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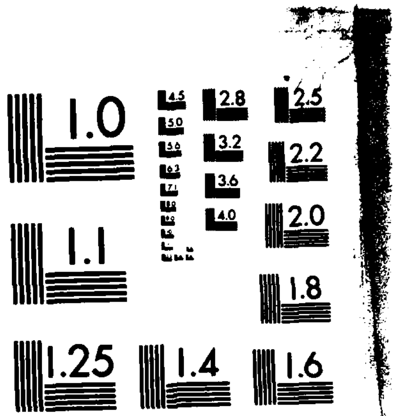
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AIR FORCE SYSTEMS COMMAND

UTILIZATION OF LOW TEMPERATURES IN ELECTRICAL MACHINES

by

L. Kwasniewska-Jankowicz, Z. Mirski

FOREIGN TECHNOLOGY DIVISION

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UTILIZATION OF LOW TEMPERATURES IN ELECTRICAL MACHINES

Lucyna Kwasniewska-Jankowicz, Zbigniew Mirski

The phenomenon of superconductivity was discovered by H. Kamerling-Onnes in 1911. It is characterized by a sudden disappearance of resistance in certain metals and alloys at very low temperatures, in the vicinity of absolute zero. This fact enables currents to flow through superconductors with high potentials practically without losses. Kamerling-Onnes found that the effect was without practical importance. For nearly half the century, the phenomenon was, indeed, without practical applications.

The first superconducting magnets appeared at the beginning of the sixties. Use of superconductivity in the design of magnets enables us to produce stong magnetic fields at a low winding volume without the necessity of using magnetic circuits. The next step is the application of superconductivity to electrical machines. In rotating electrical machines, a superconductor is used in induction circuits which do not contain active iron. The induction obtained in this way reaches the value of several T.

Recently, there has been considerable interest in superconducting machines and fast progress of investigations in many countries. The firms General Electric and Westinghouse (USA) are working competitively on a project for a 300 MW generator which is to be installed in an electric power station in 1981, and also on the design of a 1200 MW generator [1]. It is estimated that superconducting machines for propulsion will be in use in Poland in the second half of the nineties, and generators around 2000 [2].

M. Eng. Lucyna Kwasniewska-Jankowicz and Dr. Eng. Zbingniew Mirski work in the Research and Development Center for Large Electrical Machinery at DOLMEL in Wroclaw.

This interest in the new generation of electrical machines arises from the distinct superiority of superconducting machines over conventional ones.

Advantage of superconducting machines

Utilization of superconductivity in electrical machines provides advantages which are impossible to obtain in machines in any other way. Figures 1 and 2 compare overall dimensions of superconducting and conventional machines for alternating and direct current, respectively.

In general, superconducting electrical machines have the following advantages:

- considerably smaller dimensions and smaller weight,
- higher efficiency,
- reduced costs of production and use,
- possibility of further cost reduction as designs keep improving,
- larger power,
- reduced cost of transport.

Moreover, in the case of DC superconducting generators, one obtains better control properties and a reduced noise level.

A synchronous superconducting generator, as an output facility of an electrical power station, must fulfill the requirements of an energetic system. According to actual analysis, a synchronous superconducting generator has better characteristics than a conventional generator, both for steady operation and unsteady operation because of reduced reactance. It is required from a superconducting generator that its reliability and availability be at least equivalent to those of conventional generators. These properties are not yet completely investigated; the superconducting generator is not yet in use. Higher effectiveness of superconducting machines means a higher effectiveness of the whole power station and, by the same token, reduced fuel consumption.

