and formation of the flux; extraction of positive ions from the gas discharge plasma, acceleration to an energy E_1 and formation of the primary flux, passage of the latter through a target made of alkali metal vapor and, as a result of double charge exchange, obtaining a flux of negative ions with an energy E_1.

The limited dimensions of the entrance opening to the device and the structural peculiarities of the latter predetermine the distribution of the total power of the input flux of particles among several injectors located in one or several injection zones. Each injector has an independent vacuum system and several independent injection channels with their autonomous electric feed systems. This structure of the injection system permits optimization of the injection channel parameters from the point of view of technological nature and operating reliability.

In the case of injectors with an energy to 200 kev the injection channel includes the ion source and the ion-atomic channel belonging to it. The ion source is the most important element of the injector. In modern injectors ion sources such as the "duopigatron" and without an external magnetic field [3] creating ion beams with energies to 120 kev, a current to 100 amps, pulse durations to 0.5 seconds have become the most widespread. The ion source consists of two basic assemblies: a gas discharge chamber which is, as a rule, under high potential, and an ion-optical system. In the gas discharge chamber, arc discharge is ignited with an incandescent cathode forming a plasma ion emitter. The ion-optical system realizes extraction of the ions from the plasma, electrostatic acceleration and formation of the ion beam. It usually consists of three (for an energy to 40 kev) or four (for energies above 40 kev) electrodes.

The electric feed system of the ion source is split into low-voltage (discharge and incandescence feed) and high-voltage (ion-optical system feed) parts. The electric feed devices for the ion source have a number of requirements imposed on them which follow from their operating peculiarities [4].

The voltages on the electrodes of the ion-optical system and discharge current must be stabilized with an accuracy to 2-3%; otherwise their mismatch leads to worsening of the quality of the shaped ion beam and a reduction in the injector efficiency.

The voltages on the electrodes of the ion-optical system must be fed in a time of no more than 10-20 microseconds, inasmuch as during the voltage buildup time, the defocussed ion beam hits the intermediate electrodes of the ion-optical system, which can be the cause for breakdown.

The electrodes of the ion-optical system must be protected from destruction during high-voltage breakdown. For this purpose the breakdown current and the time it flows must be limited so that the energy release at the breakdown point does not exceed 1 joule.

Recovery of the voltages on the electrodes of the ion-optical system after breakdown must be insured after a time interval sufficient for recovery of the electric strength of the high-voltage gap (hundreds of microseconds).

The elements of the electric feed devices with high-voltage breakdowns can be subjected to overloads; therefore the corresponding measures must be taken to protect these elements.

The energy and control signals for the discharge and incandenscence electric feed devices must be transmitted to the high potential, the information about the output parameters of these devices must be transmitted from this potential to the ground potential.

The capacitance to ground of the equipment under high potential complicates the formation of the front and complicates the protection of both the load and the elements of the electric feed devices during breakdown; therefore measures must be taken to decrease it.

The electric feed device of the emission electrode is the most powerful and high-voltage in the feed system, and it determines its structure to a significant degree. Usually this device contains a high-voltage rectifier, its output voltage regulator, the stabilization system and the system for shaping the voltage front on the load, the load protection circuit for breakdowns occurring in it and elements for protection of the electric feed device from overloads.

The high-voltage rectifier usually consists of several series-included stages assembled from uncontrolled valves. This construction of the rectifier insures flexibility of the system, step regulation of the output voltage, the possibility of smooth regulation of the voltage of only one stage, which decreases the required power of the regulator and lowers the pulsation level on the output voltage with phase regulation. Smooth regulation is realized by means of the induction or thyristor regulator included on the network winding side of the power transformer.

The regulation within small limits and stabilization of the voltage on the load are realized using a compensation stabilizer with parallel (Figure 3,a) or series (Figure 3,b) regulating elements [5].

In the former case, the regulating element of the stabilizer made from an electron tube is included parallel to the load. In order to insure the possibility of regulation, the output resistance of the rectifier must be large. In the on-off time interval of the rectifier and during the pulse, significant currents flow through the regulating element, which determines the low efficiency of the device. However, the large value of the output resistance of the rectifier limits the short circuit current, and breakdowns in the regulating tube lead to a decrease in the output voltage; all of this simplifies the construction of the protection circuit. The inclusion of varistors in the anode circuit of an electron tube decreases the anode voltage on it, at the same time the operating conditions are facilitated, and the electron tube can be selected from among those series-produced by industry, which is an advantage of this system.

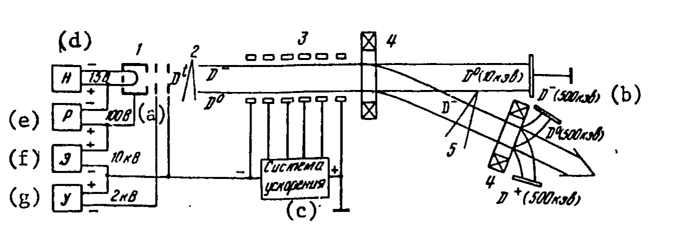


Figure 2. Circuit diagram of an injector using negative ions. 1 -- ion source; 2 -- charge exchange target; 3 -- acceleration system; 4 -- deflecting magnet; 5 -- target.

Key: a. volts
b. kev
c. acceleration system
d. H = load
e. R
f. E
g. U

The second system has become most widespread. In this case the regulating element is included in series with the load. This system insures higher efficiency by comparison with the preceding one, but a significantly higher short circuit current of the rectifier and overvoltages during the load commutations raise the requirements on the electrical parameters of the regulating tube and the protection circuit. The electron tube must withstand an anode voltage of no less than the maximum voltage at the output of the rectifier considering the commutation pips, significant anode current, high dissipation power at the anode in the quasicontinuous mode. For the injectors of the TFTR device the RCA and EIMAC companies have developed tetrodes with maximum admissible anode voltages to 200 kv, anode current to 125 amps, dissipation power on the anode 2000 kilowatts with pulse duration of 1 second [6] as the regulating tube. A characteristic feature of these tubes is operation in the left-hand side of the anode-grid characteristics. The absence of series-produced regulating tubes with such high parameters at the present time leads to the necessity for series inclusion of several tubes, which greatly complicates the circuitry [7].

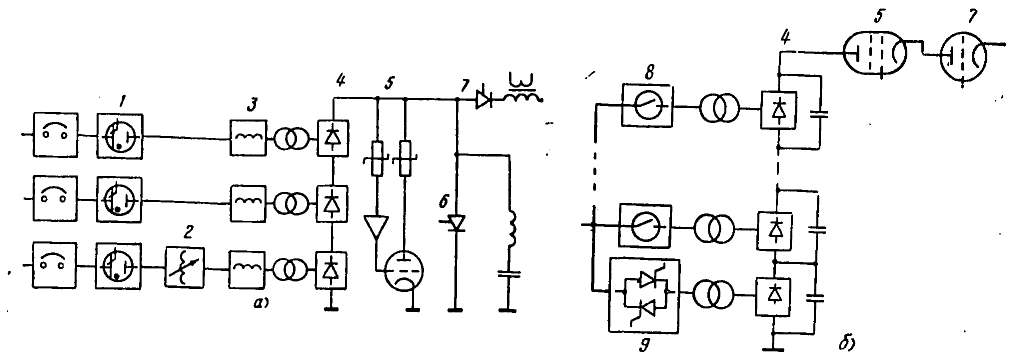


Figure 3. Block diagram of the electric feed unit with parallel (a) and series (b) regulating elements. 1 -- ignitron contactor; 2 -- induction regulator; 3 -- reactor; 4 -- rectifier; 5 -- stabilizer; 6 -- parallel switch; 7 -- switch; 8 -- vacuum contactor; 9 -- thyristor regulator.

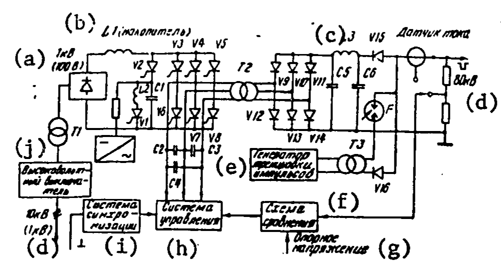


Figure 4. Electric power supply unit for the auxiliary plasma heating systems of the T-10M tokamak.

Key:
- a. 1 kv (100 volts)
- b. L1(storage element
- c. current pickup
- d. ...kv
- e. pulse conditioning oscillator
- f. comparison circuit
- g. reference voltage
- h. control system
- i. synchronization system
- j. high-voltage breaker

The shaping of the voltage front on the electrodes of the ion-optical system and protection of them during breakdowns are realized by the electron switch series included with the load. Thyristor modules, ignitrons, instruments with crossed electric and magnetic fields XFT [8], cathode ray valve commutators [9, 10] and other devices can be used as the switch. It is possible to use the series regulating element of a stabilizer for the functions of shaping the front and protection.

In the case of breakdown of the switch and simultaneous breakdown in the load, both the load and the electric power supply unit are protected by the shortcircuiting system which is usually executed from ignitrons and is included in parallel with the rectifier, and a high-speed vacuum or ignitron contactor which disconnects the rectifier from the network [11].

The stabilization, voltage front formation and load protection functions during breakdowns can be provided by other means, in addition to electron tubes. As an example we have the high-voltage electric power supply unit of the auxiliary plasma heating systems of the T-10M tokamak (see Figure 4) [12]. The front is formed using an auxiliary generator, stabilization of the pulse magnitude with the help of an inverter, and protection in the case of breakdowns, by flipping the inverter and including a discharger.

The first accelerating electrode is fed either from the ohmic voltage divider of the emission electrode [11] or from an intermediate point of the interstage rectifier through an electron tube. The electric power supply of the second accelerating electrode is built on the basis of an adjustable rectifier with electronic switch [11].

The low-voltage electric power discharge and incandescence units are constructed on the basis of stabilized thyristor rectifiers, the feed to which comes through the dividing transformer [3]. A significant requirement for simplification of protection in the case of breakdown and formation of the voltage front on the emission electrode is the necessity for decreasing the capacitance of the low-voltage equipment under high potential relative to ground. In the case of pulse feed systems, electric power supply units are used for this purpose which are based on banks of storage batteries [13].

The variety of schematic solutions of ion source electric power supplies with approximately identical electrical parameters is determined to a significant degree by the absence of electrotechnical equipment with the required parameters, in particular, electron tubes with high anode voltages and high dissipation powers on the anode. The operating characteristics of the electric power supply systems of the injectors impose additional requirements on the technical characteristics of the equipment, for example, the mechanical stability of the windings of powerful high-voltage transformers with multiple inclusions to load and disconnects, on the electric strength of the insulation of these transformers and cables in the case of nonidentical charge exchange with increased frequency for load breakdowns, and so on.

In the case of atom injectors for atoms with an energy of more than 200 kev, the injection channel includes a source of negative ions, a system to accelerate these ions, a deflecting electromagnet and, possibly, energy regulators of the unused ions.

The source of negative ions is under high potential; therefore the energy is transmitted to the electric power supply units of its electrodes through the dividing transformers, and increased requirements are imposed on the efficiency of the feed units in this case. The requirement of high efficiency pertains especially to the electric power supply unit of the ion source emission electrode. It can be constructed on the basis of a controlled thyristor rectifier with thyristor switch.

The operating peculiarities of the electric power supply unit of the acceleration system include the necessity for stabilizing voltages on its electrodes with an accuracy of ±1% of the rated value and the necessity for protecting these electrodes in the case of breakdowns. The plans for the devices proposed as electric power supply systems to accelerate negative ions propose the use of an autonomous inverter which provides for control of the unit, stabilization of its parameters on the low-voltage side and uncontrolled, high-voltage rectifier [14].

The devices in which injection of fast particles with energies above 200 kev will be used, belong to the next generation of thermonuclear devices and will be demonstration reactors, experimental or industrial electric power plants; therefore when developing the injectors for these devices, not only engineering-physical problems will be solved which are aimed at the physical realization of the required output parameters, but also synthesis of the injection systems with respect to the generalized criterion of minimum cost taking into account the total expenditures on manufacturing the equipment, the capital and operating expenditures and others for the required results from injection. Significant peculiarities of these systems include a significant increase in power of the input atom fluxes, operating in the quasi-continuous mode, high efficiency of the injectors, a significant increase in the number of injection channels, operation of the channel elements with a high level of neutron irradiation, performance of measures to insure reliability of the system and for automated repair of the failed elements, achievement of high efficiency and reliability of the electric power supplies.

The construction of the corresponding injection systems is possible in solving a number of electrotechnical problems which include the following:

The development of the electric power supply units with output voltages to 1500 kv and powers of tens of megawatts having high efficiency, low pulsation level with minimum energy capacity of the filter;

The development of economical ion source electric power supplies for 5-10 kv with a current to 100 amps under high potential;

The development of optimized structural elements of the electric power supply units insuring minimum overal dimensions of the electrotechnical equipment; circuits for putting the voltage under high potential from the electric feed units to the injector electrodes having minimum capacitance with respect to ground; external insulation of the injector elements;

Development of technological solutions for various elements of the injector, providing for series manufacture of them (in particular, vacuum-type insulating assemblies for the ion source and negative ion acceleration systems with large rectangular apertures of 1000 cm^2, and more, operating at high temperature and with neutron irradiation and also ceramic insulators for high-voltage electron tubes);

Development of electric feed units for the unused ion energy recovery units;

Assimilation of the series production of the indicated elements and devices of injectors by the electrotechnical industry.

The solution of these problems permits the creation of efficient and reliable injection systems that satisfy the requirements of the construction of economically justifiable thermonuclear reactors.

BIBLIOGRAPHY

1. "What's New in Thermonuclear Research in the USSR," OPERATIVNAYA INFORMATSIYA (Operative Information), No 4 (10), Moscow, IAZ, 1978, pp 15-19.

2. N. N. Semashko, et al., "Concept of Injector Construction for a Thermonuclear Reactor," DOKLADY VSESOYUZNOY KONFERENTSII PO INZHENERNYM PROBLEMAM TERMOYADERNYKH REAKTOROV (Reports of the All-Union Conference on Engineering Problems of Thermonuclear Reactors), Leningrad, NIIEFA, Vol 2, 1977, pp 17-27.

3. N. N. Semashko, et al., "Injectors for Large Thermonuclear Devices (T-10M, and so on)," DOKLADY VSESOYUZNOY KONFERENTSII PO INZHENERNYM PROBLEMAM TERMOYADERNYKH REAKTOROV, Leningrad, NIIEFA, Vol 2, 1977, pp 28-37.

4. A. N. Vladimirov, V. V. Topel'berg, "Principles of the Construction of Injector Electric Feed Systems," IV VSESOYUZNAYA KONFERENTSIYA PO PLAZMENNYM USKORITELYAM I IONNYM INZHEKTORAM: TEZISY DOKLADOV (4th All-Union Conference on Plasma Accelerators and Ion Injectors: Topics of Reports), Moscow, VINITI, 1978, pp 119-120.

5. M. E. Smith, "Switching Devices for Fusion Reactors," PROC. OF THE WORKSHOP ON SWITCHING DEVICES FOR FUSION REACTORS, Palo Alto, 1976, sec. 1B, pp 1-7.

6. A. Deitz, H. Murray, R. Winje, "HV Switch. Tube Development Program-TFTR," PROC. OF THE 7TH SYMP. ON ENG. PROBLEMS OF FUSION RES., Knoxville, 1977, Pub. No 77Ch-1267-4-NPS, pp 1440-1444.

7. N. S. Ponte, G. Schilling, "Modulators for High Power Neutral Beam Systems," PROC. OF THE WORKSHOP ON SWITCH. REQUIREMENTS FOR FUSION REACTORS., Palo Alto, 1976, EPRI ER 376-SR, Sec. 1B, pp 38-43.

8. G. A. Hoffman, "Switching Devices for Fusion Reactors," PROC. OF THE WORKSHOP ON SWITCH. REQUIREMENTS FOR FUSION REACTORS, Palo Alto, 1976, EPPI ER 376-SR, Sec. IC, pp 22-35.

9. V. I. Perevodchikov, "Cathode Ray Valves," ELEKTROTEKHNIKA (Electrical Engineering), No 6, 1980, pp 5-7.

10. V. I. Perevodchikov, V. Ye. Zelenov, V. S. Lipatov, I. G. Khomskiy, "Prospects for the Application of Cathode Ray Valves," ELEKTROTEKHNIKA, No 6, 1980, pp 7-9.

11. D. B. Hopkins, W. R. Baker, I. C. Lutz, et al., "The LBL Power Supply System for TFTR Neutral Beam Source Development," PROC. OF THE 7TH SYMP. ON ENG. PROBLEMS OF FUSION RES., Knoxville, 1977, Pub. No 77Ch1267-4-NPS, pp 1570-1575.

