

Saturated Cores FCL—A New Approach

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Abstract—The saturated cores FCL exhibits several attractive technological advantages: Inherent fail-safe and selectivity design, superconductivity is maintained during both nominal and fault states, the limiting process as well as the recovery after fault are passive and immediate, operation in limiting state is not time-limited, and the superconducting bias coil is made of wires available as commercial shelf-product. Despite these advantages, saturated cores FCL did not make it to commercial phase because of the large volume and heavy weight associated with its realization, a coupling problem between the AC and bias coils while in limiting state, and non-optimal limitation resulting from the presence of the bias field during fault. This work presents a novel, improved saturated cores FCL concept that overcomes the above difficulties and reopens the possibility for commercialization. Unique design topography reduces the cores volume and at the same time reduces the AC and DC magnetic coupling to about 2%. In addition, a control circuit, triggered by voltage drop across the FCL terminals, is added and disconnects the bias coil during a fault for increased limiting performances. All above-mentioned advantages of the saturated cores concept are maintained in this new design. First, a 4.2 kVA laboratory scale FCL has been designed built and studied proving the feasibility of the new design. Then, an up-scaled, 120 kVA model has been designed, built and tested at the testing laboratory of the Israel Electric Company. The prospective short current in the test bed was 5000 A, successfully limited to 2400 A. The 120 kVA model is a single phase FCL designed for 400 V, 300 A nominal conditions. Core losses and AC coils losses are 0.09% and 0.18%, respectively.

Index Terms—Fault current limiters, high-temperature superconductors, magnetic cores.

I. INTRODUCTION

FAULT CURRENT LIMITER (FCL) is one of the most attractive applications of superconductors (SC) in power systems, which has no classical equivalent [1]. The most straight forward concept for FCL is the ‘resistive FCL’, based on the intrinsic property of SC of increasing electrical resistance from zero in the SC state to a given value in the normal state, when current exceeds its critical value. FCLs of this type are under intensive development [2], [3]. However, despite the apparent simplicity of the resistive approach, this concept exhibits several intrinsic drawbacks: The AC current flows in series throughout the SC elements resulting in significant losses in normal operation mode, the operation time in fault mode is limited because of overheating of the SC elements in normal resistive state, and the recovery time required for the FCL to get back into ‘ready state’

is long. Possible locations for installations of FCL devices in the network dictate various boundaries for FCL characteristics as recovery time, limiting factor, losses level, physical dimensions, etc. This calls for FCL designs based on other concepts [4]–[6].

One of the other concepts is the saturated core FCL, which in its basic form is over 30 years old [7]–[10]. The core components of the device are a SC DC coil and a copper AC coil wrapped around a magnetized iron core. A fault current through the copper coil drives the iron out of saturation, increasing the inductance of the system and thus the impedance to the current. Current limiting operation does not rely on the transition between superconducting and normal states and the SC coil remains superconducting in all operation modes of the FCL.

The saturated core design exhibits several desired features: passive and immediate triggering; passive and immediate full recovery after a fault; failsafe operation; maintaining a superconductive state at all times; maintaining grid selectivity; and the ability to control and tune various parameters of the current limiter for specific installation locations and requirements. Despite these advantages, saturated cores FCLs have never reached a commercial stage. Major challenges to development of this device in the past have been reducing the device volume and weight, and reducing the transformer coupling between the AC grid coils and the DC superconducting bias coils.

With the development of advanced HTS tapes, the interest in saturated cores FCL re-appeared. Small models of one- and three-phase SC-FCL have been developed [11]–[13], using one core for each half-cycle and each phase. In one 3-phase FCL model, a single HTS bias coil was used to embrace 6 cores: two for each phase [13]. The problem of high AC voltage on bias coil was revealed again [14] and in a recent work [15] this problem was leaved out by using batteries as power supply for the bias coil. However, this solution is difficult to realize in upgraded devices.

In this paper we report the design and test results of a novel SC-FCL in which only one magnetic core and one AC coil is used for one phase. DC bias coil is located on a closed elongated magnetic core that serves as an open core for the AC coil. Such configuration enables decreasing the mass of the SC-FCL and the transformer coupling between AC and DC coils.

II. DESIGN AND CALCULATIONS

For verifying the feasibility of the new SC-FCL concept, we designed and built a small 4.2 kVA (400 V, 10.5 A) model, using the long ellipsoid approximation for calculating various magnetic parameters [16]. H105 grade silicon steel with high saturation induction and high permeability was used in this model. We used $B_{\max} = 2$ T and saturation permeability of about 15 in our calculations.

