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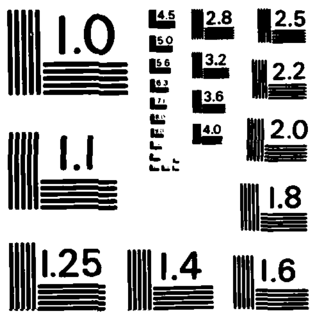

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DISCHARGING A SUPERCONDUCTING STORE INTO AN INVERTING CONVERTER

by

V.V. Andrianov, V.B. Zenkevich, et al

FOREIGN TECHNOLOGY DIVISION

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FTD-ID(RS)T-1186-83

EDITED TRANSLATION

FTD-ID(RS)T-1186-83 8 November 1983

MICROFICHE NR FTD-83-C-001352

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English pages: 7

Source: Doklady Akademii Nauk SSSR, Vol. 196, Nr. 2, 1971, pp. 320-323

Country of origin: USSR
Translated by: Carol S. Nack
Requester: FTD/TQTD
Approved for public release; distribution unlimited.

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О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ë in Russian, transliterate as yë or ë.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

GRAPHICS DISCLAIMER

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DISCHARGING A SUPERCONDUCTING STORE INTO AN INVERTING CONVERTER

V. V. Andrianov, V. B. Zenkevich, O. V. Popkov, B. N. Sergeyenkov, A. G. Sukhorukov, V. V. Sychev, V. A. Tovma, V. S. Sheynkman

(Presented by Acad. V. A. Kirillin on 16 May 1970)

Superconducting inductive power stores are promising for use in a number of areas of science and technology as backup power sources, power sources for covering peak loads in power systems, and sources of powerful electrical pulses.

A rather large amount of energy can be stored in this type of device. In particular, a plan for a store to cover peak loads with energy of 10^{13} J is being discussed [1]. Superconducting stores have a number of technicoeconomic advantages over other possible methods of storing energy, having relatively large values of stored energy. The use of an inverting converter for transmitting the energy stored in the magnetic field into the alternating-current network is often a necessary condition for the effective use of the store. At present, there is no information on any attempts to realize the process of the transfer of the energy of a superconducting store into an electrical system in practice.

It is possible to invert the energy stored in a superconducting solenoid with both a constant mean value of the inverted power, and a constant mean value of the voltage on the leads of the solenoid, which is equal to the mean value of the opposing voltage (counter-emf) of the inverter.

In the latter case, the rate of energy liberation is the maximum at a given limiting voltage value. In connection with this, we should point out the possibility of using an inverting converter as an external load when extracting energy from large superconducting magnetic systems for different purposes (powerful MHD generators, electric motors, bubble chambers, etc.) in an emergency situation (e.g., when the normal phase appears in the winding). Compared to the load resistors which are ordinarily used in these situations, semiconducting inverters are incomparably more compact, they do not require a heavy-duty cooling system, etc.

These advantages are related to the fact that only an insignificant fraction of the energy derived from the magnetic system is dispersed in inverters. Up to 99% of the energy is transmitted to the electrical network. This is very important, for in modern magnetic systems, the stored energy reaches values on the order of 10^8 J, and magnets with energy on the order of 10^9 J are in the manufacturing stage.

The urgency of studying the operation of a superconducting inductive store together with a high-speed semiconductor switch and a three-phase inverter is obvious from the above information.

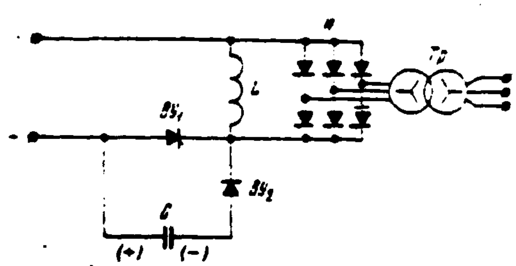

Fig. 1. Schematic diagram of experimental device. Explanation in text.

Figure 1 shows a schematic diagram of the experimental device. Superconducting solenoid L is connected to the low-voltage, high-current direct-current source through controlled rectifier VU_1. When the assigned value of current i_1 in the solenoid is reached, rectifier VU_1 is closed by the discharge of commutating capacitor C, which is connected through controlled rectifier VU_2. The energy stored in the solenoid is transmitted to the electrical system through inverter I, which is connected through transformer Tr to the three-phase alternating-current network.