12. Ye. B. Isserlin, et al., "Set of Powerful Pulse Modulators for the Plasma Heating High Frequency Devices," DOKLADY VSESOYUZNOY KONFERENTSII PO INZHENERNYM PROBLEMAM TERMOYADERNYKH REAKTOROV, Leningrad, NIIEFA, Vol 2, 1977, pp 10-16.

13. M. E. Smith, "The High Voltage Test Stand at Livermore," PROC. OF THE 7TH SYMP. ON ENG. PROBLEMS OF FUSION RES., Knoxville, 1977, Pub. No 77Ch1267-4-NPS, pp 1105-1110.

14. W. R. Praeg, "A Power Supply for High Voltage Neutral Beam Injectors," PROC. OF THE WORKSHOP ON SWITCH REQUIREMENTS FOR FUSION REACTORS, Palo Alto, 1976, EPRI ER 376-SR, Sec. 1D, pp 1-5.

[161-10845]

10845
CSO: 1860

APPROVED FOR RELEASE: 2007/02/08: CIA-RDP82-00850R000400010021-3

UDC 621.311.6;621.039.6.038.613

DESIGN OF POWER SYSTEMS FOR THE INJECTOR COMPLEXES OF THERMONUCLEAR REACTORS

Moscow ELEKTROTEKHNIKA in Russian No 1, Jan 81 pp 43-45

[Article by O. A. Gusev, candidate of technical sciences, T. G. Galkina, V. P. Goncharenko, V. M. Gusev, V. N. Kuz'min, A. G. Nechayev, engineers]

[Text] In connection with the present development of thermonuclear devices for demonstration and industrial purposes, the problem of optimizing the feed systems of the auxiliary plasma heating devices, which constitute one of the most important assemblies of such devices, is becoming an urgent one. In [1-4], various systems and methods of constructing high-voltage feed systems for the auxiliary heating devices are presented.

The high-voltage feed systems for plasma heating sources investigated in the enumerated papers, being distinguished by a number of theoretical attributes, have one common feature: they were developed either for individual experimental injectors or for injector complexes with a small number of ion sources. The use of such individual high-voltage feed systems in large devices, in the injector complexes of which it is proposed that 30-50 ion sources be installed, requires such a significant increase in material expenditures on the manufacture and the areas for installation of the equipment of the auxiliary plasma heating feed systems that the theoretical possibility of building such devices is placed in question.

In [5] a study was made of certain aspects of the use of a group feed system for accelerating electrodes of the ion sources of injector complexes of thermonuclear reactors. Inasmuch as this approach to the developments of high-voltage feed systems has not aroused theoretical objections on the part of the developers of ion sources, it appears expedient to investigate the economical and the technical peculiarities of the construction of group feed systems in more detail.

The graphs presented in Figure 1 indicate the variation in cost and areas occupied by the equipment, the high-voltage feed systems of the injector complexes, depending on the number of used high-voltage feed sources for different voltages. Estimation of the cost of overall dimensions of the high-voltage feed systems of the ion sources is presented in 1976 prices, in accordance with the systems indicated in [2, 3, 5].

Increasing the output voltage from 160 to 500 kv leads to a sharp increase in cost and overall dimensions of the equipment, inasmuch as these characteristics are determined by the class of insulation of the devices. The development of high-voltage feed systems by the group and individual principles from a voltage to 500 kv requires scientific research work and experimental design work of individual assemblies and devices which will introduce a certain amount of indeterminacy into the calculation of the economic parameters of such devices. This brings about additional difficulties in considering the size and weight indexes of the various feed systems.

Therefore the expediency of one version or another was determined by the method of "expert estimates" by the value of the purpose function F_{pur}, which is the sum of the expediency coefficients $(m_i q_i)$;

$$\text{(a)}\quad F_{\text{ц}} = \sum_{i=1}^{n} m_i q_i,$$

Key: a. pur

where m_i is the weight of the index; q_i is the weight of the expert estimate, determined by a five-point system.

On the basis of the data presented in the table and the graph in Figure 1 obtained by several methods of estimating cost and size and weight characteristics of the used equipment, it is possible to discuss the advantage of the group system of high voltage feed of injector complexes: by 2 or 3 times with respect to cost, and by 5 to 7 times with respect to occupied area.

The basic technical principles of the design and operation of group feed systems are discussed in [5].

It is necessary to point out that the use of electronic commutators in the modulators [4, 5] with an increase in the accelerating voltage of the ion sources to 400-500 kv and transition to the continuous operating mode appears to have little prospectiveness. Therefore new designs of modulators are needed which will provide the required steepness of the buildup fronts and protection of the ion sources in the case of high-voltage arc breakdowns.

One of the possible circuit diagrams of a modulator is shown in Figure 2. The basis for this layout is the protection principlesduring breakdowns in the ion sources discussed in [6] where the arc is extinguished by a countercurrent created by a pulse, low-voltage power supply at ground potential. In the proposed system the countercurrent pulse through the ion source in which the arc discharge arose is shaped from the pulse source (II) after response of the high-voltage discharger RU2 through the shunting capacitance C_{shunt} which then insures the admissible voltage buildup rate on the ion source. The capacitance

$$\text{(a)}\quad C_{\text{ш}} = I_{\text{в}} t_{\text{д}} / U_{\text{в}},$$

Key: a. shunt

where t_D is the admissible voltage buildup time $U_{C_{shunt}}$ from 0 to u_H.

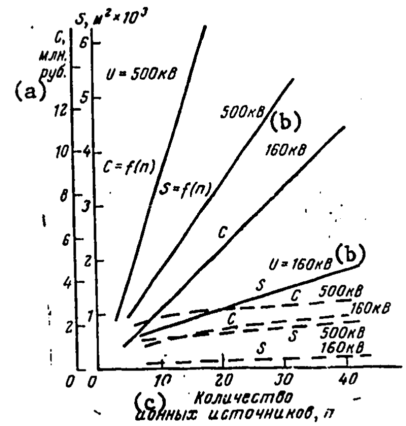


Figure 1. Approximate cost and occupied areas as a function of the number of ion sources. ——— -- individual feed systems; - - - -- group feed system.

Key: a. millions of rubles
b. kv
c. number of ion sources, n

This expression is valid for a significant value of L_b, which was indicated in [5].

The extinguishing of the arc in the ion source and slow voltage buildup on the C_{shunt} insures arcless commutation of K2. With an increase in voltage u_C the current is transferred to R_b, and it is reduced to the rated value for $R_b = R_H$. For repeated entrance of the ion source into operation, the discharger RU3 is switched on, and the arc in the previously open breaker K1 is extinguished by the countercurrent from the pulse source II charged to a voltage of inverse polarity and discharging through the circuit K1-D1-C_b-TI-C_{shunt}.

As the commuting elements K1, K2 it is proposed that high-voltage mechanical commutators be used which are based on vacuum arc-suppressing chambers. The NIIEFA Institute has developed and built a model of such commutators for the parameters 200-250 kv, 10 amps. For commutation of dc circuits by such breakers, the method proposed in [5] is used, by which the transition of the current through zero is insured by means of the pulse devices under ground potential, which gives high disconnect reliability.

The design of the feed systems of the injector complexes is not limited to the development of high-voltage feed systems. When developing feed systems for a voltage of 400-600 kv a significant problem is also brought up by the design of the low-voltage feed systems, the equipment of which is under high potential. Thus, for placement of the low-voltage equipment under 80 kv, for the T-10M injectors a useful enclosed area of $S = 250\ m^2$ was required with open execution of the insulating areas. Increasing the number of ion sources by sixfold and the high

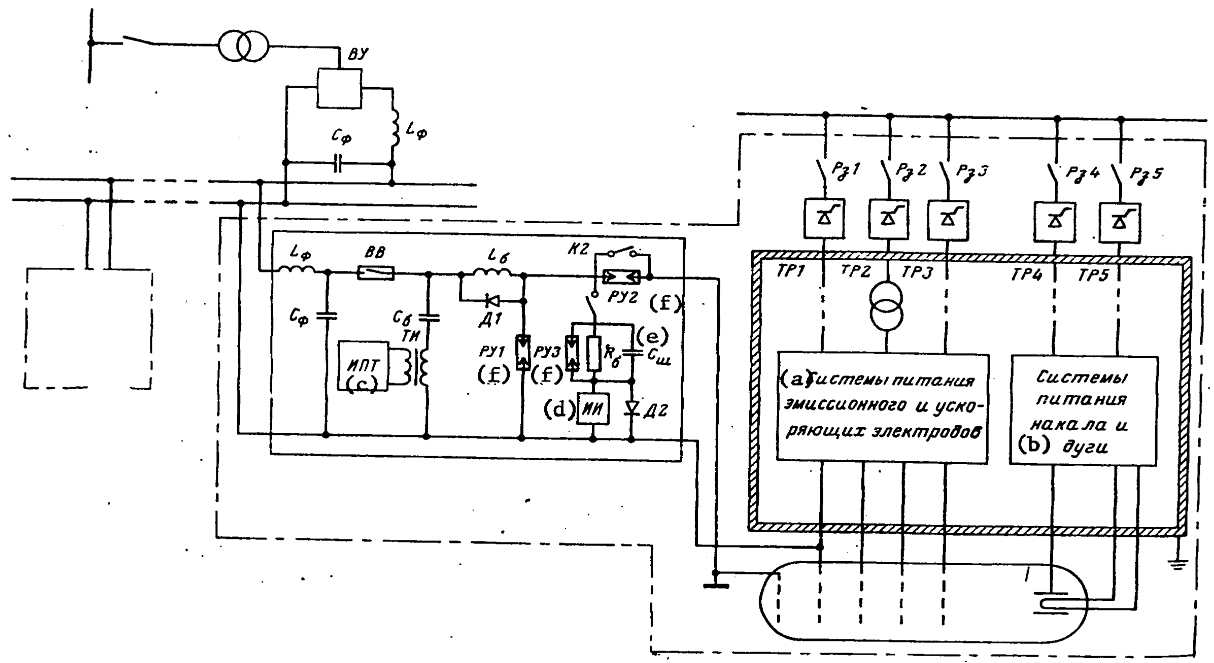


Figure 2. Modulator circuit diagram

Key:
- a. feed systems of the emission and accelerating electrodes
- b. filament and arc feed systems
- c. IPT
- d. II = pulse source
- e. C_{shunt}
- f. RU = discharger

APPROVED FOR RELEASE: 2007/02/08: CIA-RDP82-00850R000400010021-3

Index	m_i	Power System							
		U = 160 kv				U = 500 kv			
		Individual		Group		Individual		Group	
		q_i	m_iq_i	q_i	m_iq_i	q_i	m_iq_i	q_i	m_iq_i
Guarantee of execution of TZ	0.25	5	1.25	3.5	0.875	3	0.75	2	0.5
Prospectiveness	0.3	1	0.3	2.7	0.81	0.5	0.15	3.8	1.14
Supply with consolidated products	0.1	4.2	0.42	3	0.3	3	0.3	1.8	0.18
Reliability	0.22	5	1.1	4.5	0.99	5	1.1	4.5	0.99
Cost	0.1	2.8	0.28	4	0.4	1.5	0.15	5	0.5
Dimension	0.07	1.7	0.119	4.5	0.315	0.8	0.056	5	0.35
Weight	0.03	1.6	0.048	4.5	0.135	0.8	0.024	5	0.15
F_μ		3.517		3.835		2.530		3.810	

voltage feed potential by fivefold leads to an increase in the area occupied by the equipment of the high-voltage feed systems by 19 times.

Therefore when designing the new devices, an all-around solution is needed to the development of the high-voltage and low-voltage feed systems in the auxiliary heating devices. Obviously, it is necessary to have detailed development of the placement of the low voltage equipment under high potential in closed volumes with insulating medium (oil, elegas, inert gases) proposed in [5] with the regulation elements under ground potential.

One possible version of the arrangement of the low-voltage equipment in the insulated volume is shown in Figure 2. The energy is fed at high potential using dividing transformers Tp1-Tp5 with epoxy insulation installed in the same volume as the high-voltage area.

BIBLIOGRAPHY

1. W. R. Baker, STORED ENERGY AND THE LBL NEUTRAL BLAM SOURCE, Lawrence Berkeley Laboratory, Berkeley, California, 94 720, 1976.

2. Ye. B. Isserlin, G. M. Kuperman, V. M. Robina, "Set of Powerful Pulse Modulators for High-Frequency Plasma Heating Devices," DOKLADY VSESOYUZNOY KONFERENTSII PO INZHENERNYM PROBLEMAM TERMOYADERNYKH REAKTOROV (Reports of the All-Union Conference on Engineering Problems of Thermonuclear Reactors), Leningrad, NIIEFA, Vol 2, 1977.

3. A. N. Vladimirov, V. N. Stel'makov, V. V. Topel'berg, E. Z. Shenkman, "Principles of Construction of High-Voltage Feed Sources of the Ion-Optical Ion Source System," DOKLADY VSESOYUZNOY KONFERENTSII PO INZHENERNYM PROBLEMAM TERMOYADERNYKH REAKTOROV, Leningrad, NIIEFA, Vol 3, 1977.

4. N. N. Semashko, Yu. M. Pustovoyt, A. N. Vladimirov, "Injectors for Large Thermonuclear Devices (T-10M, and so on)," DOKLADY VSESOYUZNOY KONFERENTSII PO INZHENERNYM PROBLEMAM TERMOYADERNYKH REAKTOROV, Leningrad, NIIEFA, Vol 2, 1977.

5. O. A. Gusev, A. G. Nechayev, V. D. Fedorov, et al., "Design of Low-Voltage and High-Voltage Injector Complex Feed Systems," DOKLADY VSESOYUZNOY KONFERENTSII PO INZHENERNYM PROBLEMAM TERMOYADERNYKH REAKTOROV, Leningrad, NIIEFA, Vol 3, 1977.

6. W. R. Baker, et al, "Saturable Reactor-Controlled Power Supply System for TCT/TFTR Neutral Beam Source," 6TH SYMP. ON ENG. PROBLEMS OF FUSION RESEARCH, San Diego, CA, Nov 18-21, 1975.

[161-10845]

10845
CSO: 1860

UDC 621.311.6:621.039.6.038.613

ELECTRIC POWER SUPPLIES FOR THE INJECTION SYSTEMS OF THERMONUCLEAR DEVICES

Moscow ELEKTROTEKHNIKA in Russian No 1, Jan 81 pp 45-48

[Article by A. N. Vladimirov, Yu. R. Kaspari, V. N. Stel'makov, engineers, V. V. Topel'berg, E. Z. Shenkman, candidates of technical sciences]

[Text] One of the basic methods of heating a plasma to thermonuclear temperatures in devices developed by the controlled thermonuclear fusion program is injection of fast neutral particles.

The development of the injectors proceeds along the path of increasing the power of the neutral beams, growth of the energy of the injected atoms, an increase in injection pulse duration. This implies the solution of a number of quite complex electrotechnical problems connected with the development of economical and reliable high-power electric power supplies with output voltages of hundreds of kilovolts operating in quasicontinuous mode. The importance of the special developments in this area follows, in particular, from the fact that the cost of the electric power supply is at the present time more than half the cost of the entire injection system.

The injection system is fed from the network either directly or through the energy storage elements. The power is distributed between several independent injection channels. Here the electric feed system contains distribution systems, control systems, blocking and signaling systems that provide for the possibility of safe operation and convenience of maintenance of the system; the secondary electric power supplies of the electrodes and injector circuits, and so on. Whereas the former are standard elements of the electrical networks and systems, the secondary electric power supplies have a number of characteristics arising from the operating conditions of the injector and the characteristics of its elements as the loads of these devices. Therefore primary attention will be given to the latter.

Depending on the exit energies of the atoms, the injectors are constructed by two different schemes [1]; here the composition and the parameters of the electric power supplies for each scheme are different. In the case of injectors with output energy of the fast particles to 200 kev, the base of the electric power supply system is made up of the electric feed units of the positive ion source providing for the formation of an ion beam with rated power. The electric feed systems of the injectors with an energy of more than 200 kev include the electric power supplies of the low-energy negative ion sources (based on double charge exchange of the beam of positive ions of this energy or on direct entrainment of the negative ions from the gas discharge plasma) and the electric power supplies of the systems for finish acceleration of the negative ions to the required energies.

