Dynamic Desaturation Process in Saturated Cores Fault Current Limiters

Y. Nikulshin, A. Friedman, Y. Wolfus, V. Rozenshtein, and Y. Yeshurun

***Abstract*—The process of driving the magnetic core of saturated-cores fault-current-limiters (SCFCL) out of saturation has been studied numerically using finite elements calculations. The de-saturated core section was found to grow dynamically starting from the central region below the AC coils and gradually expanding towards the coil edges with increasing AC current amplitude. During the transition, the core volume underneath the coils is non-homogeneously magnetized and the system is highly non-linear. An effective core volume that contributes to the SFCL impedance during fault can be defined for different current amplitudes. Two "open core" SCFCL models have been studied and compared for their dynamic de-saturation process. The results demonstrate the importance of the dynamic effective volume size to the current limiting process and suggest that prior art approximations based on full core desaturation are not sufficient for a detailed SFCL design.**

***Index Terms*—Coil impedance, core saturation, finite elements analysis, saturated cores fault current limiter.**

I. Introduction

FAST growth of electricity generation is inevitably followed by increasing fault currents in the grids. As a result, the need for fault current limiters increases significantly [1]. SCFCL is a leading candidate for utilization in medium and high voltage electric power grids. The SCFCL has already been installed in several demonstration projects worldwide [2]–[4]. The SCFCL characteristics can be adjusted to match a wide range of grid requirements by modifying its magnetic circuit parameters such as core geometry, AC and DC coils number of turns, DC bias current etc. However, a design methodology is still lacking. Such methodology has to be based on in-depth understanding of dynamic processes of magnetic core desaturation and its dependence on AC current. In this work we use Finite Element Analysis (FEA) of transient processes in an "open core" SCFCL configuration [5], which offers reduced dimensions and less materials in comparison with other SFCL configuration [2]–[4]. A single magnetic core is used in this configuration taking care of a single-phase AC circuit.

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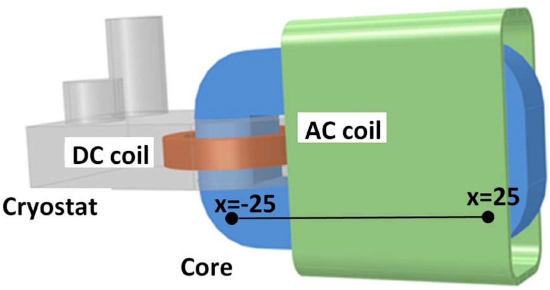

Fig. 1. 120 kVA "open core" FCL with single DC and AC coils.

II. 120 kVA Single Coil, Open Core FCL

In previous publications [5], [6], we described a 120 kVA open core SCFCL model. This FCL has a single core on which a single superconducting DC coil is mounted to form a closed magnetic circuit and a single AC coil is mounted to form an open magnetic circuit as described below. In this model, the superconducting coil was made from 1G BSCCO tapes, operates at temperatures of 40–55 K and serves as a bias DC flux source for saturating the magnetic core. Details about the HTS coil are given in [6]. This model was built and successfully tested at the Israeli Electric Corporation (IEC) laboratories. As described in [5], the design of this FCL was based on a simplified assumption that the whole core section underneath the AC coil goes from a fully saturated state (+2 T) through the fully de-saturated state to fully reversed saturation state (−2 T) during a fault current cycle. In reality, however, the transition between the core states is non-homogenous and the field intensity distribution is highly time and spatial dependent. As measurements of the physical model provide information on the average core state only, it is necessary to use FEA tools and numeric simulations to investigate the temporal and spatial dependence of the core state during a fault current cycle.

Fig. 1 displays the model simulated using Vector Fields PC Opera FEA software. The model consists of an elongated "O" type core (blue) on which the AC coil (green) is mounted to form an open magnetic circuit. The DC HTS bias coil (red) is mounted on the core in a closed magnetic circuit form, orthogonal to the AC coil. The HTS coil is housed in a cryostat, in which the core passes through a room temperature bore.