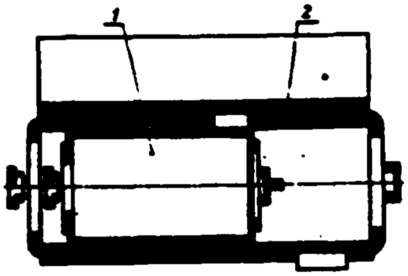

Figure 1. Comparison of overall dimensions of conventional and superconducting alternating current machines
1--superconducting generator
2--conventional generator

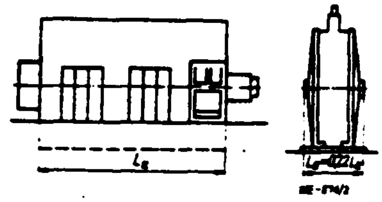

Figure 2. Comparison of overall dimensions of direct current conventional and superconducting machines

Application of superconducting induction windings in direct current machines resulting in strong magnetic fields enables us to eliminate active iron from the induction winding and the armature winding. Superconducting machines are considerably lighter than conventional machines and the rotors have a small moment of inertia.

Hence, superconducting machines have advantages over conventional machines, both with regard to their characteristics and to the cost of installation and use.

Problems found in studies

The superconductor is characterized by three parameters: critical temperature, critical current and critical intensity of magnetic field. These parameters are mutually interdependent--exceeding any of them causes the loss of superconductivity. A superconductor used in an induction winding is required to have the proper values of the above parameters and suitable mechanical properties, enabling one to bend connections at small radii.

Of the presently known superconductors, four materials have found application in electrical machines: Nb_3Sn, Nb_3Ge, NbTi and V_3Ga [3].

Because of metallurgical problems, only NbTi is produced on an industrial scale in the form of multifilament wire in a copper matrix (the matrix takes over the induction current when the winding comes out of the superconductivity state).

The parameters of a superconductor may undergo changes under the effect of mechanical stresses. A winding operating at low temperatures is acted upon by forces of magnetic origin (of the order of tens of tons) and of thermal origin, arising from stresses due to differences in values of the thermal expansion coefficients of insulating materials and superconductors. It is essential that materials are chosen properly with regard to both their mechanical strength and their coefficients of linear expansion.

The state of superconductivity may be disturbed by shifting of connections; hence they should be firmly secured. The superconductivity may be destroyed by a variable magnetic stream entering the winding. In synchronous superconducting machines, this stream is reduced by using suitable electromagnetic shielding. This variable magnetic shielding causes some losses in the winding. In order to maintain the winding in the state of superconductivity, a coolant flowing through the channels in the winding must be used.

A superconducting winding supplied with current stores the energy proportional to one-half the induction winding and to the square of the current (of the order of MJ). Discharge of this energy is accompanied by heat in the winding. At the same time, for a sudden change of the magnetic stream in time, a high potential may appear at the terminals of the winding (which does not appear in the state of superconductivity). The winding must be constructed in such a way that there is no sudden (violent) discharge of energy and that leaving the state of superconductivity is a reversible process.

Cooling of the winding with liquid helium is of enormous importance. The low efficiency of the Carnot cycle means that in order to lead away losses equal to 1 W at a temperature of 4.2 K, it is necessary to supply power of about 1000 W to the cooler (low heat of vaporization of helium). Hence efforts are made to limit the rate of flow of liquid helium to optimal values. The cooler in superconducting machines has an enormous influence on the overall efficiency of the machine.

The cooling system in superconducting machines must be designed particularly carefully. The system is composed of channels in the winding, the supply line of liquid helium, the cryostat and the cooler (refrigerator). Calculations of the heat exchange in the winding, in the state of the boiling of helium, are not easy. The coefficients of heat exchange given in the literature necessary for calculations are different from real values. It is necessary to determine them for the conditions of real windings.

In order to maintain the winding at the working temperature, a special cryostat must be built whose design differs from designs used in other branches of technology. The already mentioned low efficiency of the Carnot cycle, and by the same token the necessity of limiting the flow of heat to the winding from the outside [4], causes the design of the cyrostat to be critical. There is a close relation between the dimensions of induction winding, its efficiency and thermal insulation of the cryostat. This thermal insulation takes into account:

- actual insulation, consisting of vacuum space (vacuum of the order of 10^{-2} Pa) and containing thermal shielding [6],
- mechanical supports securing the winding, shielding and outer walls of the cryostat,
- current leads to supply the induction winding.

The designing of both cryostat itself and its elements requires extensive model studies.