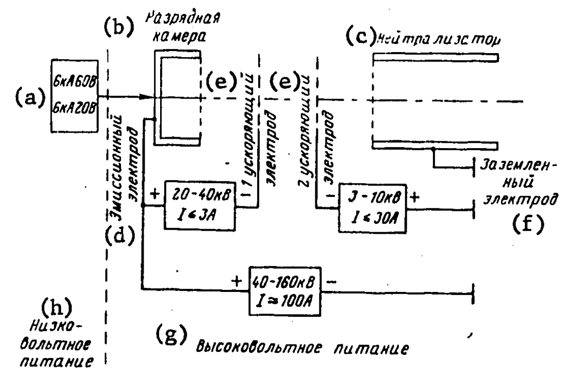


Figure 1. Ion source.

Key: a. 6 kiloamps, 60 volts, 6 kiloamps 20 volts
b. discharge chamber
c. neutralizer
d. emission electrode
e. accelerating electrode
f. grounded electrode
g. high-voltage feed
h. low-voltage feed
i. ... kv ... amps

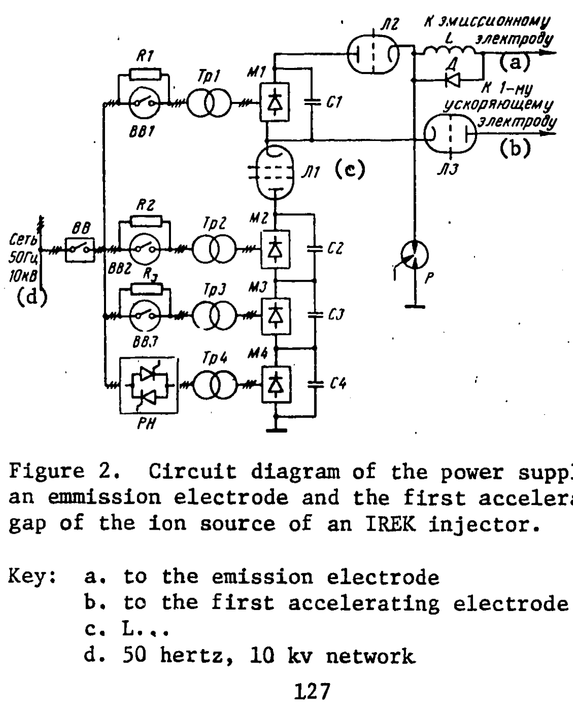


Figure 2. Circuit diagram of the power supply of an emmission electrode and the first accelerating gap of the ion source of an IREK injector.

Key: a. to the emission electrode
b. to the first accelerating electrode
c. L...
d. 50 hertz, 10 kv network

In the fast atom injectors developed in the USSR, the most widespread are the ion sources without an external magnetic field IBM [1-3] designed to obtain ion beams with currents to 100 A. The required range of exit energies of the ions is 5-10(for injectors using negative ions) to 160 kev (for injectors using positive ions).

The block diagram of an ion source with electric power supplies is presented in Figure 1. It includes the following electric power supplies:

The electrodes of the gas discharge chamber under high potential (incandescent cathode with a voltage of 10-20 volts under current to several kiloamperes and discharge electrodes with a voltage of 60-100 volts and a current of several kiloamperes) and also the electric power supplies of the ion-optical system (emission electrode with a voltage to +160 kv corresponding to the exit energy of the ions and a current to 100 amps approximately equal to the beam current);

The first accelerating electrode (for energies above 40 kev) with a voltage of about 2/3 of the voltage of the emission electrode and a current of units of percentages of the ion beam current ;

A second accelerating electrode with negative voltage of several kilovolts, current to 30% of the beam current.

These devices have a number of peculiarities following from the nature of the operation of the ion source [4]:

The necessity for stabilizing the output parameters of the electric power supplies (voltages in the ion-optical system and discharge current with an accuracy of ±2-3% of the rated value);

The necessity for shaping the high-voltage pulses on the electrodes of the ion-optical system with a front of 10-20 microseconds;

The necessity for the protection of these electrodes with breakdowns [5], admissible release of energy during breakdown in the ion source must not exceed several joules [6];

The necessity for energy transmission to high potential to feed the injector elements located there.

Beginning with the functional peculiarities, the electric power supply system can be divided into low-voltage (discharge chamber feed) and high-voltage (ion-optical system feed) parts. The low-voltage part includes the filament and discharge power supplies which are controlled semiconductor rectifiers fed from the network through dividing transformers (for example [7]). The high-voltage part includes the power supplies of the electrodes of the ion-optical system.

The basis of the high voltage part is the emission electrode power supply having the highest output voltage and power (Figure 1). In view of the relative simplicity of the system obtained and the quite high efficiency, the power supply of the emission electrode is constructed, as a rule, on the basis of a controlled rectifier with electron tube included in series with the load. In particular, the injector power supplies of the PLT [5], ISX-B [6], TFTR [8], JET [9] and T-20 [7] tokamaks have been constructed or will be constructed in this way.

The indicated principle has been taken as the basis also when developing the feed system (see Figure 2) of the electrodes of the ion-optical system of the IREK injector. The emission electrode is fed from a four-stage bridge rectifier through electron tubes L1 and L2. The bridges M1-M4 based on uncontrolled semiconductor valves are made in the form of the modules of an outside unit with oil insulation. The bridges are fed from a three-phase ac network through the dividing transformers Tp1-Tp4. The rectified voltage is filtered by capacitive filters C1-C4. The bridges were designed for a voltage of 50 kv and a current of 120 amps. The staged connection of the rectifiers insures step voltage regulation. The voltage stabilization is realized by a thyristor voltage regulator PH included on the network winding side of the transformer Tp4.

In the start modes, the charge current of the capacitors C1-C4 is limited by the resistors R1-R3 and the regulator PH. After charging, the resistors are shunted by the vacuum breakers BB1-BB3, and PH is converted to the output voltage stabilization mode. In addition, the PH regulator performs the function of high-speed protection of the bridge M4 and the transformer Tp4. An analogous mission with respect to the bridges M1-M3 and the transformers Tp1-Tp3 is carried out by the breakers BB1-BB3.

The electron tube L2 operates in the switching mode and is designed for formation of a voltage pulse with a steep front on the emission electrode. An electron tube L1 performs the function of a high-speed regulator and active filter. The electron tube L3 provides for the shaping of a pulse of negative (with respect to the emission electrode) voltage on the first accelerating electrode and also stabilization of the voltage on the second accelerating gap. Tubes L1-L3 also realize protection of the ion-optical system in the case of interelectrode breakdowns.

The energy released during breakdown is decreased by the reactor L and also the controlled discharger P which serves for fast discharge of the spurious capacitances of the circuit. The overvoltage level in the transient processes is lowered by the uncontrolled valve which shunts the reactor L.

It is proposed that the power supplies for the emission electrode of an ion source with an energy of 10 kv (for an injector with charge exchange of the negative ions) and also the power supply of the second accelerating electrode (Figure 1) be constructed somewhat differently. In order to achieve higher efficiency in this case it is expedient to use the system with thyristor pulse shaper (see Figure 3). It operates as follows.

Before shaping the pulse, the filter capacitor C_ϕ is charged to a given voltage, the thyristor module T2 is included, and a current somewhat larger than the load current is set up in the IT-L_0-T2 circuit. Then the thyristor module T1 is included, and the leading edge of the pulse is formed on the load. The front duration and its shape are basically determined by the switching time T_1 and also the spurious parameters of the circuit (the capacitance of the equipment, inductance of the connecting lines, and so on).

The flat part of the pulse is stabilized by a controlled rectifier YB. At the end of the pulse and also during breakdowns in the load, the module T3 is included, and a control pulse is fed to the commutation module BK. After inclusion of T3 to the module T2, the inverse voltage is applied. As a result, module T2 is disconnected, and the choke current is closed by the circuit YB-T1-L_0-IT-T2. The variation rate of this current is limited by the inductance L_0, which permits us to realize commutation of the module T1. For an emergency in the commutation circuit (for example, when the control pulse drops), control pulses are picked up from the rectifier YB, and disconnection occurs as a result of the oscillatory charge exchange of the filter condensate with respect to the circuit C_ϕ-T1-L_0-T3.

On the basis of the diagram presented in Figure 3, an 8 kv, 100 amp power supply was built and tested at the Laboratory of Converter Engineering of the ENIN Institute imeni G. M. Krzhizhanovskiy. TD-320 type thyristors are used in the thyristor modules of the shaper. The voltage front on the active load shunted by a capacitance of 30,000 picofarads was 5 microseconds.

Let us consider the peculiarities of the feed for the finish acceleration system in injectors with neutralization of negative ions. The finish acceleration system contains two stages [1]. The preliminary stage accelerates the ions to an energy on the order of 100 kev, after which they pass through a magnetic separator which separates the low-energy components of the beam. The second stage accelerates the ions to the required power, then in order to keep the angle of deflection invariant, instability of the voltage in the first stage must not exceed $\pm$(1-2)%. The voltage instability in the second stage primarily influences the energy oscillations and can be assumed to be equal to $\pm$(3-5)%.

The power supplies of the finish acceleration system, just as the power supplies of the ion-optical system, must provide protection in the case of interelectrode breakdowns. However, the problem of shaping the voltage front in the finish acceleration system does not arise, which permits significant simplification of the high-voltage dc commutators. An additional possibility for simplifying the high-voltage part of the power supply can be obtained from using systems that permit conversion of the dc voltage in practice without smoothing filters on the high-voltage side. From this point of view, the converter system shown in Figure 4 is of interest.

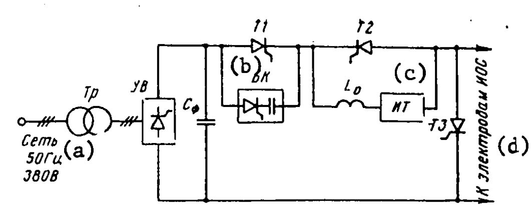


Figure 3. Diagram of an IOS power supply for a voltage to 10 kv.

Key: a. 50 hertz, 380 volts network
b. BK
c. IT
d. to the IOS electrodes

Let us demonstrate that this system has a mode in which there are no pulsations in the output voltage U_2. The proof is found under the assumption that all of the valves

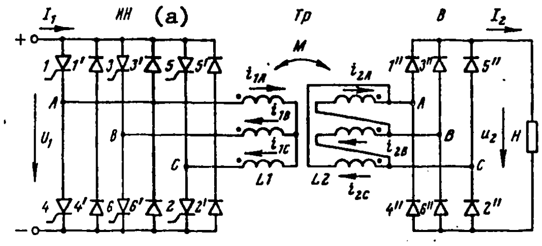


Figure 4. DC voltage converter for the power supplies of the finish acceleration system.

Key: a. IN

are ideal, their resistance in the forward direction is equal to zero, and in the return direction, infinity; the controlled valves have the property of complete contollability, and the active resistance of the windings and losses in the steel of the core are equal to zero. In addition, for simplification of the arguments we shall assume that I_2 = const.

Let us first consider the intercommutation interval. Let for determinacy the current of the valves 1 and 2 of the inverter and also valves 1", 6" and 2" of the rectifier flow. The equilibrium equations for this interval have the form

$$L_1\frac{di_{1A}}{dt}-M\frac{di_{2A}}{dt}+L_1\frac{di_{1C}}{dt}-M\frac{di_{2C}}{dt}=U_1; \quad (1)$$

$$-L_2\frac{di_{2A}}{dt}+M\frac{di_{1A}}{dt}=U_2;\ -L_2\frac{di_{2C}}{dt}+M\frac{di_{1C}}{dt}=U_2; \quad (2)$$

$$i_{2A}+i_{2C}=I_2;\ i_{1A}=i_{1C}, \quad (3)$$

where L_1, L_2 M are the inductance of the primary winding, a secondary winding and the mutual inductance of the windings.

From equations (1)-(3) it is easy to find that $U_2 = U_1M/2L_1$.

Now let us consider the commutation interval. Let at the time t_1 the valve 6 be included. Beginning with this time the processes in the system will be described by the equations:

$$L_1\frac{di_{1A}}{dt}-M\frac{di_{2A}}{dt}+L_1\frac{di_{1C}}{dt}-M\frac{di_{1C}}{dt}=U_1; \quad (4)$$

$$-L_1\frac{di_{1B}}{dt}+M\frac{di_{2B}}{dt}+L_1\frac{di_{1C}}{dt}-M\frac{di_{2C}}{dt}=0; \quad (5)$$

$$-L_2\frac{di_{2A}}{dt}+M\frac{di_{1A}}{dt}=U_2;\quad -L_2\frac{di_{2C}}{dt}+M\frac{di_{1C}}{dt}=U_2; \quad (6)$$

$$L_2\frac{di_{2B}}{dt}-M\frac{di_{1B}}{dt}=0;\ i_{1A}-i_{1B}-i_{1C}=0;$$
$$i_{2A}+i_{2C}=I_2. \qquad (7)$$

Solving the system (4)-(7), we find that also in this time interval $U_2 = (M/L_1)(U_1/2)$.

After inclusion of the valve 6, the current through the valve 2" equal to the difference $i_{2C}-i_{2B}$ begins to decrease. Let us require that at the time t_2 when the current through the valve 2" becomes equal to zero, the valve 2 be switched off. Beginning with $t = t_2$, valves 1, 6 and 5' will be made in the inverter, and the valves 1", 6" and 5", in the rectifier. The processes in the system will be described by the equations:

$$L_1\frac{di_{1A}}{dt}-M\frac{di_{2A}}{dt}+L_1\frac{di_{1B}}{dt}M\frac{di_{2B}}{dt}=U_1; \qquad (8)$$

$$L_1\frac{di_{1A}}{dt}-M\frac{di_{2A}}{dt}+L_1\frac{di_{1C}}{dt}-M\frac{di_{2C}}{dt}=0; \qquad (9)$$

$$-L_2\frac{di_{2A}}{dt}+M\frac{di_{1A}}{dt}=U_2;\quad -L_2\frac{di_{2B}}{dt}+ +M\frac{di_{1B}}{dt}=U_2; \qquad (10)$$

$$L_2\frac{di_{2C}}{dt}-M\frac{di_{1C}}{dt}=0;\ i_{1A}-i_{1B}-i_{1C}=0;$$
$$i_{2A}+i_{2B}=I_2. \qquad (11)$$

Solving the system (8)-(11), we also find this time that $U_2 = (M/L_1)(U_1/2)$. The commutation process ends after disconnection of the valve 5'. Thus, it is demonstrated that the diagram in Figure 4 presents a mode for which the output voltage of the rectifier U_2 = const. This mode arises in the case where the disconnect time of the controlled valve of the inverter coincides with the disconnect time of the rectifier valve. It is possible to demonstrate that an analogous mode will exist also onconnecting the transformer by the Δ/⅄ circuit.

In real systems, as the experiments have shown, which were performed on a physical model in the converter engineering laboratory of the ENIN Institute, the secondary voltage is not constant. This is explained by the effects of a secondary order -- nonlinearity of the valves, losses in the windings, the influence of spurious capacitances, and so on. However, as a rule, these effects have an insignificant influence on the shape of the output voltage, and the requirement on the magnitude of the output voltage pulsations on the order of 2-3% is easily satisfied with the application of output filters with relatively low installed power.

The output voltage of the converter according to the diagram in Figure 4 must be regulated by varying the input voltage U_1, for example, using an adjustable rectifier.

The load protection in the case of breakdowns can be obtained either by disconnecting the controlled valves of the inverter or by inversion (feeding the control pulses to the valves of one or all phases) simultaneously. In the latter case the inverter must be equipped with a device that permits the current buildup rate to be limited.

The existing and the developed injection systems can be provisionally divided [1] into first generation systems designed to obtain neutral atoms with an energy to 200 kev in which a relatively simple principle is used based on acceleration and neutralization of positive ions, and on the second generation systems designed to obtain neutral atoms with an energy of more than 200 kev in which first the positive ions are accelerated to 10 kev, and then they are recharged, and the negative ions obtained are finish accelerated and neutralized. All of the injection systems of the thermonuclear devices existing and being built at this time in the Soviet Union and abroad are first-generation systems. As a rule, they are fed through controlled rectifiers and commutators based on electron tubes.

The specific nature of the second-generation systems will permit the use of thyristor shapers to feed the preliminary acceleration circuit, and to feed the finish acceleration circuits, dc voltage converters based on a three-phase voltage inverter with uncontrolled rectifier.

BIBLIOGRAPHY

1. N. N. Semashko, et al., "Concept of Constructing an Injector for an Thermonuclear Reactor," DOKLADY VSESOYUZNOY KONFERENTSII PO INZHENERNYM PROBLEMAM TERMOYADERNYKH REAKTOROV (Reports of the All-Union Conference on Engineering Problems of Thermonuclear Reactors), Leningrad, NIIEFA, Vol II, 1977.

2. N. N. Semashko, et al., "Injectors for Large Thermonuclear Devices," DOKLADY VSESOYUZNOY KONFERENTSII PO INZHEKTORNYM PROBLEMAM TERMOYADERNYKH REAKTOROV, Leningrad, NIIEFA, Vol II, 1977.