The AC circuit used in the simulations includes: AC voltage source of 400 $\mathrm{V_{rms}}$, grid inductance and resistance of 0.25 mH and 0.04 Ohm respectively, 1.3 Ohm load and the SCFCL. The DC circuit includes a DC voltage source of 0.2 V and a superconducting coil with total of resistance of circuit 5 $\mathrm{m\Omega}$. The nominal current is about 300 $\mathrm{A_{rms}}$ and the prospective fault current is about 5100 $\mathrm{A_{rms}}$.

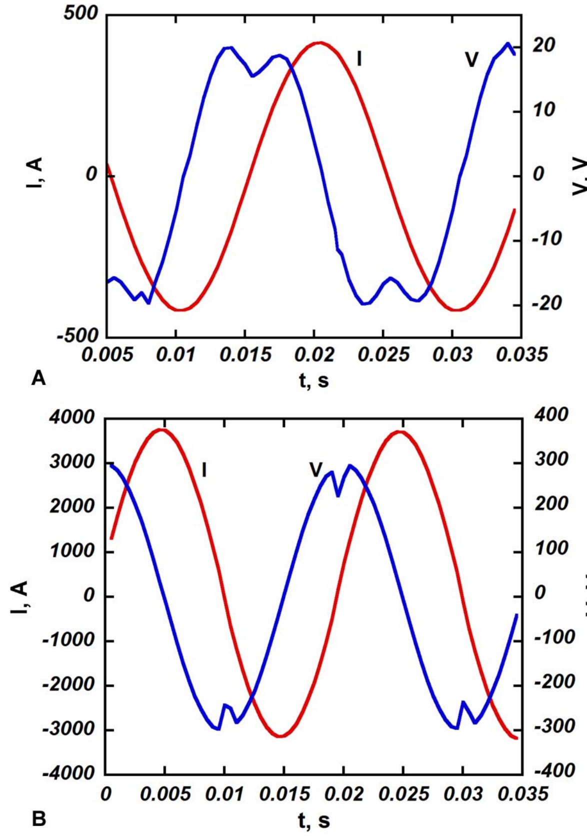

Fig. 2. Current (red) and voltage (blue) waveforms in nominal (A) and in fault (B) states.

Fig. 2 exhibits the time dependent FCL current and voltage obtained from the simulations for the nominal (Fig. 2(a)) and fault (Fig. 2(b)) states. Clearly, the current remains sinusoidal while the fingerprint of the non-linear behavior of the FCL manifests itself in the voltage curve. The general shape of the voltage curve, both in nominal and in fault states is governed by the rate of flux change in the core. When the current peaks, the rate of flux change zeroes, hence the voltage zeroes. The voltage (absolute value) increases with decreasing current due to an increase in the flux change rate. However, in contrast to an expectation that the voltage should peak when the current crosses zero, one observes a small dip in the peak of the voltage curve. This dip is a result of the lower inductance state resulting from the core going into deep saturation state.

An ideal FCL should remain deeply saturated in the nominal state at all times. The dip observed in the voltage curve of the nominal state implies that the core is driven away from the deep saturation regime when the nominal current increases and reaches its maximal amplitudes. The rms values extracted from the figures and summarized in Table I confirm this assumption as the average nominal voltage across the FCL is 15.1V, roughly a 3.8% impedance. The fault state impedance is found to be ≈50%, providing a factor of 2 current limiting as designed.

To further investigate and improve the nominal state characteristics, we have analysed the spatial distribution of the magnetic field intensity, B, in the core.