The supply line of liquid helium for a stationary system does not present any design or technological problems. But conditions become complicated in the case of rotating cryostats. It is necessary to construct special rotating seals to prevent the loss of helium. The cooling facility operates in a closed system.

In addition to the difficulties described above, there are also problems connected with the construction of conventional parts of superconducting machines. Nevertheless, the low temperature problems should be regarded as the most important, since their successful solution opens the road for further work. For these reasons, the Research and Development Center for Large Electrical Machines at Czwme Dolmel in Wroclaw created two laboratories to conduct experimental work connected with the low temperature parts of superconducting machines. These are: the Cryotechnic Laboratory for Mechanical Studies and the Low Temperature Laboratory.

Laboratory research background

The Cryotechnic Laboratory for Mechanical Studies of Materials was organized and suitably equipped in 1974. Its aim is to study materials and select those which can be used in electrical cryomachines.

The basic equipment of the laboratory consists of the universal testing machine of the Instron Company (model 1126) and a cryostat of the company Oxford Instruments in which the sample is placed. Both these instruments enable us to carry out mechanical tests of materials (static test of extension and tests of compression and bending) down to even the temperature of liquid helium (4.2 K).

At first, tests of materials were performed down to the temperature of liquid nitrogen (77 K). Measurements at lower temperatures posed considerably greater difficulties. For instance, the test of extension in liquid helium is an extremely difficult experiment. This test is characterized by a great effort (preparations for rupture of one sample takes about 12 hours and requires the whole team) and is dangerous. The first such test in Poland was carried out in our laboratory in 1975. The teststand for tenacity experiments is shown in Figure 3. Liquid helium is pumped from dewar 3 by means of syphon 4 to the working chamber of the cryostat in which the sample is located. This pumping is done by squeezing a rubber bulb 7 to create an increase of pressure over the level of liquid helium in the dewar. Evaporating helium, because of its relatively high cost, is transferred from the cryostat to the recovery system. In addition to mechanical tests, measurements of impact strength and tests of hardness were also carried out from room temperature down to the temperature of liquid nitrogen. These investigations required the construction of special teststands. It is necessary to point out that in order to perform tests at temperatures 77K and 4.2 K, it was necessary to introduce our own methods of measurement since there is lack of appropriate standards and recommendations with respect to cryogenic temperature in mechanical tests.

Figure 3. Teststand for studies at cryogenic temperatures.
1--tensile testing machine; 2--cryostat; 3--helium dewar; 4--syphon; 5--vacuum aggregate; 6--temperature gauge; 7--rubber bulb

The Low Temperatures Laboratory performs model studies of cooling systems and studies models of superconducting machines. One basic condition for carrying out experimental work on superconducting machines is to have appropriate instrumentation. The laboratory has special cryostats for low temperature studies and facilities for producing and controlling the vacuum for the thermal insulation of cryostats.

The circulation of coolant[7] is realized in an open system. Liquid helium is transferred from the dewar to cryostat by means of syphons (special pipes with thermal insulation). Helium evaporated from the cryostat passes through the measuring system to the recovery system in which it becomes compressed in a cylinder under the pressure 1.47 MPa. Special digital measuring systems provide the temperature and level of helium. The laboratory is also equipped with facilities to drive models of superconducting machines, in particular systems to supply the induction winding with current free of variable components, and loading systems for models. All these systems are fitted with digital measurement instruments.

At present, the laboratory is conducting work on introducing an automatic system of measurement and on processing data of the type ESDM 31, adapted for the digital computer Odra 1305. The automatic recording system enables us to take measurements at 90 points. The results are obtained in the form of readouts on the screen, printout and perforated tape. The results are fed to the computer.

Laboratory studies

Mechanical testing of materials and model studies of electrical cryomachines are carried out within the project 05.13 as requested by the Polish Academy of Sciences.