3. S. P. Gurin, et al., "Engineering-Technological Problems of Creating DTRT (T-20) Injectors and Ways of Solving Them," DOKLADY VSESOYUZNOY KONFERENTSII PO INZHENERNYM PROBLEMAM TERMOYADERNYKH REAKTOROV, Leningrad, NIIEFA, Vol II, 1977.

4. A. N. Vladimirov, V. V. Topel'berg, "Principles of Constructing an Electric Power Supply System for Injectors," IV VSESOYUZNAYA KONFERENTSIYA PO PLAZMENNYM USKORITELYAM I IONNYM INZHEKTORAM. TESISY DOKLADOV (4th All-Union Conference on Plasma Accelerators and Ion Injectors. Topics of Reports), Moscow, VNTITS, 1978, pp 119-120.

5. D. L. Ashcroft, H. E. Zuvers, "The Princeton Neutral Injector Power Supply System," PROC. OF THE 7TH SYMP. ON ENG. PROBLEMS OF FUSION RES.," Knoxville, 1977, Pub. No 77, Ch1267-4-NPS, pp 1147-1150.

6. W. R. Baker, "Stored Energy and the LBL Neutral Beam Source," Preprint USID-3871-LBL-1976.

7. O. A. Gusev, et al., "Designing High-Voltage and Low-Voltage Power Supplies for the DTRT (T-20) Injector Complex," DOKLADY VSESOYUZNOY KONFERENTSII PO INZHEKTORNYM PROBLEMAM TERMOYADERNYKH REAKTOROV, Leningrad, NIIEFA, Vol III, 1977.

8. A. Deiz, H. Murray, R. Winje, "The TFTR Neutral Beam Power System," PROC. OF THE 7TH SYMP. ON ENG. PROBLEMS OF FUSION RES., Knoxville, 1977, Pub. No 77, CH1267-4-NPS, pp 1151-1155.

9. P. L. Mondino, K. I. Selin, "JET Additional Heating Power Supply and Protection," PROC. OF THE 7TH SYMP. ON ENG. PROBLEMS OF FUSION RES., Knoxville, 1977, Pub. No 77, CH1267-4-NPS, pp 1558-1563.

[161-10845]

10845
CSO: 1860

UDC 621.039.6:62-503.55

SOME ASPECTS OF CONTROLLING TOKAMAKS

Moscow ELEKTROTEKHNIKA in Russian No 1, Jan 81 pp 48-50

[Article by O. A. Gusev, I. V. Mozin, candidates of technical sciences, V. G. Ivkin, engineer]

[Text] The tokamak type device comprises complicated engineering complexes containing powerful electromagnet winding systems, a toroidal chamber, a vacuum pumping system, cooling and heating systems and so on and also various instruments for plasma diagnosis. All of the systems of the device and the diagnostic devices are combined into a unit whole by the control system for the device providing for the following:

Control of the systems of the device to obtain the required operating conditions of the equipment and the installation as a whole;

Protection of the equipment under emergency conditions;

Creation of safe working conditions for the service personnel;

Assembly, preliminary processing and accumulation of a large volume of process information and information about the plasma parameters;

Presentation of information about the current state and operating conditions of the process systems to the operators and all interested people;

Presentation of data to the experimental physicists on the results of the experiment;

The joint processing of data on the results of several experiments.

The modern control systems are made automated, that is, they contain a computer, which permits significant facilitation of the control process and the processing of the experimental data. The automated systems are widely used in the area of the control of electrophysical devices, for example, charged-particle accelerators. Significant design experience has been accumulated. However, the tokamak type devices have their own physical and engineering peculiarities giving rise to the requirements on the control system:

Limited operating reserve and, as a consequence, high cost of one experiment ("shot");

Pulse operating mode -- the active part of the cycle is appreciably less than the interval between pulses;

The presence of a quite warm circulation period before the series of operating pulses;

The necessity for breaking in a large amount of equipment during the experimental process;

Experimental nature of the devices;

The presence of powerful magnetic fields and high voltages.

The first peculiarity greatly increases the requirements on the control system on the part of data gathering and documentation, that is, information on the operation of the device and the plasma parameters must be the most complete in order to have the possility of comprehensively estimating one achieved effect or another and drawing the corresponding conclusions.

In the data gathering system, a large number of different sensors are used. In addition to the widespread voltage and current pickups and the pickups that measure the conditions in the tokamak type devices, specific sensors characteristic of them must be used. As a result of the presence of powerful variable magnetic fields in the device, the sensors must be low-inductive, the communication lines of the sensors with the electronic processing equipment must be shielded. A large number of sensors are required to measure the magnetic fields, and strain gages are needed to provide information about the overvoltages and stresses in the electromagnetic windings and structural elements. A great deal of attention must be given to the temperature conditions of the windings, the chamber, and so on, which implies the necessity for using heat gages, especially in the case of superconducting windings. The presence of superconductivity requires a number of special measurements, for example, recording transition of the superconductor to the normal state. The electric voltages occurring on passage of the plasma current in the chamber housings, the voltage drop on the windings lead to the fact that a number of identical sensors, for example, the temperature gages in the chamber, turn out to be not under equipotential conditions. This requires special means or methods of measurement such as the use of galvanic decouplings, the combination of sensors by groups, and so on.

The possibility of the occurrence of large voltages in emergency situations on the device does not exclude a high potential from reaching the electronic measuring equipment, which requires protection of this equipment and its service personnel.

As has been already pointed out, in the tokamak type devices there is a quite long preparation period, during which all of the systems are put into operation and are prepared for the series of experiments. It is necessary to insure autonomy of the operation of the systems of the device in this case. In this mode the parameters are measured periodically, as a rule, in order to determine the time that any parameter reaches the prescribed value for inclusion of the next process. Basically in this mode operativeness of control is not required, and the main part of the measured signals -- status -- are used to determine the state of repair of the systems.

Since the active part of the cycle is appreciably less than the interval between pulses and the preparation period and, as has already been pointed out, the lifetime of the device is limited, at the "shooting" time it is necessary to pick up a large quantity of diagnostic information about the condition of the plasma and the behavior of the process systems of the device. In this period, in practice all of the control effects are of the nature of inclusion or disconnection of the corresponding equipment, which is insured by distribution of a defined train of synchronizing pulses and also emergency disconnect signals. In other words, the "shooting" is realized automatically by a previously given program provided for by introduction of the corresponding settings into the synchronization equipment.

In the interval between shots, approximate analysis is run in the control system, and the most important experimental results are displayed. The basic parameters of the engineering systems are checked in order to correct the operating conditions for a more successful experiment.

As for emergency disconnection, the problem arises of where and how to analyze the emergency situation? Emergency situations can be defined by the traditional hardware method by installing various blocks in the equipment or by analysis of the results of measuring the condition of the process systems of the device using a computer and output of the corresponding instructions from it to include the blocking elements. Considering the pulse nature of operation of the device and the loading of the computer during the active cycle, the best version turns out to be the creation of a rigid protection system, bypassing the computer. The computer can analyze pre-emergency situations in the preparatory period and in the interval between "shots."

The variety of process equipment and also the requirement for autonomy of control presuppose the necessity of control for several locations by specialists of different profiles. The coordination of the work from these specialists and, consequently, the device as a whole must be realized centrally from the main operator control panel.

The indicated peculiarities presuppose a hierarchical structure of the control system using a central computer and several local computers servicing individual process systems and diagnostic devices. Depending on the size of the device and the depth of automation, the class and the number of computers can be varied, but one general requirement always remains -- the hierarchical structures must be created on computers of one class or one family, although sets of computers, that is, the composition of the peripheral equipment, can differ significantly. Thus, for the vacuum system, the water cooling, electric power and coolant preparation systems in which the operations are performed not at high speed, and the computer is charged only with the problems of gathering data and certain logical calculations, almost the only requirement is the presence of the required size of ready-access memory. For such systems as the auxiliary heating systems, the control system for the position of the plasma column and also for the diagnostic complex, increased requirements are imposed on the computer with respect to input-output channel speed and computational capabilities, that is, the computer must be outfitted with channels with direct access to memory, additional arithmetic circuitry, and so on.

The same thing can be said of commutating and central computers which can be fitted with memory and auxiliary arithmetic circuitry, and machines of the same class as local computers can be offered. Sometimes more powerful computers of the same family are used as the central computer in order to increase the computational capabilities when performing statistical processing of the archives accumulated during a series of experiments although these calculations can be made also on all-purpose computers at the computer centers.

It is expedient to couple the sensors and the computer by the equipment in the CAMAC standard. Recently this standard found broad application in control systems in practice of all foreign electrophysical devices.

The equipment in the CAMAC standard is constructed on the modular principle with standard couplings between the modules and with standard information exchange formats. In general, the CAMAC standard includes mechanical, logical and electrical standards for constructing the program-controlled interface equipment between the sensors of the device and the computer. The standard provides for two versions: communications between the individual cassettes are realized either by parallel code or series code. The second version is usually used where the interface cassettes are at a significant distance from each other.

The use of the equipment in the CAMAC standard permits the control system to be made quite flexible, and the equipment composition to be varied by the addition or removal of standard modules without changing the overall structure of the interface, and fast testing of the equipment.

On the large devices, as a result of dispersion of the equipment, the most acceptable appears to be the application of an interface system with series communications line, based on the smallest use possible of a parallel system. Recently, in connection with the widespread use of microprocessors, it has become possible to construct an interface based on the so-called intelligent controllers, that is, the control modules for the individual CAMAC cassettes which, in turn, are connected to the computer by a communications line with series data transmission. Here the overall structure of the interface is in accordance with the radial principle, and in addition to synchronization and control of the cassette modules and organization of communications with the computer, the interface structure is faced with the problems of preliminary data processing (calibration of the modules, averaging of the measurement results, standardizing the signals, presetting, and so on). It is obvious that the latter structure is the most prospective.

Thus, the control system for tokamak type devices is a hierarchical structure consisting of local computers which control individual systems and diagnostic equipment and a central computer for controlling the device.

The coupling of the computers and the sensors of the device is realized using the program-controlled CAMAC modules, and the same modules provide for coupling the computers to each other. The systems and the diagnostic equipment are controlled by a group of operators and experimental physicists from panels, as a rule, of the console type equipped with man-machine communications means (alphanumeric and graphical displays, keyboard, multifunctional control elements of the "button" type, and so on). The sets of such consoles are more or less standard and are widely used, for example, in the control systems of charged particle accelerators. The software for the control system must include an efficient operation system providing for joint operation of different devices and users. The operating programs must include data gathering and processing programs, programs that service the consoles (dialog means, data representation means), testing of the equipment, servicing of interrupts and packing of information, complex programs for the switching computer, and so on. All of the operating programs must be written in a high-level language and be processed in the off-line mode before use in the control system.

In conclusion, it is necessary to note that the control system must provide for documentation of the data and also all of the operating programs, tables, and so on, which permits most efficient maintenance of it.

[161-10845]

10845
CSO: 1860

UDC 621.039.6-529

TOKAMAK PLASMA COLUMN POSITION CONTROL SYSTEM

Moscow ELEKTROTEKHNIKA in Russian No 1, Jan 81 pp 50-56

[Article by V. A. Belyakov, candidate of technical sciences, R. N. Litunovskiy, doctor of technical sciences, I. V. Mozin, candidate of technical sciences]

[Text] In spite of the significant progress made in the last tokamaks -- T-10 (USSR) and PLT (USA) -- the problem of building an efficient system for keeping the plasma column in equilibrium cannot be considered completely solved and remains one of the basic engineering problems in the tokamak. In this paper an analysis is made of the nature of the movement of the plasma column in the tokamak, and systems for automatic control of the column position in the operating and planned tokamaks are investigated.

The plasma column in a tokamak is influenced by a force which tries to increase the large radius of the column R_p. The appearance of this force is the result of the presence of electrodynamic forces which always exist in the current ring and try to push the column apart and also the inside gas dynamic pressure of the plasma (the so-called balloon effect). For equalization of the tensile forces, the plasma column must be placed in a transverse magnetic field creating a compressive force. The magnitude of the external, approximately uniform "equilibrium" field on the radius R_p (on the axis of the column) is defined by the expression

$$B_0(R_p) = 10^{-7}\frac{I_p}{R_p}\left(\ln\frac{8R_p}{a}+\beta+\frac{l_i-3}{2}\right), \qquad (1)$$

where I_p is the plasma current, amps; R_p, a are the large and small radii of the column, meters; ℓ_i is the internal inductance of the column; $\beta = 8\pi p/H^2J$ is the parameter charactizing the ratio of the gas kinetic pressure of the plasma to magnetic.

The value of B_0 pertains to the midplane (z = 0) and is obtained in the approximation of $a/R_p << 1$.

From (1) it is obvious that the magnitude of the confining field is determined primarily by the plasma current, the gas kinetic pressure and internal inductance which depends on the current density distribution with respect to the column cross section.

The confining field can be created using a system of current windings or by placing the plasma column in a toroidal chamber made of material with high conductivity. In the latter case the Foucault currents induced in the chamber walls generate the magnetic field required for equilibrium. In the ideal case of a uniform toroidal chamber having infinitely large conductivity, the plasma column will be in the equilibrium state for some shift of the relative axis of the chamber outward. In the approximation of a << b_k (b_k is the small radius of the chamber) b_k << R_k (R_k is the large radius of the chamber) the shift is

$$\Delta_0 = \frac{b_K^2}{2R_K}\left[\ln\frac{b_K}{a} + \left(1 - \frac{a^2}{b_K^2}\right)\left(\beta + \frac{l_i - 1}{2}\right)\right]. \quad (2)$$

It is obvious that the amount of the shift is determined by the column parameters (β, ℓ_i) and the geometric dimensions of the chamber (R_k, b_k) by comparison with the small radius of the column a.

In reality, the chamber (or the conducting toroidal screening equipment to it) always has quite large holes and transverse slits which have a negative effect on the stabilizing influence of the conducting surface. Thus, on introduction of n transverse slits, the shift of the column must increase approximately by $1 + nb_k/2\pi R_k$ times by comparison with Δ_0 defined by expression (2). An estimate of the effect of the transverse slits made in [1] in the approximation of smallness of the transverse size πb_k of the chamber by comparison with the longitudinal dimension $R_k 2\pi/n$. With small width of the gaps, the calculations agree well with the experimental data, but with a wide gap the theory exaggerates the effect of the gaps by several times [2].

As a result of nonideal conductivity of the chamber wall, the plasma column must gradually increase its radius, moving from position $R_p = R_k + \Delta_0$ with a rate

$$\frac{dR_p}{dt} \approx \frac{1}{\tau_K}\frac{b_k^2}{2R_p}\left(\ln\frac{8R_p}{a} + \beta + \frac{l_i - 3}{2}\right) \quad (3)$$

to the equilibrium position $R_p \to \infty$.

In (3), τ_k is the electrotechnical constant of the chamber.

Expression (3), just as formula (2), is effective for a uniform toroidal chamber. For a real chamber the geometric factor defining the magnetic flux adhesion of the column to the chamber contour in these expressions must be changed.

The use of a thick copper screen surrounding the vacuum chamber is characteristic of the tokamaks of the preceding generation with a discharge time of several tens of milliseconds. With discharge lasting from several tenths to units of seconds and increased requirements on the discharge parameters, the problem of keeping the column in equilibrium is solved by introducing controlling magnetic fields. The magnitude of the controlling magnetic field $B_v(t) \equiv -B_0(t)$ can be given by programming the current in the controlling winding on the basis of the a priori data on the course of the variation of the plasma parameters during discharge. The program of the magnetic field $B_v(t)$ can be corrected directly during discharge in accordance with the information about the position of the column. The first successful experiments with respect to introducing feedback with respect to the deviation ΔR_p into the circuit for controlling the feed source of the control windings were performed in the Soviet Union at the Nuclear Power Institute imeni I. V. Kurchatov on the TO-1 device [3]. The system of windings connected to the regulators with negative impedance made it possible to increase the discharge time to 200 milliseconds. On the English tokamak CLEO, an automatic system was used to control the column position in the horizontal and vertical planes and increase the discharge time from 110 to 220 milliseconds [4]. The control system was a feedback circuit with respect to the column position. The small power required for regulation made it possible to realize continuous control using a transistorized feed source. The error in maintaining the given column position was about 10 mm for $t < 140$ milliseconds.