The distribution of B along the long core limb is exhibited in Fig. 3 for the nominal (A) and fault (B) states. The DC coil

TABLE I
SIMULATION RESULTS OF SINGLE COIL, OPEN CORE 120 kVA FCL

Parameter	nominal state	fault state
Current, Irms	298 A	2468 A
Voltage drop on FCL, Vrms	15.1 V	207 V
FCL impedance, Ohm	0.05	0.084
Voltage drop on FCL, %	3.78	51.8

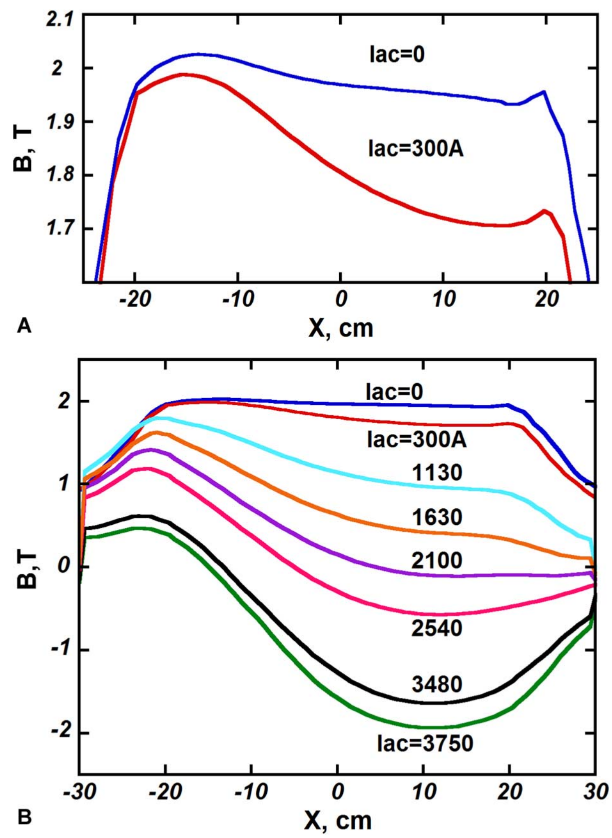

Fig. 3. Distribution of the magnetic induction in the long limb in nominal (A) and fault (B) states. Axis X as shown on Fig. 1.

is mounted on the orthogonal short limb at a position of about -27 cm. The AC coil spans on the X coordinate from -12 to $+30$ cm. Three main observations are seen in Fig. 3(a):

(i) When $I_{ac} = 0$, the DC bias strength is enough to deeply saturate the whole core section underneath the AC coil,

(ii) This statement no longer holds when I_{ac} peaks at its 300A nominal value. For this current amplitude, the remote core areas at a distance from the DC bias are driven by the AC current to induction levels of about 1.7 T, approaching the "knee" region in the steel B-H curve. This fall in the induction with increasing distance from the DC bias is responsible for the voltage levels obtained in Fig. 3(a) for the nominal state.

(iii) The induction along the core is non-homogenous and strongly depends on time and position. Therefore, to calculate the inductance of the AC coil it is necessary to take into account the exact B(x,t) dependence.

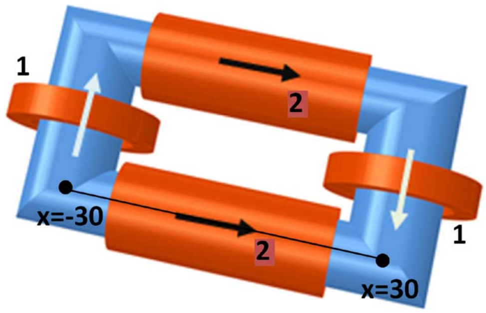

Fig. 4. Schematic arrangement of coils and core in the "double coil, open core" FCL. DC coils are marked 1 and AC coils 2. Arrows show the momentary direction of DC (light) and AC (dark) magnetic fields.

Fig. 3(b) displays profiles of the induction B for various current amplitudes during a fault cycle, showing the transition from the +2 T fully saturated core state at $I_{ac} = 0$ to the reversed saturation state, −2 T at $I_{ac} = 3750$ A. However, as clearly shown in the figure, for the −2 T case only part of the core under the AC coil is fully reversely saturated. We will define this core section as the effective core volume that contributes to the SFCL impedance during fault. For $I_{ac} = 3750$ A, this fully reversed saturation region spans from approximately $X = 0$ to $X = 20$ cm, leaving the rest of the core in a partially magnetized state. In other words, this FCL design can be further optimized to allow larger effective core length to contribute to the limiting process.

