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Battery Operation of Superconducting Magnet *

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Abstract—Battery energy can be used for superconducting magnet operation if the current of the battery is controllable. Several current-control methods are discussed: variation of electrolyte temperature, variation of exposed electrode area, and the mechanical switching of cells. A circuit for continuously controlling the current using mechanical switches was proposed and a demonstration experiment, in which “D” size Ni-Cd batteries were used for the smooth control of the current up to 45 A, was successfully performed.

I INTRODUCTION

A superconducting magnet is supposed to be a device which does not consume electricity because of its zero resistivity. But in practice, the complete system including the power supply[1] generally dissipates considerable energy. If we use a series regulator, for example, zero resistance in the magnet results in the entire voltage being taken by the regulator. Whether the voltage is taken by the regulator or the magnet itself does not change the total amount of energy wasted in the system. If the power supplies could be operated at very low voltages, the power consumption would be very small even in the case of high-current superconducting magnet. The off-set voltage of semiconductor devices excludes the use of very low voltage power supplies. As a result, semiconductor regulated power supplies are usually designed with voltages of more than several volts. The operating current of the magnets used in high energy accelerators[2] increases as the magnet performance increases. Thick conductor reduces the construction problems and the accompanying lower inductance facilitates the protection against the damage during a quench[3]. The usual high current power supplies are very costly. In addition, such power supplies sometimes even call for the on-site installation of three-phase power substations, other costly items. Use of the persistent-current mode can avoid the continuous operation of the power supply. However, even if the power supply is used for a short period just to charge the magnet, it still has to be there. A battery system for the excitation of superconducting magnets becomes an attractive option, especially if the magnet is operated for short periods of time as in the case of laboratory magnets or magnets needing to be charged for persistent current operation. In these cases, large power facilities are not necessary since the energy required to intermittently charge the magnet can be replenished slowly using a low level power supply.

II BATTERY ENERGY

A battery is a well established and effective energy storage device. For example, a lead-acid car battery of 50 Ah capacity can supply 50 A of current at 13.8 V for an hour. Therefore the stored energy of a car battery is more than 2 MJ which is sufficient to excite fairly large superconducting magnets. The maximum current allowed for a battery is usually rated as “10 C”, i.e. ten times the ampere-hour value. Since a car battery is a series combination of six 2.3 V cells, the parallel connection of such cells would yield six-times the above maximum current, i.e. 3000 A for 6 minutes. A realistic design would require more operation time and current margin. Nevertheless, it is clear that a high current battery power supply should be, at least in terms of energy management, a feasible source of energy for operating superconducting magnets. The stored energy density can be even higher in advanced batteries such as alkaline- and Ni-Cd batteries. The unit-cell voltages of these batteries are lower than conventional lead batteries. This further helps to satisfy the need for low-voltage high-current operation. The problem with the battery power supplies

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is associated with the control of the current. A superconducting magnet system has to be excited with a current that is smoothly controllable from zero to the operating level. As mentioned, if semiconductor devices are used to control the current, a large fraction of the battery energy would be dissipated in the regulator. Thus a method of controlling the battery current with lower dissipation than presently possible is needed to make a battery operation of superconducting magnet a reality.

III  Current Control of the Battery

The most desirable method of controlling the magnet current is to arrange for the current controllability to be built into the battery itself. Since output current into a given load is dependent on the temperature and the surface area of the electrodes, the feasibility of controlling these factors was examined.

A. Electrolyte Temperature Variation

The results of a test of battery current control by temperature variation of the electrolyte is shown in Fig. 1. The e.m.f. of the battery of twelve "D"-size dry cells connected in series and to a superconducting magnet was reduced by cooling with liquid nitrogen vapor.

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**Fig.1.  Chilled Battery System**  
Batteries were chilled to cut the current and warmed up by a heater to gradually increase the current.

In the environment of superconducting magnets, liquid nitrogen is considered to be an easily available material. To prevent damage to the battery, it was necessary to keep the temperature above -90°C. At -90°C, the e.m.f. of the battery is greatly reduced but there is some "dark current" which may be a problem for a high current system. The temperature of the battery was next raised, by means of an attached heater, and the output current increased as shown in the figure. At the maximum current of 8 A, the temperature of the battery was decreased again and with it the current. The current was then further reduced because of the exhaust of the energy. Excitation of the magnet was performed, but the control of the current was very rough and the excitation was not efficient enough.

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**Fig.2.  Surface Area Control**  
The effective electrode area was controlled by the fluid level of the battery. The triangular shape of the electrode was useful to have greater dynamic range of the control.

B. Electrode Area Variation

Battery current (but not voltage) can be also controlled by varying the surface area of the electrodes exposed to the electrolyte in a liquid battery cell. A set of triangular shaped lead electrodes for a lead battery was made and assembled into a cell. The electrolyte level was changed by pumping it in and out of an auxiliary vessel. A test result is shown in Fig 2. Current control in this way was in principle very smooth. However, any vibration in the liquid could easily disturb the current. Another problem with the current control through the fluid level variation was associated with the drying out of the electrode and the corrosion of the material. When the electrode is extracted to reduce the current, the dried out surface tends to fracture. The materials in the system readily corrode in the presence of sulfuric mist. Thus the control of the current was too unreliable. Gradual change in the current at the flat top of the
ramp would be a problem for the use of the magnetic field at a constant current.