At the present time there are several devices in operation in which the principles of controlling the position of the plasma column are used to one degree or another. In 1982-1985, large thermonuclear devices will be started up in the USSR, the United States, Japan and Europe. The general problems complicating the creation of a highly efficient plasma column position control system for these devices consists in the necessity for considering quite fast variations of the parameters of the column itself (I_p, β, ℓ_i), the influence of the induced currents in the structures of complex configuration surrounding the plasma column, the mutual relation of all of the outlines (the column, windings, induced currents) with high power (tens of megawatts) required for control. The solution of the optimization problem is possible only in the presence of a mathematical model of the plasma column permitting quite exact description of its behavior under real conditions and reaction to the appearing disturbances and the controlling input. For mathematical simulation of the plasma position control system with respect to the large radius, usually the following relations are used.

The equation of motion of the plasma column neglecting inertia connected with its mass is written as the condition of equilibrium of the column at each point in time, that is,

$$B_0(t) + \sum_i B_{vi}(t) = 0, \qquad (4)$$

where $B_0(t)$ is defined by the approximate expression (1); $B_{vi}(t)$ are the transverse magnetic fields at the point ($R = R_p$; $z = 0$) from external sources: the scattered field of the inductor winding; the equivalent confining magnetic field of the iron core; the magnetic fields of the control windings; the fields from the induced current circuits; the transverse components of the fields of the toroidal windings.

Each of these components is a function of the coordinates and the current. At the same time the series of them depends on the degree of saturation of the iron core.

Equation (4) is supplemented by the system of Kirchhoff equations for individual circuits[1]

[1] This approximation is admissible inasmuch as the equation of motion is written in the approximation $a \ll R_p$.

$$\frac{d}{dt}(\bar{L}\bar{I}) + \bar{R}\bar{I} = \bar{U}, \tag{5}$$

where $\bar{L}$ is the matrix of natural and mutual inductances; $\bar{R}$ is the diagonal matrix of resistances; $\bar{I}$, $\bar{U}$ are the current and voltage vectors.

In these matrices the inductance of the plasma column and the mutual inductances of the column with other circuits are functions of the column position. Therefore for differentiation with respect to time, the derivative d/dt is written as $\partial/\partial t + \partial/\partial R + \partial R/\partial t$.

The system of equations (4) and (5) is supplemented by the conditions following from complete or partial freezing of the magnetic field in the plasma and defining the behavior of the individual column parameters on variation of one of them

$$\begin{cases} \left(\frac{a}{a_0}\right)^{\alpha} = \frac{R_p}{R_{p0}}; \\ \rho_p = \rho_{p0} \frac{R^2_p}{R^2_{p0}}; \\ l_i = l_{i0}(t) \frac{I^2_{p0} R^2_{p0}}{I^2_p R^2_p}; \\ \beta = \beta_0(t) \frac{R^{7/3}_{p0} I^2_{p0}}{R^{7/3}_p I^2_p}, \end{cases} \tag{6}$$

where $\alpha = 2$ for complete freezing of the toroidal field flux; $\ell_{i0}(t) \approx 0.5$ to 2; $\ell_{i0}(t)$, $a_0(t)$, $\beta_0(t)$ are the given time functions; $\rho_0(t)$ is the plasma resistance.

Finally, the complete mathematical model of the column position control system, in addition to the indicated relations, includes equations that describe the feed circuit of the individual windings of the algorithms that processes information about the plasma column obtained using diagnostic means. The results of calculating the column dynamics using a method close to the one described for the TFTR and JT-60 devices are contained in [5, 6].

A simple, clear picture of the behavior of the columns on appearance of a disturbance can be obtained when analyzing the abbreviated system of equations.

In the absence of the circuits of currents induced in the chamber, the positions of the plasma column is completely determined by the magnitude of the external magnetic field. In the approximation $a \ll R_p$, the column reacts to "instantaneous" variation of the external field $\Delta B(t_0)$ by an instantaneous shift along the radius by the amount

$$\Delta R_p(t_0) = R_p(t_0) \frac{\Delta B(t_0)}{B_0(t_0)} \frac{1}{1 - n + \mu - \frac{1+\lambda}{F}}. \tag{7}$$

In (7), $n = -\frac{R}{B}\frac{\partial B}{\partial R}$ is the decay index of the magnetic field with respect to radius; $F = \ln\frac{8R_p}{a} + \beta + \frac{l_i - 3}{2}$; $\mu = -\frac{R_p}{I_p}\frac{\partial I_p}{\partial R}$; $\lambda = \frac{R}{a}\frac{\partial a}{\partial R}$. The value of $\lambda = -1/2$ in the case of complete freezing of the longitudinal magnetic flux. When considering the interaction of the plasma with a diaphragm $\lambda = 1$ (movement outward) or $\lambda = -1$ (movement inward). The value characterizes the degree of freezing of the transverse (poloidal) field flux. It is described sufficiently accurately by the expression

$$\mu = \left(\frac{1}{2} + \frac{\frac{3}{2} - \beta}{2\left(\ln\frac{8R_p}{a} + \frac{l_i}{2} - 2\right)}\right)\left(1 - \frac{t}{\tau_p}\right).$$

Inasmuch as the instantaneous variation of the magnetic field is considered, the amount of the shift $\Delta R_p(t_0)$ corresponds to the superconducting state of the column ($\rho_p = 0$). Then the value of the equilibrium radius increases slowly with constant $\tau_p = L_p/\rho_p$ as the magnetic field leaks out of the plasma volume and approaches the value $R_{p0} + \Delta R_p$, where ΔR_p is defined by expression (7) for $\mu = 0$, $\lambda = 0$.

This process is illustrated schematically in the Figure 1,b. Usually the column constant $\tau_p = 0.5$ to 5 seconds. Therefore in practice it is possible to neglect the additional shift of the column.

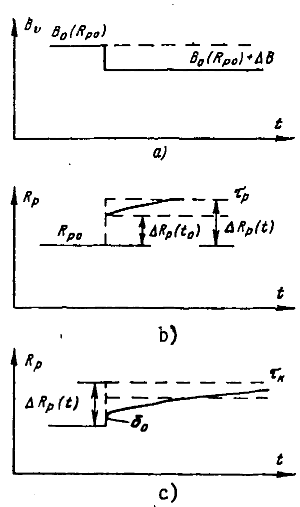


Figure 1. Diagram of the movement of a plasma column with an "instantaneous" jump of the controlling field ΔB. a -- controlling magnetic field as a function of time; b -- reaction of the column to the jump of the field ΔB in the absence of a conducting chamber; c -- reaction of the column in a presence of a conducting chamber.

In the presence of a passive circuit magnetically connected to the plasma column, the nature of movement of the column is altered significantly.

If currents are induced in the chamber on movement of the column, then the equation of motion of the column can be written in simple, clear form:

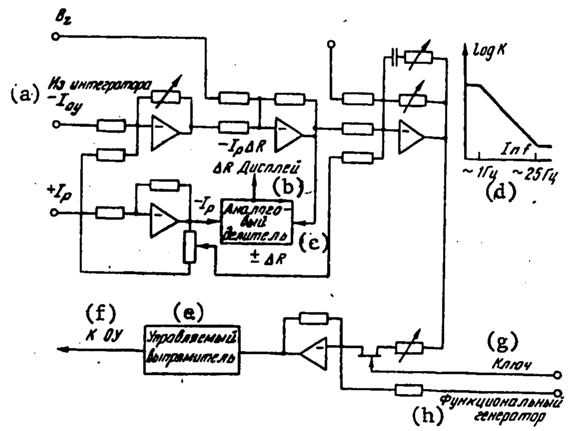


Figure 2. Block diagram of the control of the column position in the PLT device (United States).

Key:
- a. from the integrator
- b. display
- c. analog divider
- d. ... hertz
- e. controlled rectifier
- f. to the OU
- g. switch
- h. functional generator

$$10^{-7}\frac{d}{dt}[I_p(R_p-R_0-\Delta_0)]=\frac{1}{\tau_\kappa}\frac{b_\kappa^2}{2}[B_0(R_p,t)+B_v(R,t)], \quad (8)$$

R_0 and b_k are the large and small radii of the toroidal chamber.

The reaction of the plasma column to the "instantaneous" variation of any parameter (β, ℓ_i) violating the equilibrium condition, also consists in a discontinuous shift by the amount

$$\Delta_H=-\frac{R_p-R_0-\Delta_0}{I_{p0}}\Delta I_p+\frac{b_\kappa^2}{2R_0}\left(1-\frac{a^2}{b_\kappa^2}\right)\times\left(\Delta B+\frac{1}{2}\Delta l_h\right).$$

In the new equilibrium position not only the force of interaction of the plasma current with the transverse magnetic field participates in the force balance, but also the force of interaction with the "instantaneously" appearing image currents in the chamber walls with infinitely large conductivity. The magnitude of this shift, as is shown in Figure 1, c, is less than ΔR_{p0} and depends on the mutual arrangement of the axis of the column and the chamber. After leakage of the magnetic field through the chamber wall the column drifts to the position $R_0 + \Delta R_0$. The speed of this displacement is determined by the geometric dimensions and conductivity of the chamber walls.

In reality, no instantaneous changes in the plasma column parameters were observed, and the speed of movement of the column in the first phase depends to a significant degree on the disturbance buildup time. The amplitude of the disturbance is estimated as 1-2% at frequencies (equivalent to the given buildup rate) of several hundreds of hertz, approximately 5% at frequencies to 50 hertz and about 10% for a frequency of<10 hertz. The presence of a thick conducting screen complicates the penetration of the magnetic field of the control windings on the outside of the screen. At the same time, the speed of the reaction of the control system to the disturbances in the plasma column leading to shifting of it is reduced. The shielding effect of the conducting chamber walls is especially noticeable in the initial, most important stage of discharge. None of the late operating and designed tokamaks have an additional conducting shield. The role of the housing is played by a vacuum chamber usually made of material with low conductivity, for example, stainless steel.

Recently, general attention has been attracted by the physical results obtained on the PLT tokamak (Princeton, United States) [7]. This device is a tokamak without conducting shield. Its role is played by the vacuum chamber. The equilibrium of the plasma column is achieved using an external magnetic field created by a vertical field winding. This winding is inside the longitudinal field windings. As the power supply, a rectifier with thyristor regulators is used, the control of which is realized by a program from a functional generator and feedback control system. The program of the control winding current is corrected from cycle to cycle in accordance with the readings of the sensors in the feedback circuit, which permits more efficient automatic regulation of the column position. The value of $I_p\Delta$ is taken as the automatic control parameter (I_p is the current in the plasma; Δ is the shift of the column from the equilibrium position). The block diagram of the control system is presented in Figure 2. A simplified algorithm is executed in it to calculate the parameter $I_p\Delta$

$$I_p\Delta = k_1 B_z + k_2 \left(I_{0y} - \frac{k_3}{k_2} I_p\right). \quad (9)$$

The coefficients in this equation are functions of the small and large radii of the column, and for simplification of the control system they are considered constant. The displacement signal is the magnitude of the magnetic field B_z measured using two "flat" type coils with effective area of 0.66 m^2 installed symmetrically in the chamber above and below the midplane. The radius of their installation corresponds to the equilibrium position of the column (R_0). The null signal from the coils in the first approximation means that the vacuum chamber is a magnetic surface. In the control algorithm the value of $\Lambda = \beta_p + \ell_i/2 - 1$ is approximately taken into account by introducing the term with I_{0y} as a parameter (I_{0y} is the current in the vertical field winding). The signals from the sensors B_z, I_{0y} and I_p are integrated and summed using operation amplifiers. The toroidal shift is considered by introducing an additional program input ΔR. This correction is approximately 5 cm. The control input to the thyristor regulator is the sum of a signal proportional to $I_p\Delta$ shaped in this way and the signal from the functional generator, where the amplification in the feedback circuit is selected empirically by the operator. In the algorithm used, the influence of the magnetic fields created by the eddy currents in the structural elements of the tokamak on the column equilibrium is not taken into account. Therefore when they make a significant contribution to the field, which occurs in initial and final stages of discharge, the signal in the feedback circuit is calculated with large errors, and the feedback control system cannot be used. By the estimates on the current "plateau," the control system provides an accuracy on the order of a centimeter. The reaction time of the system is 5 milliseconds (the chamber constant is 0.3 milliseconds).

The TFR-600 tokamak (France) [8] is a modified version of the old TSR-400. In the new version of the tokamak, fast control of the column position is obtained using a dual thyristor switch system offering fast variation of the transverse field $\pm 3\cdot 10^{-3}$ tesla in a time of about 5 milliseconds. The previously existing conducting copper screen was removed, and the time constant of the vacuum chamber was 0.1 milliseconds. The tokamak has an iron core which has a significant destabilizing effect on the plasma column. In addition, it becomes necessary in the control algorithm to consider the effect of the iron yoke on the system parameters.

The programmed vertical field winding fed from two series-connected thyristor regulators with a total power of 3 megawatts gives a field of up to $4\cdot 10^{-2}$ tesla. A 16 bit microprocessor is used as the programmer. The same microprocessor is used to correct the current program for the next discharge by the data for measuring the plasma column parameters.

The windings included in the feedback circuit and shown in Figure 3 are decoupled with the basic winding using an external inductance of 74 millihenries. Two windings giving an additional up to $\pm 3\cdot 10^{-3}$ tesla to the magnetic field are fed from a capacitor bank through a system of high-speed thyristor switches T_{11}, T_{31}, T_{12}, T_{32} (Figure 3). In the null position the winding is shortcircuited to itself, and the current drops with the winding time constant. For charging the battery there is a thyristor regulator of 3 kv/700 amps.

The sensors for sensing the horizontal and vertical position of the column are electromagnetic probes. The signals from them are processed by analog devices which execute the operations of addition (subtraction) and multiplication (division). In the system for controlling the vertical position of the column shown in the lower part of Figure 3, two thyristor regulators with a power of 100 kilowatts are used. The radial field B_r is regulated within the limits of up to $\pm 2\cdot 10^{-3}$ tesla with a time constant of 10 milliseconds.

The experimental studies of the tokamak with activated column position control system demonstrated that the deviations of the column did not exceed 1 cm on the current plateau and several centimeters in the initial discharge phase. It is noted that the poor reproduction of the plasma parameters from discharge to discharge is to a significant degree connected with the difference in gas admission from the vacuum chamber walls.

The TFTR thermonuclear device designed at the Princeton Laboratory (United States) [5] belongs to the class of general tokamaks. The large and small radii of the plasma column are 248 and 85 cm. The maximum plasma current is to 2.5 megamps, and the discharge time is up to 5 seconds.

The control winding of the TFTR tokamak consists of 56 turns with a maximum current to 80 kiloamps. Part of the turns in a row with the inductor winding are joined into a "hybrid" winding. The control winding is used to create a programmed vertical field and also to the control position of the plasma column on the basis of information received from the sensors from R_p, $\dot{R}_p$, I_p, $\dot{I}_p$, B_v, $\dot{B}_v$, I_H, I_E (Figure 4). Thyristor regulators assembled by the 12-phase circuit are used as the power supplies. The information about these parameters after the corresponding processing in the analog modules goes to a comparison circuit.

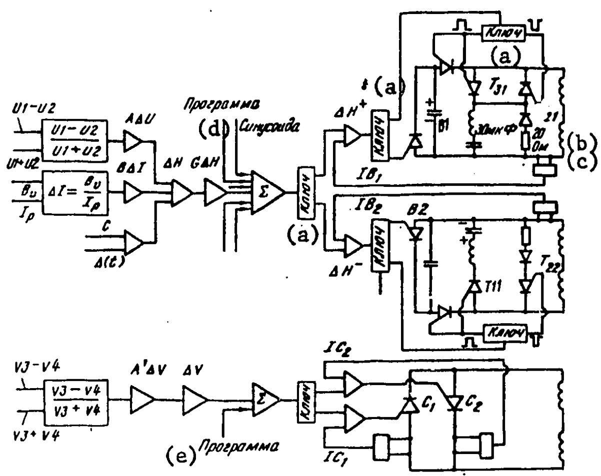


Figure 3. Block diagram of the horizontal and vertical column position control of the TFR-600 tokamak (France). U1, U2, U3, U4, V1, V2, V3, V4 are signals from the magnetic probes installed near the plasma column.

Key: a. switch
b. ... microfarads
c. ... ohms
d. sine curve program
e. program

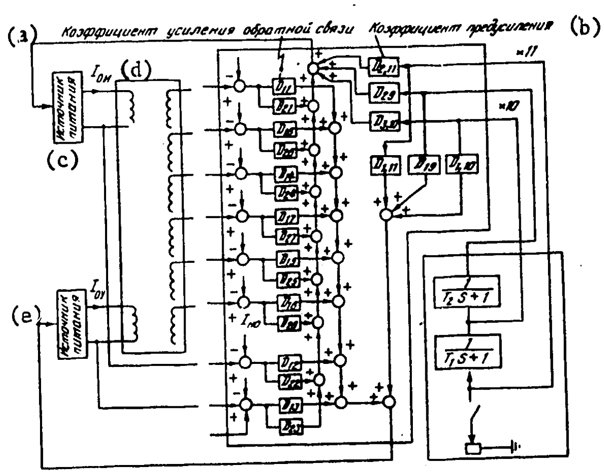


Figure 4. Block diagram of the column position and plasma current control system of the planned TFTR tokamak (United States).