III. 120 kVA Double Coil, Open Core FCL

The single coil design presented in the previous section has offered an impedance change from 0.05 to 0.084 Ω between nominal and fault states. While the limiting factor of this design is sufficient for most grid requirements (≈50% fault current clipping), the ratio of impedances (1.68) in the fault and the nominal states should be higher for practical devices. In an effort to improve this ratio, we have modified the design to include two DC bias coils and two AC coils. The basic principles of the design remain unchanged namely, open AC magnetic circuit, closed DC magnetic circuit and an orthogonal mounting of AC and DC coils.

Fig. 4 shows the arrangement of the coils and core in this improved design. It includes two DC bias coils **1** mounted on the short limbs of the magnetic core and two AC coils **2** mounted on the long limbs. Light arrows indicate the direction of the DC magnetic field and dark arrows indicate the direction of the AC magnetic field in one half-cycle of the AC current. The direction of the dark arrows reverses with the reversal of the AC current.

The DC bias coils form a closed magnetic circuit and generate magnetic flux along the whole core. It saturates the core in a way that long limbs are magnetized in opposite directions. The AC coils are directed in the same direction so that they form an open magnetic circuit. When the AC current exceeds a certain level, one of AC coils drives the correspondent limb out of saturation while the other AC coil drives the other limb into a further deeper saturation state. AC coils switch roles when the AC current polarity reverses.

TABLE II
Simulation Parameters of 120 kVA FCL

	Parameter	Double coil model	Single coil model
Ferromagnetic core	Overall length, cm	76	68
	Overall width, cm	40	37
	Cross-section, cm^2	113	144
DC bias coils	Inner diameter, cm	20	20
	Height, cm	5.4	5.4
	Number of turns	2x540	1x1080
AC coils	Inner dimension, cm	14	14x40
	Length, cm	40	44
	Number of turns	2x16	20
Impedance, Ohm	Nominal state	0.01	0.05
	Fault state	0.047	0.084

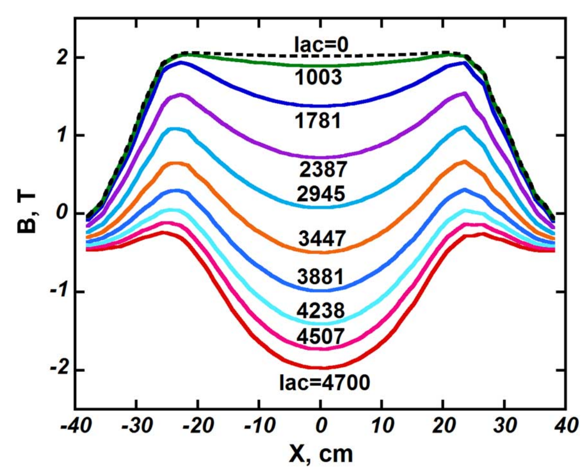

Fig. 5. Induction profile, B, in the core for various current values. Axis X as shown on Fig. 4.

Table II summarizes the physical parameters of both models. Generally speaking, both models resemble in their physical characteristics. The overall dimensions of the double coil model increase by roughly 10% but the core diameter decreases by about 20%. The total ampere-turns in the DC circuit are kept identical however, evenly split between two coils.

Fig. 5 displays the induction profile along the long limb opposing the DC flux direction for various current amplitudes during a half-AC cycle. One immediately notes that the profiles are now symmetrical around $X = 0$, the center of the core and AC coils. This symmetrical behavior is an outcome of the two DC coils, which evenly contribute to the magnetic induction from both sides of the long limb. One may also note that the nominal state profile ($I_{ac} = 300$ A) is now flattened and more homogeneous in comparison to the profiles seen in Fig. 3.