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The model is characterized by two geometrical parameters:
 $\alpha = S_{Fe}/S_C$ is ratio between the core cross-section (S_{Fe}) and the AC coil cross-section (S_C);
 $m = L_{core}/d$ is ratio of the core length (L_{core}) to the diameter of a core limb, d (approximating it to a circular cross section);

The apparent permeability μ^* of the core was calculated as [16]:

$$\mu^* = \frac{\mu}{(1 + N \cdot (\mu - 1))}, \quad (1)$$

where μ is the mean core permeability and N is the demagnetization factor:

$$N = \frac{1}{m^2 - 1} \cdot \left[\frac{m}{\sqrt{m^2 - 1}} \cdot \ln(m + \sqrt{m^2 - 1}) - 1 \right] \quad (2)$$

The equivalent schematic diagram of the device is close to two reactances connected in series: X_{Fe} is the sum of the AC coil reactance with core and $X_{air} \cdot (1 - \alpha)$ is the reactance of the coil with an air core:

$$X_{Fe} = X_{air} \cdot (1 - \alpha + \alpha \cdot \mu^*) \quad (3)$$

$$X_{air} = n \cdot S_{Fe} \cdot (n/l_C) \cdot (1/\alpha) \cdot \mu_0 \cdot \omega \quad (4)$$

where n is number of turns of the AC coil, l_C is length of the coil (m), μ_0 is air permeability and $\omega \sim 314$ is the circular frequency.

Estimation of preliminary parameters of the magnetic core and the AC coil is based on the maximal RMS voltage on the FCL in fault limiting state, $U_{FCL} = 200$ V and the allowable voltage drop on the FCL in nominal state ΔU_{nFCL} that is taken as in [7] to be 4.5% of U_n , i.e. 18 V. These two requirements result in formulae (5) and (6):

$$n \cdot S_{Fe} = U_{FCL}/444 \quad (5)$$

$$n/l_C \leq 101242 / (I_n \cdot (\mu_s^* + (1 - \alpha)/\alpha)) \quad (6)$$

where I_n is nominal current, μ_0^* is apparent permeability in saturation state.

The DC bias coil saturates the long magnetic core when the AC coil carries a nominal current. The Ampere-turns value of the bias coil was first estimated as a product of the required necessary field strength and the length of the core perimeter. FEM calculations using PC-OPERA software have been performed to estimate the static magnetic field distribution in the core at different bias currents during normal and fault states. The distribution of the magnetic field intensity in the core at the AC current peak, in nominal operation mode taught us that although B is quite homogenous throughout the core, H and therefore μ decrease as we move along the long limbs away from the bias coil. The local dependence of μ was taken into account in calculations of AC coil apparent inductance and led to values close to those obtained in subsequent experiments.

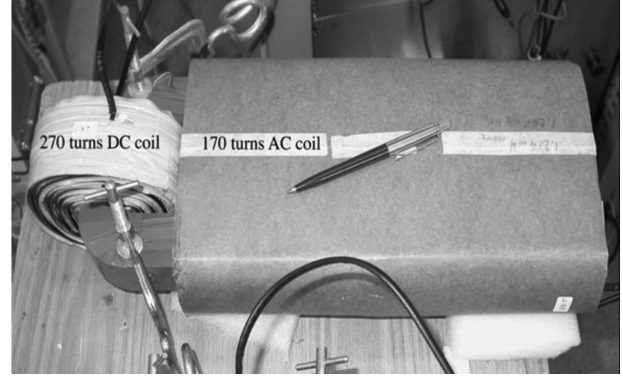


Fig. 1. Photo of the 4.2 kVA FCL. 270 turns DC coil (left) and 170 turns AC coil are mounted on the same magnetic core.

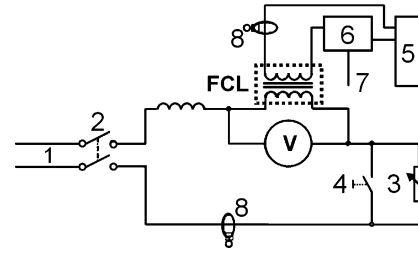


Fig. 2. Test circuit: 1—400 V AC source; 2—breaker; 3—load; 4—making switch; 5—DC power supply; 6—DC disconnecting switch; 7—voltage drop on FCL; 8—current probes.

III. EXPERIMENTAL

A. 4.2 kVA Model

A single-phase 4.2 kVA model (Fig. 1) was built for studying the influence of the device parameters on the voltage drop across the FCL terminals at nominal, overload and limited current states. For this bench mode, it was unnecessary to use SC coils, hence a 270 (16 kA)-turns DC bias copper coil was used. Both AC and DC coils were wound using copper wires with 4×1 mm² cross section to allow short time experiments with DC currents up to 60 A. The C-core was made of silicon steel of H105 grade with a cross-section of 40×40 mm².