Key: a. feedback amplification coefficient
b. preamplification coefficient
c. power supply
d. I_{0I}
e. I_{0U}

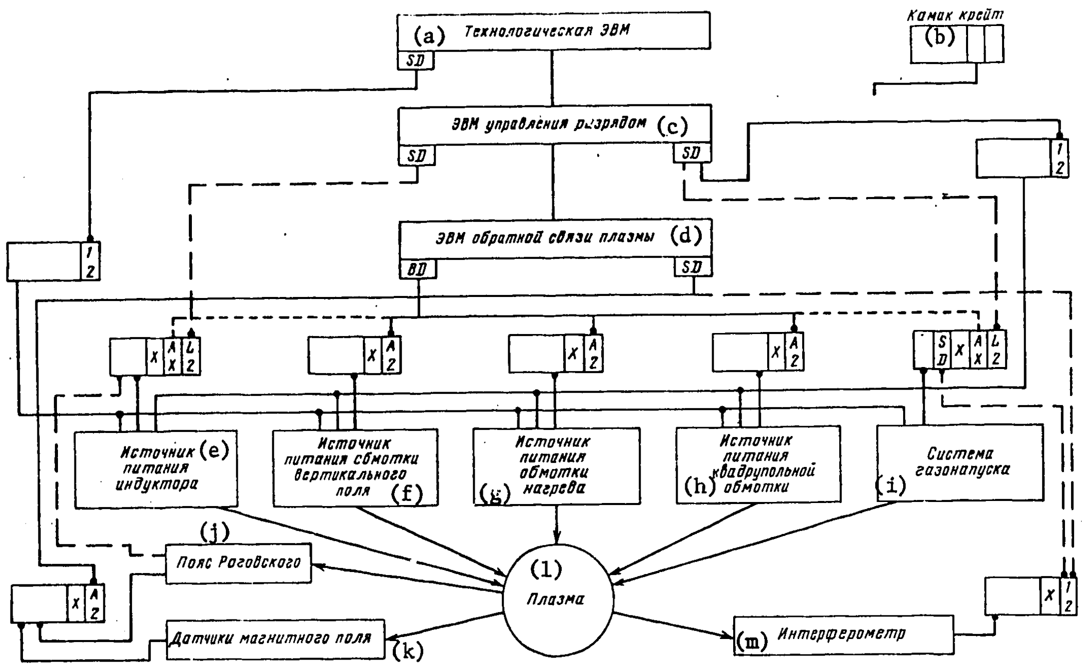


Figure 5. Block diagram of the plasma column parameter control system of the JT-60 tokamak (Japan).

Key:
- a. process computer
- b. CAMAC crate
- c. discharge control computer
- d. plasma feedback computer
- e. inductor power supply
- f. vertical field winding power supply
- g. heating winding power supply
- h. quadrupolar winding power supply
- i. gas admission system
- j. Rogowski loop
- k. magnetic field sensors
- l. plasma
- m. interferometer

The study of the dynamics of the plasma column based on its mathematical model similar to that described in the preceding section revealed the important role of the eddy currents induced in the vacuum chamber. On the basis of a study of the column reaction to variation of its parameters (for example, when the plasma current varies by 0.25 megamps in 50 milliseconds) for the control system with different discreteness, the conclusion was drawn of the possibility of using a 12-phase feed system for the control windings. The maximum error in the radial position of the column was 4 cm, when the plasma current varies by 0.25 megamps in the time 30 milliseconds with control discreteness of 8.4 milliseconds. The control reaction insures the given position and current of the plasma with a time constant of approximately 20 milliseconds.

Among new designs for large tokamaks a special role is played by the Japanese JT-60 [6]. Its distinguishing feature is broad application of computers of different

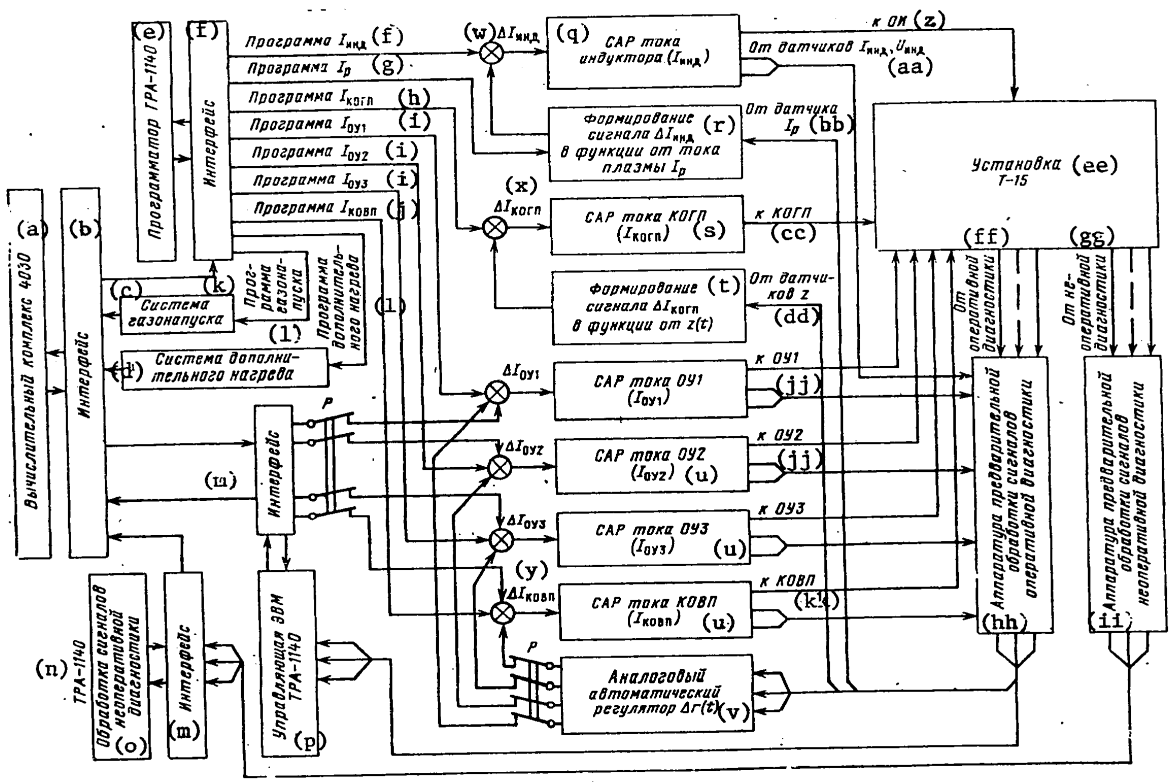


Figure 6. Block diagram of the control of the plasma current stabilization system and plasma current position on the T-15 device (USSR).

Key:
- a. computer complex 4030
- b. interface
- c. gas admission system
- d. auxiliary heating system
- e. TRA-1140 programmer
- f. program I_{ind}
- g. program I_p
- h. program I_{KOGP}
- i. program I_{OY}...
- j. program I_{KOVP}
- k. gas admission program
- l. auxiliary heating program
- m. interface
- n. TRA-1140
- o. processing nonoperative diagnostic signals
- p. TRA-1140 control computer
- q. inductor current automatic control system (I_{ind})
- r. signal shaper ΔI_{ind} as a function of plasma current I_p
- s. KOGP current automated control system (I_{KOGP})
- t. signal shaping ΔI_{KOGP} as a function of z(t)
- u. ... current automatic control system (I_{KOVP})
- v. analog automatic regulator $\Delta r(t)$

(key continued on next page)

Key to Figure 6 (continued):

w. ΔI_{ind}
x. ΔI_{KOGP}
y. ΔI_{KOVP}
z. to the OI
aa. from the I_{ind}, U_{ind} sensors
bb. I_p sensor
cc. to the KOGP
dd. from the Z sensors
ee. T-15 device
ff. from the operative diagnostics
gg. from the nonoperative diagnostics
hh. equipment for preliminary processing of the operative diagnostic signals
ii. equipment for preliminary processing of the nonoperative diagnostic signals
jj. to the ...
kk. to the KOVP

class both to control the device as a whole and for feedback purposes to control, in addition to the position, such plasma parameters as the temperature, density, shape of transverse cross section, current and distribution of the current. The control algorithms are put into the programs of the controlling computers, the feedback computers and the data gathering computers.

The introduction of this device into operation is planned in 1985. The JT-60 is also a tokamak without a conducting housing. In order to control such column parameters as current, vertical and horizontal shift, shape of the transverse cross section, individual groups of windings are used: resistance heating horizontal, vertical and quadrupolar fields. All of the windings are placed inside the toroidal field winding outside the vacuum chamber. Concentration is regulated by the gas admission system.

The block diagram of the control of the JT-60 is presented in Figure 5. Two stages in its investigation are reflected here. In the first stage single loops controlled separately were investigated. The plasma current, the horizontal and vertical positions, ellipticity of the transverse cross section and plasma density are controlled, respectively, using the power supplies of the inductor, the vertical, horizontal and quadrupolar fields, and the gas admission system. The feedback computer is used here only to calculate the shifts of the plasma and its ellipticity beginning with the magnetic probe signals. The communications for this first stage are illustrated by the dotted lines. This system is based on the classical control theory. Simulation shows that on introduction of disturbances in I_p and R_p as a result of interconnection of the circuits, the setup time for the given R_p is 60 milliseconds (although R_p reaches the required value in approximately 10-20 milliseconds). This mutual influence is also manifested in the regions of stability of operation of the system decrease.

In the second stage (the dotted lines in the figure are replaced by points), a study was made of the control algorithm with many variables. In this case all five groups of CAMAC modules operate from the feedback computer. Such plasma parameters as temperature, current distribution, and so on are introduced into the weight feedback control function.

In the control algorithm the magnetic fields from the eddy currents in the tokamak structures are also taken into account.

As the sensors for the control system broad use is made of the electromagnetic diagnostic sensors which are the basic ones: electromagnetic probes $B_{p,n}$ and $B_{p\tau}$ (normal and tangential components of the poloidal magnetic field) -- for calculation of the shift of the column and its deformations; Rogowski loop -- for measuring the discharge current; single-turn windings -- for measuring the voltage on the column bypass, windings for measuring the diamagnetic flux of the longitudinal magnetic field. As the additional sensors, physical diagnostic sensors are used: for measuring n_e, T_e, ℓ_i, β. All of the electromagnetic diagnostic pickups are placed inside the chamber of the device. With respect to its parameters, the designed T-15 Soviet device is similar to the large foreign TFTR and JT-60 tokamaks. The maximum current in the plasma is 2.3 megamps, the large and small radii of the column are 240 and 70 cm, and the current pulse duration is up to 6 seconds.

For resistance heating of the plasma, a system with closed magnetic circuit was used. The inductor winding is fed from the 12-phase thyristor regulator operating in the rectifying-inversion mode with commutation system. The vertical field control windings are divided into three sections with independent thyristor power supplies, and they are included parallel to the inductor winding. The superconducting winding of the longitudinal magnetic field having 24 sections, radiation copper shielding protecting the superconducting winding from thermal emission from the vacuum chamber and the vacuum chamber with time constant of about 2 milliseconds complicate the penetration of the external magnetic field into the region occupied by the plasma. Therefore near the chamber there is an additional correcting winding of the vertical field fed from a capacitor bank (2 kv/8 kamps) controlled by a three-position thyristor commutator. The maximum field given by the winding is $\pm 3 \cdot 10^{-2}$ tesla. For correction of the vertical shifts of the column a horizontal field winding is provided which gives up to $\pm 2 \cdot 10^{-2}$ tesla.

The block diagram of the plasma column position and current control system is illustrated in Figure 6. In the computer complex a program is generated for the circuits of the electromagnetic system, gas admission and additional heating. The role of the programmer is played by the TRA-1140 processor. Each of the external plasma current stabilization and vertical and horizontal position loops has internal winding current stabilization circuits which permit the given current program to be maintained with an accuracy of about 0.3%. The required information about the column parameters (R_p, $\dot{R}_p$, I_p, $\dot{I}_p$, β), the currents and voltages on the windings goes from the operative diagnostics gathering system after processing in the APOS system (the preliminary signal processing equipment). The external plasma current stabilization and vertical column position circuits are resolved by purely analog means. The fast column horizontal position control circuit includes only analog circuits. For correction of the program, the class 1140 computer is used between discharges. The algorithm for processing the information coming to the input of the TRA-1140 permits generation of the required control signals for entry of the correction adders into the program of the controlling and correcting windings. For correction of the program between discharges information is also used which was obtained by the nonoperative diagnostic channels (concentration, plasma temperature, and so on).

The investigated plasma column position control systems for the column in the tokamaks are only part of the complete plasma parameter control system (current, position, conductivity, temperature, concentration, and so on) including the gas admission and auxiliary heating systems. The creation of such systems is a problem of the near future.

BIBLIOGRAPHY

1. V. S. Mukhovator, V. D. Shafranov, "Plasma Equilibrium in a Tokamak," NUCLEAR FUSION, No 11, 1971, p 605.

2. S. Matsuda, T. Ohga, S. Jtor, N. Suzuki, "Effect of the Conducting Shell and Its Gap on Generation of the Vertical Magnetic Field in a Tokamak Device," JAPANESE JOURNAL OF APPLIED PHYSICS, Vol 13, No 10, 1974, p 1604.

3. L. J. Artemenkov, et al., "Experiments on the TO-1 Tokamak having an Automatic System for Controlling the Equilibrium," IV EUROP. CONF. ON CONTROLL. FUSION AND PLASMA PHYSICS, Vol 1, 1973, p 153, Moscow.

4. I. Hugill, A. Gibson, "Servocontrol of Plasma Position in CLEO-Tokamak, NUCLEAR FUSION, No 14, 1974, p 611.

5. R. Gran, M. J. Rossi, F. Sobierajski, "Plasma Position Control for TFTR Using Modern Control Theory," VII SYMPOSIUM OF ENGINEERING PROBLEMS OF FUSION RESEARCH, Knoxville (USA), 1977.

6. "Status of JT-60," PROGRAM III MEETING ON ENGINEERING OF LARGE TOKAMAK EXPERIMENTS, Paris, 1978.

7. K. Bol, "PLT Radial Position Control," PLT REPORT UNDATED.

8. R. Dei-Gas, I. Blum, I. P. Moreraa, P. Plinate, "Slow and Fast Feedback Circuits for the Plasma Equilibrium in the TFR-600 Tokamak. Numerical Simulation of the Multitransformer Equations," VII SYMPOSIUM OF ENG. PROBLEMS OF FUSION RESEARCH 25-28 October, Knoxville (USA), 1977.

[161-10845]

10845
CSO: 1860

INSTRUMENTS, MEASURING DEVICES AND TESTERS, METHODS OF MEASURING, GENERAL EXPERIMENTAL TECHNIQUES

UDC 621.396.049(088.8)

A DEVICE FOR TESTING INTEGRATED CIRCUITS

USSR Patent Class H 01 L 21/70, No 2,463,621 18 May 80 (disclosure No 734,833 21 Mar 77)

DOMENIKOV, V. I., KUDRYAVTSEV, A. Ye. and MIKHAYLOV, N. V.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1B418 P]

[Text] The device makes it possible to test all types of integrated circuits with planar output leads in 1.25 steps for thermal stability and reliability, as well as to perform design and parametric high-temperature and overload tests with the aid of only one kind of thermostat. Figures 3.

[177-2415]

OPTOELECTRONICS, QUASI-OPTICAL DEVICES

UDC 621.383.8:621.382

SYSTEM OF SCANISTOR CHARACTERISTICS AND PARAMETERS

Barnaul ELEMENTY OPTOELEKTRONNYKH USTROYSTV in Russian, 1979 pp 86-109

GOS'KOV, P. I., ORDIN, B. M., GALIULIN, R. M., KOSTIN, V. A., MIKHALEV, V. A. and KOZHUKHOVA, Ye. A.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1V77 by Ye. V. Gamsakhurdiya]

[Text] The characteristics and parameters of scanistors are classified into three groups. The energy group includes the current-illuminance characteristic, the sensitivity threshold, and the dark current. The space-time group includes the resolution and the coordinate characteristic. The directory group includes the operating characteristics, the dependence of the scanistor parameters on the bias voltage and on the interrogation voltage, the temperature characteristics as well as time and frequency characteristics. A methodology of measuring the scanistor parameters and characteristics is outlined. Also described are those parameters and characteristics which serve as criteria for the technology of series manufacture and for a rational quality inspection during production. Figures 7; references 24.