The superconducting solenoid was made from a cable consisting of 21 copper-plated superconducting wires (alloy 65BT) with a diameter of the copper part of 0.3 mm, and 28 copper wires of the same diameter. Three superconducting and four copper wires were twisted together with spacing of 10 mm and made into a single strand by coating with indium. The seven strings thus made were twisted with spacing of 30 mm, again coated with indium, and insulated with lavsan. The total diameter of the cable was 3.5 mm.

In order to avoid eddy current losses, the frame of the solenoid was made from a fabric-based laminate. Channels were cut in the frame for the purpose of cooling the winding. The solenoid consisted of 12 layers (78 turns in each layer), between which channels for liquid helium were made using paper-based laminate inserts 0.5 mm thick in order to cool the winding. The width of the windings varied from the inner layers to the outer layers from 6 to 10 mm.

The solenoid had the following dimensions: inner diameter - 60 mm, outer diameter - 144 mm, length - 250 mm. The total weight of the solenoid, together with the contact system, was 15 kg.

The leads of the winding were soldered to the contact plates and cooled conductors over a length of 500 mm. The contact plates, conductors and outer layer of the solenoid were carefully electrically insulated.

The solenoid was placed in a cryostat made of stainless steel with an inner diameter of 180 mm and a height of 1400 mm.

The preliminary tests on the solenoid showed that its critical current does not depend on the current build-up rate up to values of 130 A/s (6 kOe/s) and is equal to 947 A, which is equal to the critical current of a short specimen in the corresponding field. At the critical current value, the magnetic field strength was 42 kOe, the total stored energy was $1.01 \cdot 10^4$ J, and the mean current density on the winding was $8.4 \cdot 10^3$ A/cm^2. The inductance of the solenoid was 0.022 H.

Figure 2 shows the curves of the currents and voltages which qualitatively illustrate the system's operation.

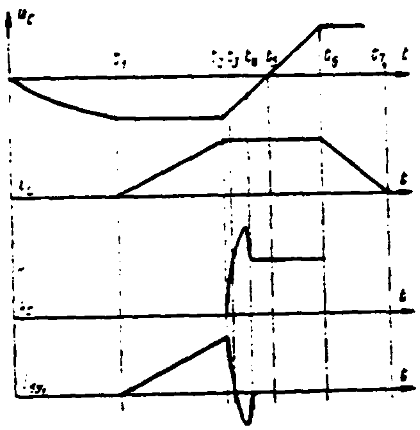

Fig. 2. Changes in currents and voltages which qualitatively illustrate the operation of the system (the scales are not observed on both axes). U_c - voltage on capacitor C; i_L - current flowing through superconducting solenoid L; i_C - current flowing through capacitor C; i_{BY_1} - current flowing through controlled rectifier VU_I.

The working cycle begins with charging of capacitor C by negative (relative to that shown on the diagram) polarity.

After the capacitor is completely charged, at time t_1, the opening signal is sent to rectifier VU_1, and and the current in the solenoid begins to build up at a rate which corresponds to the value of the voltage of the low-voltage source.

At time t_2, when the current in the solenoid reaches the assigned value, which is determined by a special discriminator, the opening signal is sent to rectifier VU_2. The discharge current of capacitor C flows through rectifier VU_1 in the opposite direction, thereby reducing the pumping current in rectifier VU_1 to zero. During period of time t_2 - t_3 (around 10 μs), which is determined by the build-up time of the current in rectifier VU_2, the current passing through the capacitor reaches the value of current I_1. During time t_3 - t_4 (30-40 μs), the blocking properties of rectifier VU_1 are restored when the reverse current flows through it.

During period t_4 - t_6, the voltage on the solenoid terminals reaches the value of the counter-emf of the inverter. The period of time t_4 - t_6 is 400-500 μs. A positive voltage appears on capacitor C from point in time t_5 as a result of recharging under the effect of the emf of self-inductance of the solenoid.

From point in time t_6, the energy stored in the solenoid begins to be transmitted through the inverter to the three-phase alternating-current network.

The semiconductor inverting converter is made in the three-phase bridge layout [2] using silicon controlled rectifiers.

The counter-emf of the inverter is assigned by the angle of advance of opening of the thyristors β.