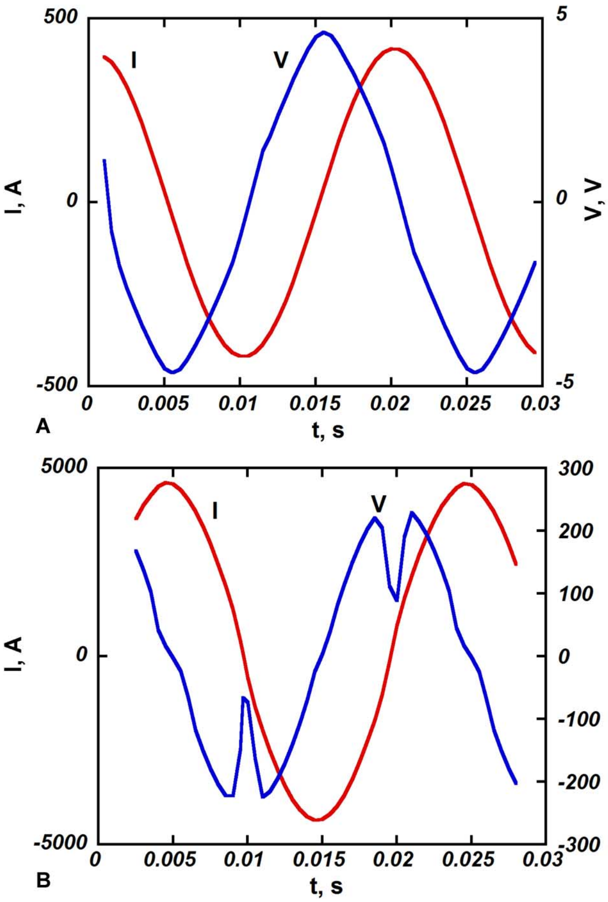

Fig. 6. Current and voltage waveforms at nominal (A) and fault (B) states.

TABLE III
SIMULATION RESULTS OF 120 kVA FCL WITH TWO AC COILS AND TWO DC COILS

Parameter	nominal state	fault state
Current, I_{rms}	296 A	3051 A
Voltage drop on FCL, V_{rms}	3.12 V	145 V
FCL impedance, Ohm	0.01	0.047
Voltage drop on FCL, %	0.78	36.2

Fig. 6 shows the current and voltage waveforms at nominal (A) and fault (B) states. Table III summarizes rms values extracted from Fig. 6. The voltage drop across the FCL terminals is now 3.12 V namely, an impedance of 0.78%, 5-fold improvement in the nominal impedance in comparison to the single coil design. In addition, the small dip in the peak of the voltage curves is gone indicating that the FCL's nominal impedance is practically constant and the FCL behaves practically as a linear device during nominal state.

The more homogenous profile causes a decrease in the limiting factor of the FCL. Since now the profile is symmetrical, a narrower core section reaches reversed saturation and the fault impedance decreases. The voltage across the FCL at fault is found to be 145 V, namely 36.25% clipping. Despite this drop in clipping, the ratio of impedances in fault and nominal states sharply jumps from 1.68 in the single coil design to 4.7 in the double coil design.

IV. SUMMARY

The time dependent voltage and current curves and the field induction distribution have been analysed for two "open core" SFCL models rated at 120 kVA. A model that consists of single DC, single AC coils exhibits asymmetric, non-homogenous field distribution that leads to an impedance change factor of 1.68 between fault and nominal states. This ratio increases to 4.7 in a model, which consists of double DC, double AC coils. In both models, during the transition, the core volume underneath the coils is non-homogeneously magnetized and the system is highly non-linear. An effective core volume that contributes to the SFCL impedance during fault was defined for different current amplitudes. In an optimized SCFCL this effective volume has to be maximized for maximal contribution of the core to the current limiting process.

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