The scheme of the test circuit is shown in Fig. 2. Prospective short current was limited to a predefined value by additional air coils. A making switch connected in parallel with the load served for shorting it and a breaking switch was used for disconnecting the fault current. In part of the tests we've implemented a DC supply disconnection during a fault event. For this purpose we've used a fast transistor switch controlled by the voltage drop on the FCL. Details on the disconnection system will be published elsewhere.

B. 1120 kVA Model

The principal of the 120 kVA (400 V, 300 A) FCL (Fig. 3) is the same as of the 4.2 kVA model. The C-core was wound with the same H105 grade silicon steel and had a cross-section of 120×120 mm². Core winding technological considerations have set the core length to 0.68 m. Two AC coils, 20 turns each, were connected in parallel and made from copper rectangular bus 5×25 mm². Length of the integrated AC coil was 0.44 m.

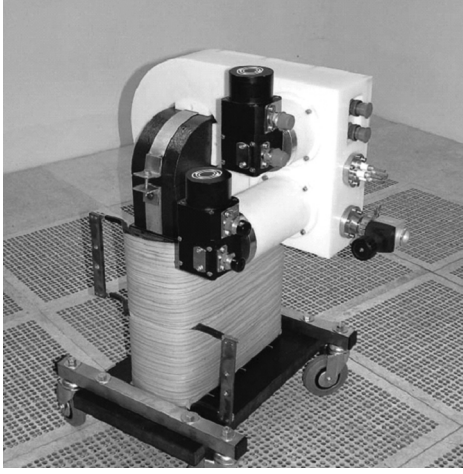


Fig. 3. Ricor's 120 kVA FCL. Delrin made cryostat with 2 cryocoolers contains DC HTS coil and mounted on the magnetic c-core.

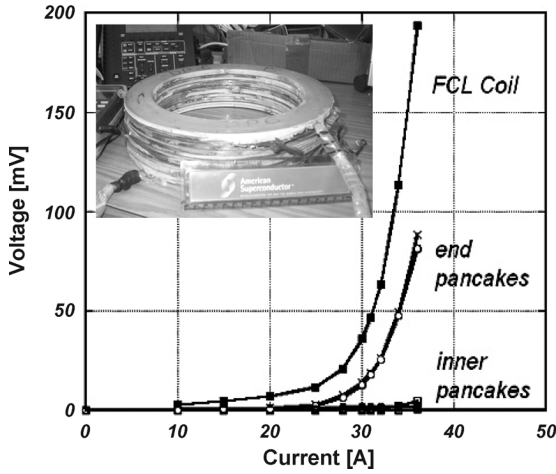


Fig. 4. I-V curves measured for double pancakes composing the DC coil (temperature 77 K). Inset: Photo of the coil made from a stack of 7 double pancakes.

U_{FCL} used in the design was 245 V and the voltage drop in the nominal state was 18 V (4.5%).

HTS DC bias coil was made from a stack of 7 double pancakes, 180 turns each, summing to 1260 total turns. We used the BSCCO-2223 wire manufactured by American Superconductor Corp., with minimal critical current of 115 A. Pancakes were manufactured by wet winding process using epoxy and Nomex insulation. I-V curves of all single and double pancakes as well as stacks of 2, 3, 4 and 7 double pancakes were measured in liquid nitrogen before assembling the coil. Typical I-V curves are exhibited on Fig. 4. Critical currents, n -values and inductances of all double and stacked pancakes exhibit low scattering of data indicating a good homogeneity of the wire and reproducibility of the winding process.

The cryostat body was made from Delrin to minimize metallic components and eddy currents (Fig. 3). Two “Coolstar” cryocoolers manufactured by RICOR were used: one double-stage (model 6/30) and one single-stage (model 0/40). Both operated with the same compressor [18].

The 120 kVA FCL was tested in the laboratories of the Israel Electric Corp. (IEC). The test circuit is similar to the one used

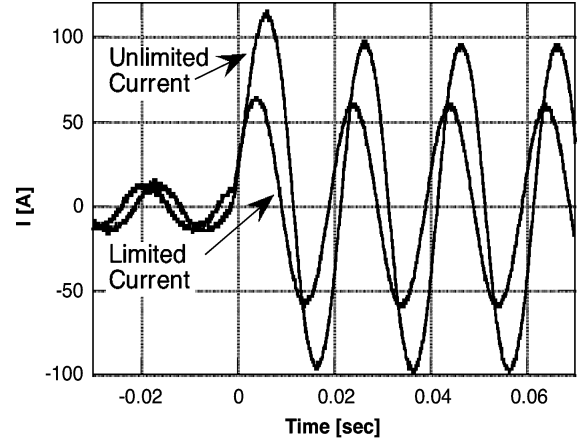


Fig. 5. Prospective short current and limited current for the 4.2 kVA FCL.

for the 4.2 kVA model (Fig. 2). A 24 kV/400 V transformer was used as a power source simulating the grid. A variable water resistor rated up to 120 kVA served as a load. A making switch was used for shortening the load and a set of parallel and/or series copper air coil were inserted in series with the power source to determine the prospective short current. The maximal value of the prospective short current was limited to 5000 A by a breaker. The breaker set the short circuit duration within the interval 200–500 ms.