In our mechanical investigations, we were concerned primarily with austenitic steels Cr-Ni and their welded junctions and with plastics as construction and insulation materials. At present, austenitic steels form the basic material for welded constructions of the rotors of synchronous cryogenerators. Because of severe conditions of operation, these steels should possess a high margin of elasticity and not be magnetized under operating conditions. These requirements could be satisfied by steels characterized by stability of the crystallographic structure, that is by lack of transition from paramagnetic austenite into ferromagnetic martensite. Stainless steel 1H18N9T, which was subjected to preliminary tests, underwent martensite transition already upon cooling to the temperature of liquid nitrogen. It is unsuitable, therefore, for construction of cryogenic machines, since the martensite increases magnetization of the steel, lowers electrical characteristics, and increases the possibility of brittle fracture in welded constructions of cryomachines.

Welding is the technique without which no complex device can be made. In experimental work at the laboratory, particular attention was directed to the correctness of welding technique and to quality of the obtained junctions. For welding of steels, we used the TIG method which is the most frequently used technique for joining alloy steels. We studied the effects of the chemical composition of the weld, linear energy of welding and of thermal treatment of junctions on thier properties at cryogenic temperatures.

Three austenitic steels with different contents of nickel (OH17N4G8, OOH17N14M2 and OH22N24M4TCu) were subjected to more extensive investigations. The strength (tenacity) of investigated steels increased clearly with a lowering of temperature, while their plastic properties worsened. The higher the nickel and austenite-forming element content in steel, the more stable was the austenite structure and in this connection, the smaller was the drop of plasticity with a drop in temperature.

On the basis of mechanical tests carried out in our laboratory, and studies of physical properties conducted in the Institute of Low Temperatures and Wroclaw Polytechnics, it was shown that the high requirements for cryomachines are relatively best satisfied by the steel OOH17N14M2 and its welded joints [5].

This steel has high mechanical properties at the temperature of liquid helium ($R_{0.2}$ = 740 MPa, R_m = 1412 MPa, A_5 = 48% and Z = 46%). Moreover, this steel is practically nonmagnetic under the action of strong magnetic fields up to 3980 kA/m. For it shows antiferromagnetism below the Neel temperature (23.5 K). The best plastic properties of welded junctions were obtained by using linear energy equal to 970-1470 kJ/m. Such junctions do not require oversaturation since this lowers the mechanical properties at the lowest temperatures in comparison with the raw state of the junction.

In studies on the optimal selection of steel, we also used methods which consider the effect of stress concentrators. Tests were made on the extension of samples with a two-sided notch of radius r = 0.25 mm. Cyclic bending tests were performed on samples with an analogous notch and methods were employed concerning the field of fracture mechanics, through which the coefficient K_{IC} and the critical opening of the crack δ_c in COD sample were determined.

It appears quite probable that in the future, in future generations of cryogenic machines, technology will be based on plastics to a larger degree than at present, and these plastics will be reinforced suitably with fibers. For these reasons, our laboratory is examining a series of plastics available in this country. The investigated material included foils, tapes, epoxy-glass laminates, glass roving saturated with epoxy resin, tarflenobronze and others. Also, tests were made on various adhesives used to join plastics.

The properties of plastics were determined on the basis of classical mechanical tests, such as tests for tenacity, impact strength, compression and bending. Also, the effect of thermal fatigue on the mechanical and electrical properties of plastics was examined. Strength properties of these materials most often increase with lowering of temperature. Moreover, the plastics hardened and sometimes they crack, even if they are not acted upon by any external force. The decisive effect on cracking of composite materials, because of differences between thermal shrinkages of fibers and base, results in stresses arising from thermal fatigue. Laboratory tests of thermal fatigue were carried out up to 80 cycles; one cycle consisted of cooling the sample to the temperature of liquid nitrogen and subsequently warming up to room temperature. This treatment caused significant changes in mechanical and electrical properties of epoxy-glass resins. These properties depend on the direction of reinforcement. For instance, after 80 thermal fatigue cycles, the strength to compression decreases after loading parallel to the layers of glass fibers, and increases when the loading is perpendicular to these layers, as compared with the initial material at the temperature of liquid nitrogen [6].

Testing of joints glued with epidian 5 BHM showed that it is brittle and not resistant to thermal fatigue in the range of temperatures 293-77 K. It should not be used in cryogenic machines. Studies of various plastics have not been completed yet, and they will continue together with studies of other materials within a broader project.

