Superconducting Magnet System Concept With Mechanical Energy Transfer in the Magnetic Field

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Abstract—There is an interest in designing superconducting magnet systems working in a persistent current mode. These systems continuously generate magnetic fields with disconnected power sources that work like permanent magnet devices. This paper proposes a magnet-system concept based on direct mechanical energy transfer in the magnetic field. Short circuited superconducting coils do not have current leads and power sources. To pump the mechanical energy in the superconducting coil, a magnetizer is used that is magnetically coupled with the coil. The mechanical removing of the magnetizer from the magnet induces a persistent current in the superconducting coil and generates the magnetic field. The iron-dominated magnet system concept was investigated using OPERA3d code, which confirmed the validity of the proposed approach.

Index Terms—Concepts, field simulations, magnetizer, mechanical energy, persistent current, superconducting magnets.

I. INTRODUCTION

Most superconducting magnet systems are energized by an external power source. A known approach is to use superconducting magnets that work in a persistent current mode, such as in MRI solenoids [1]. Several high-temperature superconducting (HTS) magnets were recently investigated at Fermilab [2], [3], [4]. Magnets worked during a short period of time in a current transformer mode using a primary copper coil to pump energy into a secondary, short-circuited HTS coil. It allowed the decoupling of warm primary and superconducting secondary while also eliminating superconducting current leads, quench detection, protection systems, and continuously working power supply. The theory of superconducting current transformers is well-known since 60th [5] and routinely used to test short-circuited superconductor samples. This paper investigates a novel concept to pump mechanical energy in the magnetic field of dipole magnets. Proposed mechanically energized magnets could be used in various applications [6]: beam storage ring magnets, undulators, electron-positron colliders where magnetic fields below 1.5 T. For example, Fermilab Recycler Ring used permanent magnets [7] with the magnetic field in gaps 0.25 T.

II. SHORT-CIRCUITED SUPERCONDUCTING COILS

For the new dipole magnet will be used H-type dipole [4] HTS coils shown in Fig. 1. These coils generated a very stable magnetic field during long period of time without field and current decay.

The CERN future Lepton Collider needs thousands of dipoles with a field only 0.056 T. In this project superconducting magnets instead of room temperature magnets could save 36 MW power. Short-circuited superconducting coils do not need power supplies, cabling, and sophisticated monitoring systems. HTS coils could work at LN₂ temperature. For the proof of principle was used a small model which was built and successfully tested [11].
It should be noted that short-circuited superconducting coils also could be based on LTS NbTi or Nb_3Sn superconductors having superconducting splices.

### III. MAGNETIC AND MECHANICAL ENERGIES IN MAGNETS

In general, accelerator magnets are energized from power sources. But most electrical generators transfer mechanical energy of rotor rotation through the rotational magnetic field to electrical energy that is induced in a stator. Some electrical machines are also used in rotors, superconducting coils, or permanent magnets. The principle of mechanical energy transfer to the magnetic field can also be used in accelerator magnet systems. It is useful to analyze this process and compare it with that of conventional electromagnets. The proposed dipole magnet system concept is shown in Fig. 2.

The C-type dipole magnet is initially combined with another part: the magnetizer. The dipole magnet consists of a C-type ferromagnetic core with a short-circuited superconducting coil mounted on the magnet flux return yoke. The gap side of the magnet has the magnetizer attached, which also has a C-type core and magnetization coil, the latter of which could be non-superconducting. The magnetizer initially generates the common magnetic flux with the dipole coil, as shown in Fig. 2. At that time, the dipole coil is in a non-superconducting state. The dipole coil then cools down to the superconducting state and starts to operate in a “frozen flux” mode. The current in the magnetizer coil is now reduced to zero and the magnetizer can be disconnected from the power source. This is in agreement with Lentz’s law, as it is a continuously circulating current in the dipole superconducting coil providing the magnetic flux constant condition (flux conservation law). In this case, the dipole coil total current equals the magnetizer’s previous total current. At this time, the magnetizer should be mechanically removed from the dipole, as shown in Fig. 3.

