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# Design considerations in MgB2-based superconducting coils for use in saturated-core fault current limiters

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**Disciplines**

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# Design considerations in $MgB_2$-based superconducting coils for use in saturated-core Fault Current Limiters

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***Abstract*— Saturated-core Fault Current Limiters (FCLs) are devices that have many applications and potential for use within power networks. At a commercial scale these devices require high H-field magnets to saturate the steel core, which can typically only be achieved through the use of superconducting coils. Here we present several challenges that arise in the application of superconducting coils in FCLs, and discuss how to address these issues through a case study $MgB_2$-based coil. It is found that significant AC magnetic fields, Lorentz forces and Joule heating in components occur during normal and fault operation; however, these issues can be mitigated when properly addressed.**

***Index Terms*—Computer aided engineering, Superconducting coils, Fault Current Limiter**

## I. INTRODUCTION

SATURATED-CORE Fault Current Limiters (FCLs) have recently been the focus of research and commercial investigation [1-3], primarily due to their relative maturity with respect to other FCL technologies, and their scalability across different voltage and fault current levels. Saturated-core FCLs harness the non-linear magnetic behavior of steel in their operation. Steel cores (with coils carrying the AC line current wrapped around them) are driven into saturation by high ampere-turn DC coils. A schematic of a single-phase saturated-core FCL using a single DC coil to saturate the cores is shown in Fig 1a, while Fig. 1b shows the same FCL using a two DC coil arrangement for core saturation. The permeability of the saturated steel is similar to air, and thus the AC coils appear to the network as if they were air-core inductors. Each AC coil is wound so that the instantaneous MMF is opposite in each coil. When a fault occurs, the high current in the AC coils generate a magnetic field that is large enough to overcome the DC field, thus alternatively driving each core out of saturation for each half AC cycle and giving the respective AC coil the impedance of an iron-core inductor. This desaturation process, and resulting increase in impedance, is the mechanism by which the fault current is limited.

DC coils with high ampere-turns are necessary to adequately saturate the cores in commercial-scale FCLs. In practice, superconductors are the only conductors that allow a high enough current density while maintaining low resistive losses.

There are several issues that must be addressed when using DC coils in FCL applications, in particular: 1. the effects of small-scale fluctuations in the magnetic field on the superconducting wire during normal-state operation (due to coupling with the AC coils); 2. the large-scale changes in the system magnetic field during a fault event; 3. the anisotropic and time-varying force on the DC coils; 4. the significant heating in coil components during a fault event. These issues are intrinsic to the operation of saturated-core FCLs and as such are present in any saturated-core FCL design.

Previous commercial-scale FCLs have used BSCCO tape for the superconducting element in the coil [1]; however, cost considerations have led to the search for an alternate superconducting element. $MgB_2$-based superconducting wire has many positive attributes that make it an attractive solution; particularly the low cost-per-meter, relatively high critical current in magnetic field, and long single-piece lengths. However, relatively poor thermal conductivity, intolerance to strain and low critical temperature result in careful attention being required when designing an $MgB_2$-based coil for FCL applications.

In order to study and address the issues arising from using $MgB_2$-based superconducting wire in an FCL application, a small-scale conduction-cooled demonstrator coil has been designed and simulated as a case study, and has recently been manufactured. This coil has been developed to integrate into an existing FCL that has been characterized and reported on in the literature previously [4], which will allow for comparison and contrast of results. The outcomes and design solutions from this demonstrator coil will be generally applicable to larger coils for commercial-scale saturated-core FCLs.