At this time, the Low Temperatures Laboratory is carrying out the following experimental investigations:

- study of cooling system for cryostats of a unipolar superconducting machine,
- model studies of a unipolar superconducting machine.

Theoretical work on a cooling system for a unipolar superconducting machine, carried out in this center [9], has shown that the main thermal stream reaches the cryostat through current leads (terminals) of the induction winding. The literature contains a description of the method of optimalization of these current leads. However, for calculations, we need values of coefficients which can be determined experimentally. Hence, we prepared a special model at a 1:1 scale which contains the current leads and the whole cooling system of the upper part of cryostat in the unipolar superconducting machine. The lower part of the cryostat is modeled by a container with liquid helium, fitted with a heater of regulated power. This model will allow to establish the optimal solution to the current leads and the optimal cooling system for a unipolar machine.

Figure 4. Model of a unipolar superconducting machine

The studies consist of measuring the distribution of temperatures in the model and in measuring the amount of evaporated helium, depending on power (energy) generated in the cryostat at various levels of liquid helium in the area of the current. The current lead (terminal) is an element in a superconducting machine whose overheating may be the cause of serious emergency situations. An interruption in the current passage causes energy production in the cryostat. The arc arising between the cryostat and metallic casing causes overheating and disturbance to the vacuum insulation. A sudden rise of the temperature of helium to 300 K results in a 700-fold increase of pressure in the cryostat. This dangerous situation is the reason why the work was started on this problem.

Studies of the model of the unipolar superconducting machine (Figure 4) are intended to check the validity of accepted design solutions of the low temperature part of machine. Because of considerable differences in values of the coefficients of linear expansion for copper and epoxy resin (materials in the superconducting winding) with a change in temperature, the process of cooling should proceed very slowly so that the stresses do not cause fracture of the spool. For this reason, the rate of cooling was accepted as 5-8 K per hour. During this process of cooling, the temperature is controlled by means of sensors mounted in the cryostat. At the same time, an average temperature of superconducting winding is measured, utilizing the relation between the resistance of copper and the temperature.

As yet, we have not been successful in maintaining the state of superconductivity for a longer period of time because of failures of the vacuum system, manifested by a sudden appearance of the rise of pressure in the vacuum area of cryostat, and by the same token an increase of the flow of thermal stream to the winding area, hence a sudden rise of the temperature of the spool.

Observations carried out during consecutive tests led to the conclusion that the lack of tightness was caused by sleeve gaskets between the vacuum area and the area which contains the superconducting winding. Further work will involve finding a more suitable vacuum seal for this type of cryostat.

Although the final aim of these studies is to check and establish characteristics of the whole machine, it is impossible to achieve this goal without obtaining positive results at this stage of study, specifically on a cryostat of a unipolar superconducting machine.

Safe, danger-free operation of superconducting machines requires the constant control of temperature of both the winding itself and of various points in the cooling system. For this purpose, it is necessary to have suitable measuring systems capable of working in the presence of strong electromagnetic fields in a rotating cryostat [9]. Work has been started also on this problem.

The Research and Development Center is also performing theoretical and experimental investigations on the construction of rotating gaskets (seals) in cryostats of synchronous machines.

In the future, it is intended to start work on thermal insulation and behavior of helium in a rotating cryostat, and also on the dynamics of rotors expected to operate at high speeds of revolution.

Summary

The interest in superconducting machines over the last few years arises from their superiority over conventional machines with respect to both their characteristics and the costs of their construction and use. Superconducting machines, as new generation machines, must pass through all stages of development before they start to be produced serially.

It is necessary, therefore, to conduct studies of theoretical, design-construction and experimental nature on models of sub-systems and whole machines, and in the field of material engineering.

In the area of the above problems, our center is carrying fruitful cooperation with the Institute of Low Temperatures and Structural Studies of the Polish Academy of Sciences, with the Institute of Electro-Machine Systems of the Wroclaw Polytechnics, and with the Institute of Electrical Machines of the Silesian Polytechnics.

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