Strong magnetic forces are needed to separate both assemblies. But during this process, all the used mechanical energy is transferred through the redirected magnetic flux in the dipole magnet to the dipole magnet-stored energy concentrated in the magnet gap. The substantially increased dipole coil current continues to provide the magnetic flux constant condition. It is supposed that superconducting coil capable to carry the induced current. Most of the mechanical energy is used in the magnetizer removing which transferred and mostly concentrated in the magnet gap.

Initially, the ferromagnetic core forms a closed ferromagnetic loop without gaps. Thus, a very low total current for the iron core magnetization is needed. The proposed energy transfer process strongly depends on the material magnetic permeability which was approximated by an analytic function \( \mu(B) \).

From the simplified formulas, we can understand the magnet parameters’ influence on the currents \( I \) and the superconducting dipole coil total current \( I_{sc} \) (see Fig. 2) can be defined as:

\[
I_{cu} = \frac{B_{fe} \cdot L_{fe}}{\mu_{c} \cdot \mu} \quad (1)
\]

\[
I_{sc} = \frac{B_{fe} \cdot L_{fe}}{2 \mu_{c} \cdot \mu} + \frac{B \cdot \delta \cdot \delta}{\mu_{c}} \quad (2)
\]

It is supposed that the magnetic flux is constant for both circuits, and the \( L_{fe} \) length of the flux path for the closed circuit in the iron yoke is two times shorter than for the open one. The efficiency of stored in the magnetic field energy transfer will be:

\[
K_{ef} = \frac{W_{sc}}{W_{cu}} = \frac{I_{sc} - I_{cu}}{I_{cu}} = 1 + \frac{\mu(B_{fe}) \cdot B \cdot \delta \cdot \delta}{B_{fe} \cdot L_{fe}} \quad (3)
\]

where \( \mu(B_{fe}) \) in (3) is the iron magnetic permeability approximation. At fixed magnet geometry, the efficiency of the superconducting current increase is proportional to the iron magnetic permeability and the magnet gap field (see Fig. 4).

For example, for 0.75 T magnetic field in the 10 mm and 1.0 T in the iron the efficiency will be \( K_{ef} = 58 \) (see Fig. 4).
So, the energy extracted from the magnetizer Cu coil will be 58 times lower than the mechanical energy that is transferred in the magnetic field. If we increase the magnet gap two times, the energy transfer efficiency will also increase two times. Of course, the maximum energy transfer will be if all ferromagnetic material is removed from the superconducting coil (air core magnet).

IV. MAGNETIZER

The magnetizer is a novel element used by accelerator magnets to pump mechanical energy in the magnetic field. There are various types of magnetizers used in the industry, and they are named lifters because they lift and transport ferromagnetic pieces. There are two general classes of lifters: electromagnets [8] and permanent magnets [9]. The permanent magnet lifter has a handle to rotate the permanent magnet block inside the assembly to short-circuit the magnetic flux inside and eliminate the lifting force. Of course, the permanent magnet lifter magnetic circuit should be redesigned to eliminate the magnetic flux through the magnetizer that is provided by the superconducting coil. The most advanced lifters combine both approaches but, for the separation, they use a short capacitor bank discharge in the opposite direction to reduce the force needed for the separation. In the paper investigated C-type core Magnetizer with copper coil as shown in Fig. 2 with parameters in Table I. There are various methods of magnetizer removal, which will be discussed in the next section.

V. MECHANICAL ENERGY TRANSFER

The mechanical energy transfer process was investigated using OPERA3D software [10] and a short-length (60 mm) dipole magnet model with a gap of 10 mm. HTS coil parameters were used from the previous H-type dipole model [4]. It is critical for this application to define the best method of mechanical energy transfer in the magnetic field by energizing the HTS coil. The well-known effect is that sliding magnetized objects is relatively much easier than pulling them out. Fig. 3 shows the magnet model with the horizontal magnetizer moves (dx).