In this paper, each of the issues listed above are briefly outlined, and a discussion is given on how they have arisen in

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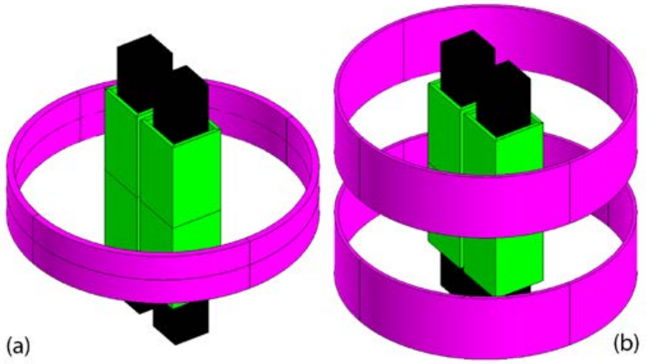

Fig. 1. A single coil open-core saturated-core FCL configuration is shown in (a). A two-coil (or Helmholtz-like) configuration is shown in (b). The DC coils are shown in magenta, the AC coils in green, and the electrical steel cores in black.

the demonstrator FCL and $MgB_2$-based coil, and also how these issues have been addressed.

## II. DEMONSTRATOR DEVICE PARAMETERS

### A. FCL parameters

The electrical and geometric parameters of the FCL in this case study have been reported in [4]. The FCL is a single-phase open-core design, with square cross-section cores and AC coils. The FCL can operate in either a Helmholtz-like DC coil arrangement (i.e. with two DC coils), or with a single DC coil. Fig. 1(a) shows a single coil arrangement, and Fig. 1(b) shows the FCL in the Helmholtz-like two-coil arrangement. The DC coils are depicted in magenta; The AC coils in green and the steel cores in black.

At a commercial scale, the two DC coil arrangement has several advantages - most notably, the steel cores can be more uniformly saturated, which leads to a better overall device performance and lower AC insertion impedance. Additionally, the use of two DC coils results in less coupling between the AC and DC coils, which reduces the likelihood of a B-field induced quench during an AC fault event. A single-coil arrangement, however, reduces the complexity, cost and overall risk of the FCL system. We focus in this study on the two-coil arrangement, due to the likelihood of this arrangement being used in a commercial-scale application.

### B. $MgB_2$-based coil parameters

The geometric and operating parameters for the $MgB_2$-based coil are summarised in Table I. The coil ID and central $B_0$ field were chosen to fit the FCL core biasing requirements, with all other parameters subsequently determined from these driving parameters, through multi-objective optimization methods. The software package OptiY was used to perform optimization, whereby $B_0$ was maximised and the peak B-field on the coil volume minimised. All parameters were based on a wire diameter of 1.13mm, a value encompassing the $MgB_2$ wire and insulation given by the wire supplier.

TABLE I
DEMONSTRATOR FCL PARAMETERS

| Parameter | Value | Units |
|---|---|---|
| Core cross-section | 80 × 80 | mm |
| Core height | 600 | mm |
| DC coil inner diameter | 600 | mm |
| DC coil height | 113 | mm |
| DC coil radial build | 11.3 | mm |
| DC coil number of turns | 1000 | turns |
| DC coil $B_0$ central field | 0.3 | T |
| DC coil operating temperature | 20 | K |
| DC coil operating current | 50 | A |
| AC voltage | 540 | $V_{RMS}$ |
| AC normal-state current | 32 | A |
| AC fault-state first peak current | 3582 | A |
| AC fault-state steady state current | 2875 | A |
| AC line frequency | 50 | Hz |

Geometric, electrical and operating parameters for the demonstrator FCL and $MgB_2$-based coil.

## III. DISCUSSION OF FCL-SPECIFIC ISSUES

### A. Magnetic Fields

Magnetic fields in superconducting coils are an issue of critical importance, as high magnetic fields can lead to B-field induced quenching – especially in $MgB_2$-based coils as $MgB_2$ has a relatively low tolerance to impinging magnetic fields. In FCL applications, the two main sources of magnetic field on the superconducting coil are the coil self-field and the transient magnetic field arising from the saturation-desaturation cycle of the FCL during an AC fault event.

Minimization of the self-field in a superconducting coil while maintaining an acceptable $B_0$ is a multi-faceted problem. There are equations that can be used to analytically determine $B_0$ and maximum field on the coil [5], which were used as the basis for a multi-objective optimization study for the demonstrator coil.