IV Mechanical Switch System

A. Description of The System

Since the magnet current has to be controlled, in most cases, smoothly and precisely, some means of electrical control is necessary. Figure 3 is a schematic of the system for the control of the current at a very low voltage level. The main or base level current to the magnet is supplied from a battery. Each cell of the battery has a current limiting resistance and a con-tactor switch to turn it on and off. Thus by means of incremental switching, the current to the magnet can be changed in step-wise manner. The voltage of the battery is low enough to eliminate contact arc as a problem.

![Fig. 3. Mechanical Switch System](image)

Combination of switched batteries and the small power supply can form a continuously controlled current source.

A small auxiliary power supply connected in parallel with the battery system smooths out the steps and enables current to be controlled continuously. The total current is detected by a direct current transformer (DCCT) and compared to the reference setting. The feedback loop adjusts the current of the auxiliary power supply. If the current of the auxiliary power supply, as detected at another DCCT, exceeds the limit of that power supply, during an increasing ramp, the next cell is switched on through the logic circuit. As soon as the switch is turned on, the current of the auxiliary power supply automatically decreases to adjust the total current to the desired level. Conversely for a decreasing current ramp, switches are turned off and the auxiliary power supply is appropriately adjusted. Thus, the circuit automatically follows the current pattern given to the reference voltage. Figure 4 shows the pattern of each part of the current for a linearly increasing magnet current. An important secondary advantage of the arrangement is that the auxiliary power supply works as a battery charger when the load is disconnected. Battery recharging can be made to take place automatically whenever there is no load on the system.

![Fig. 4. Current Pattern](image)

Step wise change of battery current \( \left( I_b \right) \) is automatically smoothed out by the saw-tooth wise current \( \left( I_a \right) \) of the auxiliary power supply.

B. Demonstration Experiment

A demonstration experiment was conducted in which a battery of "D"-size Ni-Cd cells was used to excite a 6 cm bore solenoidal magnet. The test result is shown in Fig. 5. It can be seen that the magnet current was controlled in a very smooth and linear trapezoidal shape. However, the auxiliary current deviated from simple expectation due to the effects of the inductive voltage and the resistance of the current leads. These cause a decrease in the height of the current steps. The current leads are more influential at high current levels. Also there was a large kick-back at the edge of the ramp as a result of a change of current sharing between the cells and the auxiliary power supply. The voltage balance equation of the system when \( n \) cells are switched on in the circuit is:

\[
I_n \frac{dI}{dt} + r_l I_n + \frac{r}{n} (I - I_a) = V,
\]

where \( I \) is the total current and \( I_a \) is the current from the small power supply. \( L \) is the inductance of the
magnet and V is the voltage of the battery. If $dI/dt$ is changed quickly, the large change in $I_x$ that is required to keep the balance sometimes causes a change of $n$. In this case, adjustment of the timing of switch operation becomes important. Otherwise, ON-OFF switching oscillation may take place. Such an oscillation is seen in the down ramp of the data of Fig. 5. An improvement in control logic in which system time constants are taken into account will correct this problem.

Battery operation of superconducting magnets is found to be feasible in terms of energy management. Current control through change of electrolyte temperature and electrode area was shown to be possible. A practical control scheme using a mechanical switch system associated with small auxiliary power supply was proposed and demonstrated in the operation of a superconducting magnet up to 48 A, 2.5 T. The test result was completely satisfactory and indicated that scale-up to high current level is feasible. Controlled battery energy sources would be useful and advantageous for magnets which are intermittently operated, namely magnets for laboratory use or magnets with persistent switches.

C. Practical Applications

Based on the successful result of the demonstration experiment, a variety of practical designs were considered. A 200 A power supply using Ni-Cd batteries would be suitable for the excitation of MRI magnets in hospitals. It could be hand carried and plugged into the ordinary power outlet. Cooling water is not required. Since MRI magnets are operated with persistent switches, the requirement of power supply operation is most likely 1 hour a month. One power supply can be used at many places. A high current power supply of 10 kA capacity for the use of magnet R&D would be built using alkaline batteries. A 1200 Ah battery is commercially available; it has a volume of 32 litter. If we use 30 of them, the total volume of the battery will be less than 1m$^3$ for 3 hour operation at a time. Quench testing of high current magnets[4] may be performed using such a power supply. The battery can be re-charged overnight while the quenched magnet is being re-cooled. High current dc switches are not commercially available but air operated switches with large contact area and small gap can be easily made for this application. The action of the switch does not have to be quick.

V Conclusion

Battery operation of superconducting magnets is found to be feasible in terms of energy management. Current control through change of electrolyte temperature and electrode area was shown to be possible. A practical control scheme using a mechanical switch system associated with small auxiliary power supply was proposed and demonstrated in the operation of a superconducting magnet up to 48 A, 2.5 T. The test result was completely satisfactory and indicated that scale-up to high current level is feasible. Controlled battery energy sources would be useful and advantageous for magnets which are intermittently operated, namely magnets for laboratory use or magnets with persistent switches.

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