It is supposed that during the magnetizer movement always superconducting coil stays in a superconducting condition which was confirmed in previous experiments [2], [3], [4]. In this case, for the analysis was used the magnetic flux conservation law:

$$\Psi_{sc} = \text{Const.} \quad (4)$$

OPERA3D simulations were used to calculate the magnetic flux connected with superconducting coil for different magnetizer core position relatively the dipole core. The variation of magnetic flux was eliminated by adjusting the superconducting coil current to fulfill the relation (4).

The simulation results are shown in Figs. 5 and 6.

One can see that the gap field follows the induced current in the superconducting loop. But the larger distance, $dx$, experiences the lower effect of separation. The peak force initially needed to separate the magnet and magnetizer is 330 kg (See Fig. 6), which exponentially decays with the separation distance. This value agrees with the magnetic Maxwell pressure (5) estimation for a 1.16 T average field on separated surfaces:

$$F_x = \int_S \frac{B^2}{2\mu_0} \cdot dS \quad (5)$$

The other option for the separation is to move the magnetizer vertically as shown in Fig. 7. Before this moving the magnetizer coil current transferred in the superconducting coil and at this stage the magnetizer coil has a zero current, and this coil is not shown in Fig. 7.
The vertical magnetizer movement has lower current and gap field variation than the horizontal one, as shown in Fig. 8. But the total energy transfer is equal to the energy transferred at the horizontal magnetizer movement.

In this case, the gap field and induced current have lower variation with separation distance. Fig. 9 shows the current and the separation force variation.

The primary advantage of the vertical magnetizer moving is that the required peak separation force is a hundred times lower than for the horizontal movement at the same value of mechanical energy transfer.

VI. COMPARISON WITH CONVENTIONAL ELECTROMAGNET

Relatively low magnetic-field HTS magnets could replace conventional, room-temperature electromagnets or permanent magnets for some applications. But the reduced operational power losses in HTS magnets come from the superconductivity by using cryogenics. It is not obvious which approach is better from a magnet system efficiency perspective. The previously described HTS dipole magnet was estimated as a room-temperature magnet with a water-cooled copper coil. The magnet also has a 10 mm gap, and the peak field in the gap is 0.7 T. A coil with a total current of 5.6 kA is needed for this field. The optimal current density for these types of magnets is 4 A/mm². In this case, the copper cross-section will be 1400 mm². The coil power dissipation will be 0.9 kW for the 1 m magnet length. At the average cost of electricity in the US, 0.12 $/kWh, the operational cost of this magnet will be 0.11 $/h or 964 $/year. The liquid nitrogen production cost is 0.18 $/liter. So, the HTS magnet cryostat evaporation rate should be 0.6 l/h to make even operational costs. The preliminary estimated the LN₂ evaporation rate will be 0.04 l/h which is much less than 0.6 l/h. Of course, it is a very rough estimation that is not included for the room-temperature magnet costs of power supply, cabling, water cooling systems, protection, and monitoring systems. But at least it makes a compelling case for the use of HTS magnets at low magnetic fields for some applications.

V. CONCLUSION

The proposed and investigated HTS magnet concept reveals a way to pump mechanical energy in the magnetic field of the accelerator dipole magnet. A removable magnetizer is used, which could be an electromagnet or a permanent magnet. It is critical that this type of magnet consist of a magnet and magnetizer separation. The magnetic field and force analysis showed that the separation across flux lines needs a separation peak force an order of magnitude lower than that along flux lines on separated surfaces. A brief comparison with a conventional room temperature magnet demonstrates the choice of HTS magnet systems for low-field applications. The proposed mechanical energy transfer concept was successfully verified by building and testing an HTS dipole magnet [11] (See Fig. 10).

For future accelerators could be used this proposed type of magnet where one detachable and movable magnetizer could energize string of magnets one after other.
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