The transient magnetic field on the superconducting coil during normal-state and fault-state operation is critical to account for and minimize where possible. There is no analytic method for performing such a study, so FEA techniques must be employed. For the demonstrator device, the FCL was modeled in Magsoft FLUX3D [6] as per Fig. 1(b). An appropriate electrical circuit was modeled (as in [4]), and the simulation was run for a fault event. The magnetic flux density at a point on the top edge of the top coil – where the coil and the xz-plane intersect – is shown in Fig. 2. Due to the low aspect ratio of the coil, this is the region of highest magnetic field on the conductor. As can be seen in Fig. 2, the perpendicular field on the wire is approximately equal to the total magnitude (the black curve), and is large even during normal-state operation. During a fault, the magnetic field on the wire peaks at 0.66 T, and fluctuates between that peak and 0.54 T throughout the fault event. These field values were taken into account when designing the coil and in choosing

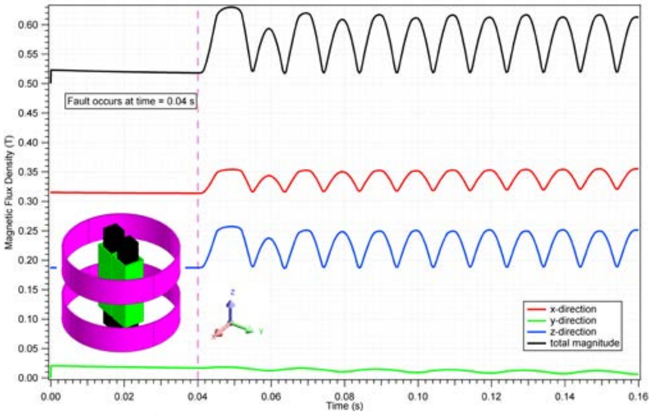

Fig. 2. Magnetic field magnitude (in black) and components on the top edge of the top DC coil – the point of maximum field during a fault event.

appropriate de-rating factors when determining the coil $I_C$. The cyclic nature of the magnetic field – both in normal-state and fault-state operation – also raises concerns about AC losses and the subsequent potential for heating in the wire. To mitigate this issue, OFHC copper was selected as the material for the coil former, which acts as a heat sink and large thermal mass to absorb and remove any heat generated from AC losses.

### B. Heat generation in components

Saturated-core FCLs with an open-core structure can have considerable magnetic coupling in structures around the steel cores. When the flux in each core rapidly changes during a fault event, this can cause large transport currents in any electrically conductive parts that form a closed loop around the cores – such as oil tanks, cryostats, DC coils and solid formers. These transport currents lead to Joule heating of the components, and may be greatly reduced by cutting the closed loop in one or more places.

In the demonstrator coil, OFHC copper was chosen as the former material to become an integral part of the cooling system, while also providing mechanical stability for the wire. A standard method of manufacturing such a former would be to cast the former from a thermally (and electrically) conductive material such as aluminum or copper – or roll a billet to create a joined ring. Both these methods result in a closed loop current path, which previous experimental studies on cryostat materials have shown to result in high transport currents and heating in the component. It was therefore deduced that a similar principle could be applied to the former, by introducing a slit to reduce the transport currents. A G10 fiberglass insert was incorporated to maintain mechanical strength of the former. This was expected to reduce the transport currents in the former during normal-state and fault-state operation. However, after the former had been manufactured, ongoing detailed simulations showed that the inclusion of a slit results in a rise in Joule heating when compared to a former without an electrical slit, as shown in Fig. 3. This result is counter-intuitive considering previous experimental results and it has been found that  the shallow skin depth of copper at cryogenic temperatures is playing a significant role. In a continuous ring, the current is distributed only on the inner surface of the former up to the skin depth and the rest of the copper thickness carries almost zero current; however, cutting the former causes this inner surface current to return along the outer surface of the former and essentially doubles the heat load. As such, the thickness of the former may be a factor, where it is suggested that a thinner copper former with a slit could reduce the joule heating. In light of these results, this phenomenon should be taken into careful consideration when analyzing Joule heating in components at cryogenic temperatures.