During the process of discharging the superconducting solenoid at a constant angle β, the mean value of the voltage on the solenoid remains virtually invariable, while in this case, the invertible power decreases with the decrease in the current in the solenoid.

The duration of discharge of the solenoid at the same value of stored energy is determined by the given counter-emf of the inverter - as the counter-emf increases, the discharge time decreases.

A special circuit for automatic control of the angle of advance of opening of the rectifier β is necessary for working in the mode of a constant invertible power; this circuit increases the voltage on the leads of the solenoid as the current decreases.

The problem of the behavior of the superconducting winding during rapid changes in current and field is significant when a superconducting solenoid is working with an inverter. As was indicated, when the solenoid is excited at a rate of up to 130 A/s, the normal phase did not occur in the winding, and the critical current had the same value as during a slow build-up.

It is characteristic of the operation of the inverter that although, as was already indicated, the mean value of its counter-emf is constant, the instantaneous voltage values vary for this type of inverter with a frequency of 300 Hz (at a network frequency of 50 Hz) and an amplitude with a value comparable to the mean value of the counter-emf.

Figure 3 shows an oscillogram of the current flowing through the solenoid and the voltage on its leads during discharge to an inverter. The initial current on the oscillogram corresponds to point in time t_6 of Fig. 2. The initial value of the current in the store is 822 A, and the stored energy is 7.5 kJ. The mean assigned value of the counter-emf of the inverter is 280 V (up to 380 V in other tests).

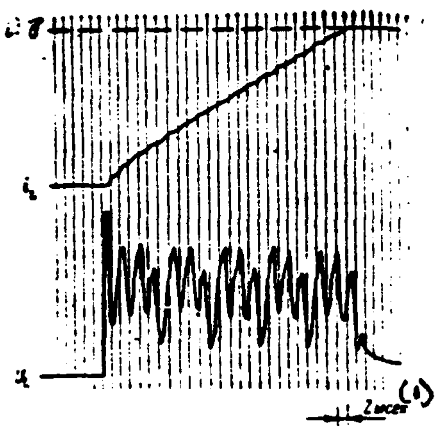

Fig. 3. Oscillogram of voltage (U_L) on leads of superconducting solenoid and current (i_L) through solenoid. KEY: (1) ms.

One can see that although the mean value of the voltage on the solenoid leads remained constant during the discharge process, the instantaneous values of the voltage varied with an amplitude of 130 V and frequency of 300 Hz. The maximum rate of change of the current during the test was $2 \cdot 10^4$ A/s, the mean value was $1.6 \cdot 10^4$ A/s, and the total discharge time was 50 ms. The maximum mean current drop rate in the tests reached $3 \cdot 10^4$ A/s. No manifestation of a normal zone in the winding was recorded, even at such high values of the current reduction rate.

With the three-phase bridge inversion system used, the brief control pulses (t[illegible] = 50 μs) fed to the inverting thyristors follow each other at a frequency of 300 Hz. If the emf of self-induction of the solenoid reaches the value of the counter-emf of the inverter for the assigned angle of advance β within the period of time between contiguous control pulses of the inverting thyristors, the discharge of the solenoid through the inverter is delayed until the next control pulse of the inverting thyristors is sent. This leads to a further build-up of voltage with positive polarity on the commutated capacitor C under the action of the emf of self-induction of the solenoid. This explains the initial voltage jump on the solenoid leads (the oscillogram in Fig. 3). This phenomenon is eliminated by introducing synchronization of the moment of breaking the solenoid pumping circuit by the inverter control circuit or by the preliminary connection of the inverter through a separate, low-power direct-current source.

The inconstancy of the amplitude of the saw-tooth voltage which appears to a certain extent on the solenoid leads is caused by the corresponding asymmetry of the three-phase alternating-current network, and it can be eliminated by changing the adjustment of the control circuit.

It should be noted that because of the high rate of change of the magnetic field strength which occurs when the solenoid is discharged, the energy losses connected with the currents induced in the metal parts of the cryostat can become significant. In the tests which were conducted, the losses reached 20%. The practical use of superconducting energy stores with short discharge times makes it necessary to use specially-designed cryostats. A cryostat made from a dielectric material is the optimum in this regard.

In conclusion, we will point out that the initial tests of the use of a superconducting inductive store together with a semiconductor inverter which were conducted revealed the theoretical possibility of creating highly effective devices of this type.

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Received
9 June 1970

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