[177-2415]

UDC 621.383.8:621.382

NOISE IN THE MICROZONE OF A SEMICONDUCTOR SCANISTOR

Barnaul ELEMENTY OPTOELEKTRONNYKH USTROYSTV in Russian, 1979 pp 126-129

KUZ'MIN, Yu. G.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1V76 by Ye. V. Gamsakhurdiya]

[Text] The equivalent circuit diagram of a noisy semiconductor scanistor is constructed. The noise current in this device (with sources of excess and flicker noise disregarded) is principally determined by thermal and shot effects. Here the noise in the emitter junction and in the collector junction of an open or a closed semiconductor scanistor is calculated, as well as the total noise in the presence of a luminous flux. Noteworthy is the insignificant effect which the impedance of an open emitter junction has on the total scanistor noise. It is also demonstrated that illumination increases the intrinsic noise of a closed semiconductor scanistor, the total noise being lower with an inductive than with a capacitive load and the intrinsic noise being higher in an open than in a closed device. In the absence of a luminous flux the noise current is the same in an open and in a closed device. Figures 1; references 5.

[177-2415]

UDC 621.383.52:621.383.8

AREAS OF APPLICATION FOR CONTINUOUS AND MULTIELEMENT TYPES OF TWO-COORDINATE SCANNING SEMICONDUCTOR PHOTODETECTORS AND A COMPARISON OF THEIR CHARACTERISTICS

Barnaul ELEMENTY OPTOELEKTRONNYKH USTROYSTV in Russian, 1979 pp 68-85

GOS'KOV, P. I.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1V78 by Ye. V. Gamsakhurdiya]

[Text] A comparative analysis is made of continuous two-coordinate scanistors and photodetector matrices on the basis of charge-coupled devices and photodiodes. Two-coordinate scanistors--analog converters of optical signals to electrical ones--are technologically simpler to produce and feature a higher sensitivity, spatial resolution and reliability. Photodetector matrices operate in the memory mode with an arbitrary selection and make it possible to generate

signals in digital form, but they are technologically more complex and also more sensitive to mechanical effects. Figures 5; references 52.

[177-2415]

UDC 621.383.8:621.383.52

PERFORMANCF OF AN MF-16 PHOTOMATRIX IN THE SIGNAL DETECTION MODE

Barnaul ELEMENTY OPTOELEKTRONNYKH USTROYSTV in Russian, 1979 pp 110-125

AKSENOV, S. Ye. and GULYAYEV, I. Yu.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1V70 by Ye. V. Gamsakhurdiya]

[Text] Because a MF-16 photomatrix of MOS photodiodes has been found to operate insufficiently fast in the charge storage mode, with an attendant nonuniformity of the video signal and a rather narrow dynamic range of illuminance, it is proposed that it be operated in the direct signal detection mode. The sensitivity of a matrix operating in this mode is determined by the sensitivity of the photodiodes and by the current gain of the MOS transistor, but does not depend on the interrogation speed, which makes high-speed operation feasible. The dependence of the output voltage and of both voltage and current sensitivity on various parameters, in the signal detection mode, has been plotted on the basis of measurements made on a test model of an MF-16 matrix. Figures 11.

[177-2415]

UDC 621.383.81

AN OUTPUT SCREEN FOR A BRIGHTNESS INTENSIFIER

USSR Patent Class H 01 J 31/50, No 2,452,035 15 Oct 79 (disclosure No 691,958 10 Jan 77)

GANICHEV, V. A., ZAYDEL', I. N., KOROBOV, M. I. and SPEKTOR, A. A.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1A80 P]

[Text] An output screen for an image brightness intensifier is proposed which consists of an insulating substrate, a luminophor layer and a conducting film between them. For higher glow intensity and electrical strength, the conducting film is made of a cermet material based on chromium disilicide and borosilicate glass 300-500 Å thick.

[177-2415]

UDC 621.383.811

A DEVICE FOR CONTROLLING THE IMAGE BRIGHTNESS OF AN ELECTROOPTICAL TRANSDUCER

USSR Patent Class H 04 N 5/58, No 2,559,108 15 Mar 80 (disclosure No 720,807 26 Dec 77)

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1A82 P]

[Text] A second comparator and a controllable sawtooth voltage generator have been added. A device for controlling the image brightness of an electrooptical transducer is proposed which consists of an integrator and a comparator connected in series, with the second input and the output of the comparator connected respectively to the first output of the reference-signal generator and the first control input of the commutator, with the input and the output of the commutator connected respectively to the power supply and the transducer input.

[177-2415]

UDC 621.383.811

A MULTICHANNEL ELECTROOPTICAL SYSTEM

USSR Patent Class H 01 J 31/50, No 2, 542,376 28 Feb 80 (disclosure No 660,493 9 Nov 77)

MONICH, V. A., MONICH, Ye. A. and RYKALIN, V. I.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1A91 P]

[Text] A multichannel electrooptical system is proposed which consists of detectors with an optical data output, an electrooptical transducer and a multichannel photorecording element. For a more efficient recording of random processes, a multichannel optical fiberglass delay line is inserted between the detectors and the electrooptical transducer, and a control circuit is connected to the shutter.

[177-2415]

UDC 621.383.812(088.8)

A MULTICAVITY IMAGE BRIGHTNESS INTENSIFIER

USSR Patent Class H 01 J 31/50, No 2,555,688 25 May 80 (disclosure No 736,212 15 Dec 77)

ANDREYEV, A. V., LISOVSKIY, G. V. and RAYEVSKIY, N. V.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1A85 P]

[Text] A multicavity image brightness intensifier is proposed. In order to widen the operating range of input luminance, the luminescent screens of the intensifier are made of a luminophor whose glow spectrum varies depending on the space density of the impinging electron flux. The screens are made of yttrium oxysulfide activated with terbium.

[177-2415]

PUBLICATIONS

UDC 621.398.001.42

ADJUSTMENT OF TELEMECHANICAL DEVICES AT INDUSTRIAL ENTERPRISES

Moscow NALADKA USTROYSTV TELEMEKHANIKI NA PROMYSHLENNYKH PREDPRIYATIYAKH in Russian 1980 (signed to press 24 Oct 80) pp 2-3, 96

[Annotation, foreword and table of contents from book "Adjustment of Telemechanical Devices at Industrial Enterprises", by Aleksandr Davidovich Shain and Aleksandr Grigor'yevich Levin, Izdatel'stvo "Energiya", 20,000 copies, 96 pages]

[Text] This book treats the structural principles of remote control, telesignaling and telemetering devices used at industrial enterprises and describes principal functional units of remote control, telesignaling and telemetering systems. The authors discuss the methods of their adjustment, their failures that may occur and ways of correcting them, measuring instruments used for their adjustment, and the servicing procedures during their operation.

The book is intended for electricians and personnel engaged in the adjustment and operation of telemechanical devices at industrial enterprises.

Foreword

Modern industrial enterprises are characterized by the development of complex automation of production and the introduction of automatic control systems. The introduction of complex automation of production requires up-to-date methods of monitoring and controlling production processes and reliable transmission of information from distant objects. Telemechanical devices are one of the types of technical facilities performing such functions.

Telemechanical devices have been used for a long time in regional power systems and at railroads, therefore much experience has been accumulated in these areas in the operation of telemechanical devices. At industrial enterprises, a wide introduction of telemechanical devices has started relatively recently. This makes it necessary to familiarize the personnel of industrial enterprises and adjusting organizations with the structural principles and operation of industrial telemechanical devices, as well as with the principles of their adjustment.

In preparing this book, the authors used the instructions of plants manufacturing telemechanical devices and the experience in their adjustment by the association Soyuzkhimpromenergo.

The book gives brief descriptions and adjustment methods of telemechanical devices which are used most frequently for the telemechanization of power supply systems for industrial enterprises.

Readers are requested to send their remarks and suggestions to the address of the "Energiya" publishing house: 113114, Moscow, M-114, Shlyuzovaya nab., 10.

Contents

[201-10,233]

10,233
CSO: 1860

ADJUSTABLE SELF-COMPENSATING ELECTRICAL POWER TRANSMISSION LINES

Kishinev UPRAVLYAYEMYYE SAMOKOMPENSIRUYUSHCHIYESYA LEP in Russian 1980 (signed to press 19 Feb 80) pp 2, 114-5

[Annotation and table of contents from book "Adjustable Self-Compensating LEP", edited by V. M. Postolatiy, V. L. Ivanov, N. P. Radchenko and F. M. Yerkhan, Izdatel'stvo "Shtiintsa", 560 copies, 116 pages]

[Text] Annotation

Results of investigating normal modes of adjustable self-compensating electrical power transmission lines (USVL) are presented. Possible methods and schemes for regulating USVL modes and determining useful areas of application are considered. Some types of phase-regulating devices are investigated as a means of controlling USVL modes. Line power losses are analyzed. "Overcompensation" modes of USVL circuits are examined, as are some questions of the methods of calculating commutation overvoltages. Relay-type devices for protection from inter-circuit short-circuiting of USVL are investigated, and an estimate of short-circuiting levels on the reliability of power system components is given. The results of investigating the characteristics of fiberglass insulation and certain insulating components are given.

The handbook is intended for scientific workers, specialists of planning organizations and electrical power systems.

Table of Contents

[185-6900]

6900
CSO: 1860

UDC 621.314.214

AUTONOMOUS MULTIPHASE VOLTAGE INVERTERS WITH IMPROVED CHARACTERISTICS

Kiev MNOGOFAZNYYE AVTONOMNYYE INVERTORY NAPRYAZHENIYA S ULUCHSHENNYMI KHARAKTERISTI-KAMI in Russian 1980 (signed to press 20 Oct 80) pp 2, 180-181

[Annotation and table of contents from book "Autonomous Multiphase Voltage Inverters with Improved Characteristics", by Vladimir Yefimovich Tonkal', Eduard Nikitovich Grechko, and Stanislav Ivanovich Bukhinskiy, Izdatel'stvo "Naukova dumka", 1350 copies, 182 pages]

[Text] This book discusses the theory and design of autonomous multiphase voltage inverters with improved technical and economic characteristics. The authors investigated the energy relations and other characteristics of multiphase bridge inverters, composite inverters, and multiphase inverters with voltage modulation and intermediate high frequency. They analyzed the existing methods of compensating reactive power in autonomous inverters and examined the peculiarities of a new compensation method which received the name intercompensation. They examined the system and original control circuits of inverters.

The book is intended for use of scientists, engineers, and technicians specializing in the area of conversion techniques.

Figures -- 77, tables -- 25, bibliography -- 70 items (pp 177-179)

Contents

[203-10,233]

10,233
CSO: 1860

UDC 621.391.82

CONTACT INTERFERENCE IN RADIO RECEPTION

Moscow KONTAKTNYYE POMEKHI RADIOPRIYEMU in Russian 1979 (signed to press 14 Sep 79) pp 2, 115-16

[Annotation and table of contents from book "Contact Interference in Radio Reception", by Andrey Yakovlevich Klementenko, Boris Alekseyevich Panov, and Valerian Filippovich Sveshnikov, Voyenizdat, 22,000 copies, 116 pages]

[Text] This book gives a definition of contact interference. The authors present the fundamentals of the theory of this type of radio interference. They explain its physical substance and examine the spectral composition and amplitude characteristics. Practical recommendations are given on the ways of controlling contact interference and methods for ensuring the conditions of electromagnetic compatibility of radioelectronic equipment of mobile objects in the presence of contact interference.

This book is intended for use by radio specialists engaged in the development and operation of mobile communication centers and radioelectronic equipment.

Contents Page

[187-10,233]

10,233
CSO: 1860

UDC 550.837

DIVERGENT ELECTRICAL PROSPECTING

Kiev DIVERGENTNAYA ELEKTRORAZVEDKA in Russian 1977 (signed to press 13 Jul 77) pp 2, 179-180

[Annotation and table of contents from book "Divergent Electrical Prospecting", by Yaroslav Stanislavovich Sapuzhak, L'vov Mathematical Physics Branch, Institute of Mathematics, Ukrainian SSR Academy of Sciences, Izdatel'stvo "Naukova dumka", 800 copies, 180 pages]

[Text] This book presents the basic theses of the theory and methods of detailed electrometric studies with bilateral divergent units in natural and artificial electric fields.

By means of theoretical calculations and simulation, the author studied the nature of theoretical and experimental charts of various divergent units over typical inhomogeneous structures and developed the fundamentals of the interpretation of field materials.

The author also gives the results of experimental field observations in individual sections which confirm the data of his theoretical and experimental studies.

Figures -- 52, bibliography -- 33 items.

Contents

[204-10,233]

10,233
CSO: 1860

UDC 621.382:621.383:535.376

ELEMENTS OF OPTOELECTRONIC DEVICES

Barnaul ELEMENTY OPTOELEKTRONNYKH USTROYSTV in Russian Intercollegiat Regional Library at the Barnaul Polytechnic Institute, 1979, 198 pp

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1V109 K]

[Text] This is a collection of articles dealing with analysis and synthesis of basic elements of optoelectronic devices for processing of diverse optical information. New designs of optoelectronic elements and devices for measurement of nonelectrical quantities are examined, and an error analysis is included. Figures 80.

[177-2415]

UDC 65.011.46

EVALUATION OF THE EFFECTIVENESS OF COMPLICATED TECHNICAL DEVICES

Moscow OTSENKA EFFEKTIVNOSTI SLOZHNYKH TEKHNICHESKIKH USTROYSTV in Russian 1980 (signed to press 8 Jul 80) pp 190-192

[Annotation and table of contents from book "Evaluation of Effectiveness of Complicated Technical Devices", by Nikolay Matveyevich Chumakov and Yefim Ioniyevich Serebryanyy, Izdatel'stvo "Sovetskoye radio", 7000 copies, 192 pages]

[Text] The authors examine the methods of evaluating the effectiveness of complicated devices with consideration for several particular indexes of their quality for substantiating the selection of the most acceptable variant. This book is intended for specialists engaged in the designing and operation of complicated devices.

Contents

[188-10,233]

10,233
CSO: 1860

UDC 638

FUNDAMENTALS OF THE PHYSICS OF SEMICONDUCTOR LAYERED SYSTEMS

Kiev OSNOVY FIZIKI POLUPROVODNIKOVYKH SLOISTYKH SISTEM in Russian 1980 (signed to press 22 Apr 80) pp 2, 281-282

[Annotation and table of contents from book "Fundamentals of the Physics of Semiconductor Layered Systems", by Vladimir Grigor'yevich Litovchenko, Izdatel'stvo "Naukova dumka", 1750 copies, 283 pages]

[Text] The book generalizes the results of studies on the physical properties and processes characteristic of layered semiconductor systems of various types (thin films, surface and presurface layers, multiphase structures, sharply anisotropic layered semiconductors) and discusses the basic methods of the formation of the structures, methods of their studies, concentration effects, scattering processes, and their photoelectric, luminescence and optical properties. It discusses promising directions of further studies of layered systems (collective effects, superconductivity phenomena).

The book is intended for specialists working in the area of the physics of semiconductors and planar integrated electronics, as well as for undergraduate and graduate students specializing in the physics of semiconductors, dielectrics, and microelectronics.

Figures -- 92, tables -- 7, bibliography -- 774 items (pp 251-280)

Contents

[189-10,233]

10,233
CSO: 1860

HANDBOOK OF MEASURING INSTRUMENTS FOR RADIO COMPONENTS

Leningrad SPRAVOCHNIK PO IZMERITEL'NYM PRIBORAM DLYA RADIODETALEY in Russian 1980 (signed to press 25 Jul 80) pp 249-53

[Annotation and table of contents from book "Handbook of Measuring Instruments for Radio Components", by Solomon Lazerevich Epshteyn, Aleksandr Pavlovich Vikulov and Valentin Nikolayevich Moskvin, edited by Ye. A. Gaylish, Izdatel'stvo "Energiya", 60,000 copies, 256 pages]

[Text] Table of Contents

Section 2

INSTRUMENTS FOR MEASURING RESISTOR CHARACTERISTICS

Annotation

The handbook presents technical data and brief descriptions of more than 150 types of specialized instruments and equipment used in the mass production of radio components. Attention is given the design features and circuitry of the instruments examined.

The handbook is intended for a wide group of specialists involved in the operation and development of measurement equipment, and also may be useful for students in institutions of higher learning and technical training schools.