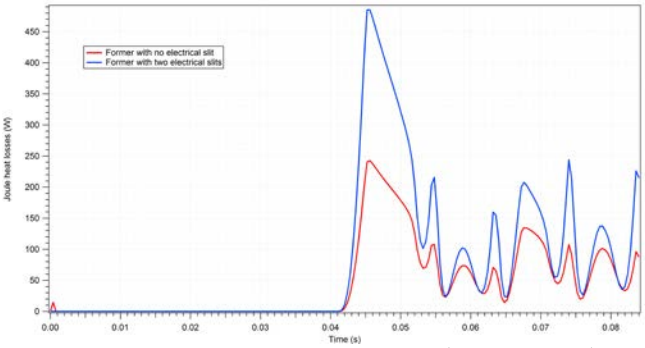

Fig. 3. Heat generated in the OFHC copper former during fault-state operation.

### C. Forces

Considerable forces are generated during the operation of saturated-core FCLs, particularly those with open-core structures employing two DC coils. This is due to the large forces between the cores and DC coils, which act to compress the two DC coils towards the vertical centre plane of the cores. Depending on the core configuration – particularly if the FCL is rotationally symmetric – additional forces in the lateral plane of the DC coils can also be present, however the largest force is in the vertical direction. These forces are periodic, and depend on the AC frequency of the FCL system. This can lead to significant damage to the DC coil if the AC frequency (or any of the harmonics) aligns with the natural frequencies of the coil support structure.

The forces are generated by the electromagnetic interaction of current and magnetic field. The Lorentz force is described by the cross product of current density and the magnetic field:

$$\vec{F} = \vec{J} \times \vec{B}$$

Since there are two cores, which change flux at different times and are located asymmetrically in the DC coil, there is not only an axial force component on each DC coil, but also significant lateral force components as well. This is because a higher or lower magnetic field will be present on either side of the DC coil at any given time.

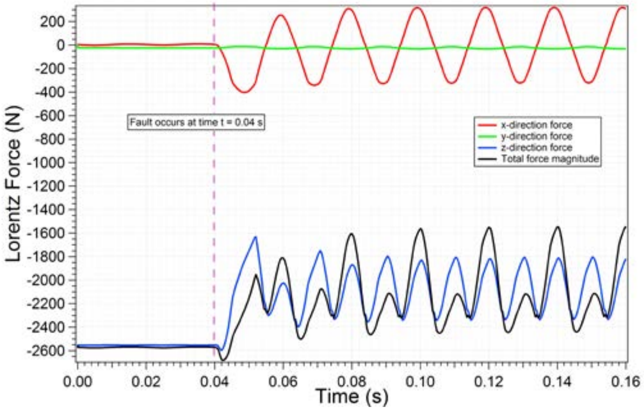

Fig. 4. Force components and magnitude (in black) on the superconducting coil during normal- and fault-state operation.

Simulations were performed on the demonstrator FCL model to determine the overall force on the $MgB_2$-based coil mass due to the electromagnetic forces in the system, with the results shown in Fig. 4. As can be seen in Fig. 4, the largest component of force in the two-coil arrangement is in the z-direction, along the axis of the cores, as expected. The force tends to draw the two coils together during normal-state operation; however, it reduces during a fault event. There are also considerable forces in the x- and y-directions, which are due to the rotational asymmetry of this FCL arrangement.

To address this issue in the demonstrator coil, a support system consisting of G10-based struts was devised, which allow for adequate mechanical strength while maintaining poor thermal conduction from the room temperature cryostat to the $MgB_2$ coil. This support system is shown in Fig. 5, where the main supports are angled from the vertical to provide additional support in the lateral directions, and smaller struts are included to resist torque in the system induced by the moving three-dimensional force vector during a fault.