IV. RESULTS AND DISCUSSION

A. 4.2 kVA Model

Normal operation test—The FCL voltage was measured at nominal ($I = 10.5$ A) and overload ($I = 16$ A) modes and the values obtained were 18 V and 30 V, respectively. As expected, the increase of the operating current causes an increase in the FCL impedance. During normal operation the obtained voltage drop was about 4.5%. In an example for a possible future realization of such FCL device, using a 4.5% voltage drop FCL in series with a 12% Uk transformer, could serve as a replacement for a 18% transformer. Hence, the 4.5% drop is acceptable in most scenarios, and contributes to reducing the grid impedance. Also, this value of the FCL voltage drop in normal state can be tuned to fit a specific installation demands by selecting the bias current. An increase in the bias field pushes the Iron core into a deeper saturation therefore reduces the FCL impedance significantly.

It is important to note that increasing the bias current affects also the current level at which limiting mode “triggers”, however, due to the nonlinear nature of the saturated core FCL this effect is much less significant. Typical result of a fault current test is shown in Fig. 5. During the fault, the voltage drop on the FCL depends on the corresponding impedance of the grid model and the FCL. In medium voltage applications, a most reasonable location for the FCL would be close to a transformer in a way that the FCL impedance angle matches that of the AC system. Assuming grid impedance Z_g being mostly inductive, one can find the limiting factor to be:

$$I_{sc}^{pr}/I_{sc}^{lim} = U/(U - U_{FCL}), \quad (7)$$

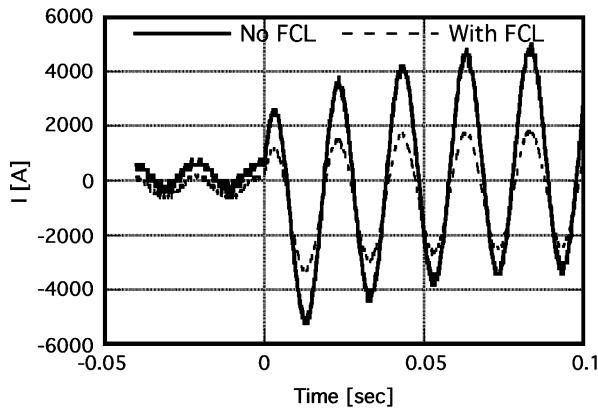


Fig. 6. Prospective short current (no FCL) and limited current for the 120 kVA FCL.

where I_{sc}^{pr} and I_{sc}^{lim} are the prospective and limited short current values, U is the grid voltage and U_{FCL} is the voltage drop on the FCL during fault. The limiting factor obtained in this test is about 1.6. Clearly, as the grid impedance decreases, the prospective short current and the voltage drop on the FCL increase and as a result the limiting factor increase as well. Experiments performed with prospective currents of 170 A have demonstrated limiting factors of about 2.4. This issue will be further discussed in details in a separate publication.

B. 120 kVA FCL Model

The 120 kVA (400 V, 300 A) FCL described here is a scaled up version of the 4.2 kVA FCL described above. Here, the FCL voltage was 17.8 V in the nominal state (300 A). A DC bias current of 20 A is enough to achieve this 4.4% voltage drop and to support the normal mode of operation. At this bias level the nominal losses obtained are 380 W (0.32%). When the DC level is increased to 30 A, the voltage drop is 3.7% and losses are reduced to 0.27%. Typical fault test results are shown in Fig. 6, exhibiting a limiting factor of about 1.9. Again, when the prospective current is further raised, the limiting factor can be further increased. For example, for 8000 A prospective short current, one may obtain limiting factors of about 2.6. The experimental setup used here didn't allow reaching this level of prospective current. An improved setup is being prepared at the time we write these line to verify the expected limiting factors.

V. SUMMARY AND CONCLUSION

A novel saturated core FCL has been designed, built and tested. The concept is based on a closed magnetic circuit for the DC bias field and an open circuit for the AC grid coils. This

design allows for a compact design with tunable limiting factors near 2. A 4.2 kVA SC-FCL model with copper coils and a 120 kVA SC-FCL superconducting model demonstrated the limiting mode of the FCL exhibiting low losses and low voltage drop on the FCL in nominal current mode.

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