[184-6900]

6900
CSO: 1860

UDC 530:519.2:539.107.5:538.56:550.834.621.3

NEW BOOK DISCUSSES STATISTICAL RADIOMETRY

Kiev STATYSTYCHNA RADIOMETRIYA in Ukrainian 1979 (signed to press 12 Sep 79) pp 2, 263-4

[Annotation and table of contents from book "Statistical Radiometry" by Roman Fedoriv, Vydavnytstvo "Naukova dumka", 450 copies, 264 pages]

[Text] Basic positions of statistical radiometry, its problematics and areas of application are formulated in the monograph for the first time. Statistical radiometry area of research includes the informationally slight (incidental) nuclear, x-ray, and light signals and impulsive acoustic radiation transmitting measuring information during experimental determination of properties of surroundings, objects and new materials. Methods and means of changing incidental signals in statistical radiometry are examined with the goal of adjusting measuring information and bringing it to a point for further utilization (interpretation, automatic control, etc.).

[The book] is intended for scientific and engineering technical workers dealing with the automation of scientific research and production measurements, and also students in advanced physics department courses.

[It contains] 91 illustrations, 4 tables, bibliography pp 256-262 (150 names).

Table of Contents

[186-9443]

9443
CSO: 1860

UDC 621.39:338

RADIOELECTRONICS AND COMMUNICATIONS IN THE NATIONAL ECONOMY

Moscow RADIOELEKTRONIKA I SVYAZ' V NARODNOM KHOZYAYSTVE in Russian 1980 (signed to press 28 Aug 80) pp 2-6, 121

[Annotation, foreword by G. M. Krylov, candidate of technical sciences, and table of contents from book "Radioelectronics and Communications in the National Economy", collected articles edited by G. M. Krylov, Izdatel'stvo "Svyaz'", 5700 copies, 120 pages]

[Text] The articles in this collection give a brief description of the achievements of modern radioelectronics and communications. The authors show the possibilities and prospects of using radio equipment in various spheres of the national economy: ASU [automatic control systems] of the city of the future, the use of effective and stable space communication system, communication systems of a large metallurgical plant, the use of radioelectronics in construction, etc.

The book is intended for a broad sector of engineers and technicians and will be useful for students of technical schools and higher educational institutions.

Foreword

Acceleration of the scientific and technical progress in all sectors of the national economy is an important problem for the construction of the material and technical base of communism. The solution of this problem increasingly depends on a wide and intensive utilization of the achievements of radio engineering, electronics, communications, and computing technology. It is these sectors that are developing most dynamically at the present time and in many respects determine the achievements of our science and technology in increasing the effectiveness of production and in the improvement of the quality of products. At the present time, it is practically impossible to name any sphere of human activities where radio engineering methods and devices are not used. It can be stated without exaggeration that radioelectronics and branches of science and technology developing on its basis have become one of the decisive factors of the scientific and technological progress.

In recent years, large industrial complexes embodying the latest achievement of the scientific and technological revolution have been created or are under construction in various regions of the country. They are: oil fields of Tyumenskaya Oblast, which are expected to play the main role in solving the fuel and energy problem of the country in the next few years; the giant of the domestic automobile-building industry KAMAZ [Kama Automobile Plant]; the largest railroad Baykal-Amur Trunk Line

(BAM), and many other construction projects which will radically change the structure of the national economy and will open up possibilities for wide development of the productive forces of various regions of the country and, of course, Moscow -- the prototype of the city of the communistic future of our country.

It is natural that science in general and radioelectronics and communications in particular are involved in solving both the main problems of scientific and technological progress and concrete problems posed by industry and the needs in scientific and technical services of the largest national economic complexes.

The tour of the regions of Siberia and the Far East by the Secretary-General of the CPSU Central Committee, Chairman of the Presidium of the USSR Supreme Soviet Comrade L. I. Brezhnev, his meetings and talks with scientists, engineers, and workers gave a new impetus to scientific investigations and contributed to accelerated introduction of their results into practice. This trip showed again the close attention given by our party to the complex development of the eastern regions of our country, which is the most important condition for successful solution of the far-reaching national economic problems of communist construction.

The wide utilization of radioelectronic and communication equipment as one of the means which contribute to achieving a high effectiveness of various branches of modern production makes it necessary to inform specialists regularly and effectively on the potentialities of modern radio engineering devices and on the special characteristics of their use in solving various technical problems. It is also necessary to keep in mind that such information must be sufficiently popular and intended for specialists of a very wide range of specialization: scientists, engineers, technicians, workers, students, and quite often for those who specialize in areas which are very far from radioelectronics and communications. Evidently, this will give a broader idea to a large sector of readers about the potentialities of modern radioelectronic and communication equipment, prospects of its further development, and methods of using it in solving concrete problems both of a narrow applied nature, and fundamental, which in many respects determine the scientific and technological progress. Also it should not be forgotten that timely information about achievements in any branch of the soviet science and technology, particularly radio engineering, electronics, and communications, is of great propagandistic significance. It contributes to educating young people on concrete examples of outstanding workers and innovators in industry and makes it possible for young specialists to understand more fully and clearly the state and tendencies for development in the field selected by them.

The above confirms the necessity and expediency of regularly publishing scientific and technical collections presenting effectively and in a popular form the latest achievements of radio engineering, electronics, and communications, advanced engineering experience, and experience of innovators accumulated in these fields, and the use of radioelectronics and communication devices in related fields.

This principle was taken as a basis in compiling this collection. Its articles describe various problems encountered by specialists working in practically all sectors of the national economy which have to be solved with the use of radioelectronic and communication equipment. In accordance with this, the materials published in this collection are practical in nature and most of them describe concrete experience of specialists directly participating in the production process. Also treated are the problems of political and educational nature which elucidate the content of the CPSU resolutions on further acceleration of the scientific and technological progress.

The articles in this collection present some results of the fruitful and multiform activities conducted by scientists and engineers specializing in the area of radioelectronics and communications in the national economy of the country at the great construction sites of communism. The efforts of specialists are directed toward solving such urgent problems as the automation of technological processes and control processes, the development of mechanization and reduction of manual labor, creation of effective and reliable communication systems, etc. Successes achieved in solving these problems are the result of persistent work of teams of scientists and engineers capable of developing science and technology at the highest level.

This collection presents sufficiently diversified materials treating very different national economic problems whose solution requires the use of radioelectronic and communication equipment. In accordance with this, the articles of this collection present a professional, but at the same time sufficiently popular, survey of the state of some areas of radioelectronics and communication which in many respects determine the pace of the scientific and technological progress. Moreover, this collection has materials reflecting various uses of radioelectronic and communication equipment in constructing large-scale industrial complexes of the country in the current five-year-plan and in solving scientific and technical problems of different scales: from global problems to those of a very concrete and limited nature determined by specific type of production.

In fact, such problems as effective and stable space communications, the possibility of practical use of radio astronomy, and the creation of a complex automated control system for a very large city or region of the country deserve not only the most profound research, but also popularization.

Such problems as the development of a communication system at a large plant, the use of radioelectronics in construction, the provision of a high technical and economic effectiveness, and other problems are of a more specific nature and make it possible to illustrate the broad potentialities of modern radioelectronics and communications in various production complexes. Moreover, it will be of interest for the general reader to learn about various engineering solutions determined, for example, by severe natural conditions in the northern and eastern regions of the country which contribute to effective functioning of the devices themselves and the engineering system as a whole.

These materials seem to be heterogeneous at first glance, but they have one main common characteristic: great attention of our party to radioelectronics and communications, the most dynamically developing fields of our time. Their use in various areas of science and technology is among those factors which ensure the necessary and ever increasing pace of the acceleration of the scientific and technological progress and contribute to the solution of such important technical and economic problems as the raising of the effectiveness of modern production and improvement of the quality of products.

The above convincingly confirms the fundamental idea expressed at the 25th CPSU Congress by Secretary General of the CPSU Central Committee Comrade L. I. Brezhnev that "...only on the basis of accelerated development of science and technology it is possible to achieve the final goals of the social revolution -- to build a communist society". Scientists, engineers, and workers specializing in the fields of radio engineering, electronics, and communications are making their valuable contritution to the solution of this problem.

Contents

[199-10,233]

10,233
CSO: 1860

UDC 621.383.8:621.396.96:621.396.6

SYSTEMS OF SPACE AND TIME CONVERSION OF INFORMATION

Kiev SISTEMY PROSTRANSTVENNO-VREMENNOGO PREOBRAZOVANIYA INFORMATSII in Russian 1979 (signed to press 18 Jun 79) pp 2, 250-251

[Annotation and table of contents from book "Systems of Space and Time Conversion of Information", by Yan Yefimovich Belen'kiy and Vladimir Viktorovich Koshevoy, Physicomechanical Institute, Ukrainian SSR Academy of Sciences, Izdatel'stvo "Naukova dumka", 1000 copies, 252 pages]

[Text] This monograph presents the results of studies by the authors on the analysis of systems of space and time conversion of information. They studied symmetry properties of the processes and systems of space and time conversion of information in relation to the coordinate axes. It is shown that none of the coordinate axes, space or time, is exclusive. They determined the relations for the carrying capacity and specific carrying capacity of the system and studied the vector properties of the carrying capacity. Much attention is given to the maximum carrying capacities of systems of space and time conversion of information. It is shown that these systems perform two types of information conversion: generalized diffraction and generalized attenuation.

Theoretical propositions are illustrated by examples of multiunit acoustic antennas, multichannel electronic switches, a free medium, and systems which include all of the above-mentioned elements.

This book is intended for specialists working in the area of information measuring techniques, electronics and pulse engineering, acoustics, and antenna engineering, as well as for those engaged in the problem of selection and conversion of information about two-dimensional fields of various physical nature varying with time.

Contents

[200-10,233]

10,233
CSO: 1860

UDC 001.89.004.15:621.396.13

TECHNICAL AND ECONOMIC EFFECTIVENESS OF COMPLEX RADIOELECTRONIC SYSTEMS

Moscow TEKHNIKOEKONOMICHESKAYA EFFEKTIVNOST' SLOZHNYKH RADIOELEKTRONNYKH SISTEM in Russian 1980 (signed to press 17 Oct 80) pp 2, 275-258

[Annotation and table of contents from book "Technical and Economic Effectiveness of Complex Radioelectronic Systems", by Feliks Fedorovich Yurlov, Izdatel'stvo "Sovetskoye radio", 7000 copies, 280 pages]

[Text] The author analyzes the technical and economic effectiveness of complex radioelectronic systems on the basis of the principle of the minimum expenditures or the maximum effect. He proposes new methods of reducing technical solutions to a comparable form. Problems of selecting the effectiveness criteria of radio electronic systems, vectorial optimization, and solutions under the conditions of indeterminacy are examined on the basis of the economic theory and the theory of complex systems. The material presented in this book is chiefly the results of theoretical and experimental studies conducted by the author and can be used in selecting the most effective variants of radioelectronic systems for various purposes.

This book is intended for broad sections of specialists in radioelectronics and related fields of science and technology. It can be used by instructors and undergraduate and graduate students of upper division courses in higher educational institutions.

Figures -- 18, tables -- 26, bibliography -- 75 items.

Contents

[190-10,233]

10,233
CSO: 1860

UDC 621.314.572:621.382.2.072

THEORY AND CIRCUITS OF INCREASED FREQUENCY THYRISTOR INVERTERS WITH WIDTH REGULATION OF VOLTAGE

Leningrad TEORIYA I SKHEMY TIRISTORNYKH INVERTEROV POVYSHENNOY CHASTOTY S SHIROTNYM REGULIROVANIYEM NAPRYAZHENIYA in Russian 1980 (signed to press 29 Jul 80) pp 157-159

[Annotation and table of contents from book "Theory and Circuits of Increased Frequency Thyristor Inverters With Width Regulation of Voltage", by Aleksandr Vasil'yevich Donskoy and Valentin Danilovich Kulik, Izdatel'stvo "Engergiya", 9000 copies, 160 pages]

[Text] Table of Contents

Annotation

The book examines new methods and devices for width regulation of voltage of resonance-type high-frequency thyristor inverters without forced thyristor switching. A great deal of attention is given the practical utilization of developed circuits in industrial units and to the engineering methodology of their design.

The book is intended for engineering-technical and scientific workers specializing in the area of converter technology, and may be useful for students of institutes of higher learning.

[183-6900]

6900
CSO: 1860

UDC 621.314.5

TRANSIENT ELECTROMAGNETIC PROCESSES IN SYSTEMS WITH RECTIFIERS

Kishinev NESTATSIONARNYYE ELEKTROMAGNITNYYE PROTSESSY V SISTEMAKH S VENTILYAMI in Russian 1980 (signed to press 20 Nov 80) pp 2, 207-208

[Annotation and table of contents from book "Transient Electromagnetic Processes in Systems with Rectifiers", by Petr Fomich Merabishvili and Yevgeniy Mikhaylovich Yaroshenko, Izdatel'stvo "Shtiintsa", 1390 copies, 208 pages]

[Text] This monograph examines the theory and analysis of the dynamics of electromagnetic processes in rectifier converters and surveys the basic methods of computing rectifier circuits. The authors present the fundamentals of the theory of the spectral-operator method based on the use of commutation functions and the Laplace transformation. The authors developed mathematical models for various power circuits of converters: single-phase and multiphase autonomous inverters and rectifiers. They give results of their studies both on the instantaneous and average values of the variables.

This book is intended for scientists, engineers, and technicians specializing in the area of power conversion engineering, industrial electronics, and the thoery of electrical circuits and the electric drive. It will be useful also to graduate students and students of upper levels in these fields.

Content

[202-10,233]

10,233
CSO: 1860

SEMICONDUCTORS AND DIELECTRICS,
CRYSTALS IN GENERAL

UDC 537.311.33

EFFECT OF AN ELECTRIC FIELD ON RECOMBINATION PROCESSES IN CdS:Cu SINGLE CRYSTALS

Kiev UKRAINSKIY FIZICHESKIY ZHURNAL in Russian Vol 25, No 7, 1980 pp 1078-1081

SHMILEVICH, A. M., SERDYUK, V. V. and CHEMERESYUK, G. G.

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1G80]

[Text] The photosensitivity of CdS:Cu single crystals excited by light within the range of intrinsic or extrinsic absorption drops irreversibly, beginning at some threshold intensity of an applied electric field. This results in a discrepancy between the current-voltage characteristics obtained by first increasing and then decreasing the voltage. An expression is derived here for the photocurrent-voltage characteristic. The data shown here indicate that an electric field can strongly influence the filling of recombination centers with holes, while the nature of processes stimulated by an electric field at low temperatures is the same as thenature of processes which occur at high temperatures and do not depend on the magnitude of the applied voltage. Figures 3; references 9.

[177-2415]

UDC 539.128.412(088.8)

A METHOD OF MEASURING THE EFFECTIVE MASS OF CURRENT CARRIERS IN SEMICONDUCTORS AT MICROWAVE FREQUENCIES

USSR Patent Class G 01 N 27/78, No 2,591,567 25 Jun 80 (disclosure No 742,788 16 Mar 78)

DAVYDOV, A. B., ZAKHAROV, V. A. and SHTRAPENIN, G. L., Institute of Metal Physics, Ural Science Center, USSR Academy of Sciences

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1B407P]

[Text] The purpose of this invention is to simplify and refine the determination of the effective mass of current carriers in semiconductors with a high carrier concentration. The purpose is achieved by placing the specimen inside a waveguide so that it makes an electric contact with the waveguide walls around the perimeter of a waveguide cross section. The existence of an electric contact between semiconductor specimen and waveguide walls provides a short-circuit path for depolarizing currents into the waveguide walls and suppresses depolarizing fields which would otherwise prevent detection of a cyclotron resonance. Figures 2.

[177-2415]

UDC 621.382.23.029.64

UNBALANCED LUMINOUS RECTIFICATION OF BANDS IN SCHOTTKY BARRIERS BASED ON WIDE-BAND SEMICONDUCTORS

Leningrad PIS'MA V ZHURNAL TEKHNICHESKOY FIZIKI in Russian Vol 6, No 17, 1980 pp 1040-1044

[From REFERATIVNYY ZHURNAL: ELEKTRONIKA in Russian No 1, Jan 81 Abstract No 1B98 by V. F. Korzo]

[Text] The object of this study is the nature of unbalanced luminous rectification of bands in a metal-semiconductor contact at 300 K, a contact made on p-GaSe crystals with wide bands (E_0 = 2 eV) and a relatively high resistivity. The effect of barriers at grain and inhomogeneity boundaries on the distribution of the space charge and on the drift of minority carriers is also analyzed. Measurements were made on Al-GaSe diodes produced by thermal deposition of aluminum on a cold freshly beaten surface of p-GaSe with $p = 10^{13}$ cm^{-3}. The relaxation has been found to depend exponentially on the barrier height in a contact.

[177-2415]

CSO: 1860 - END -