A harmonic analysis of the z-direction force for the two-coil arrangement, once the fault has reached steady-state, is shown in Fig. 6, with the inset showing the harmonic analysis of the first 40 ms of the fault (corresponding to two AC cycles). The largest peak at 100 Hz is a result of the 50 Hz AC line frequency.

To ensure that these forces would not induce resonance in the “sprung mass” of the demonstrator coil – i.e. the former and $MgB_2$ winding supported by the G10 struts – a frequency analysis of the entire design was performed. The natural frequencies of the “sprung mass” are shown in Fig. 6. In this case, there were no overlaps between the driving force frequencies and any of the natural frequencies, and thus no further action was required. If there had been a resonance identified, several mitigation methods could have been employed, including pre-tensioning of the G10 struts to adjust the natural frequencies, or adding damping weights to the “sprung mass” to achieve a similar result.

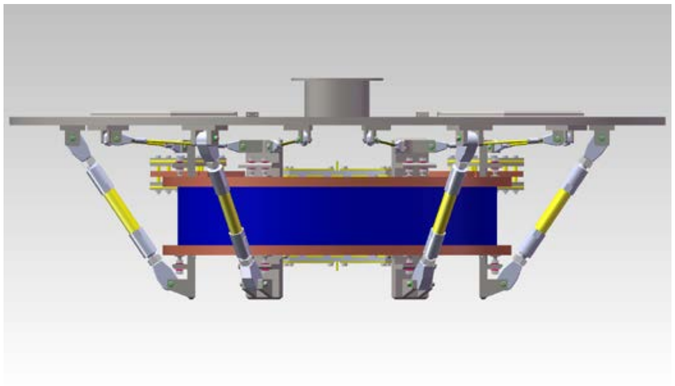

Fig. 5. Support structure of the demonstrator coil. G10-based struts are shown in yellow, $MgB_2$ coil shown in blue, and the OFHC copper former shown in brown.

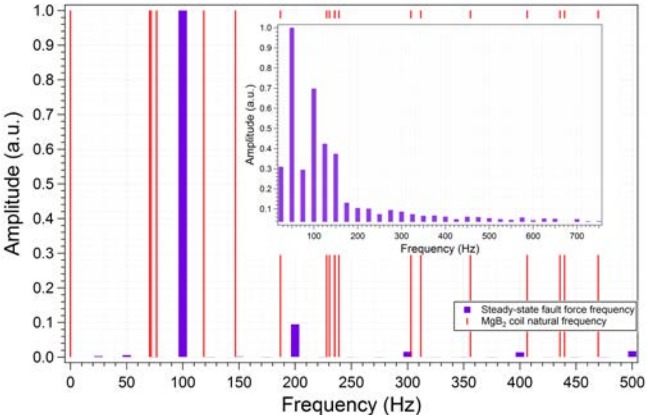

Fig. 6. Frequency spectrum of steady-state z-direction force (purple), and “sprung mass” natural frequencies. Inset: Frequency spectrum of first two peaks.

## IV. CONCLUSIONS

Several important factors that must be addressed when designing $MgB_2$-based coils for use in FCL applications have been presented and discussed with reference to a demonstrator coil. It was determined that special care must be taken to ensure the fluctuating magnetic fields and considerable forces present in the system are simulated and accounted for in any structural design decisions. Methods to mitigate any associated issues, including appropriate de-rating factors for coil $I_C$, calculations to account for the fluctuating magnetic field; designing a support structure that can resist the high static and transient forces; and using a copper-based former to act as a heat sink during a fault have been suggested and implemented for the demonstrator coil design.

Whether it is advantageous to include an electrically isolating slit in the former to reduce eddy current-induced Joule heating losses has been discussed, and it is clear that further investigation of this matter is required to ascertain the ramifications of such a design decision.

## ACKNOWLEDGMENT

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