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# Double storey three phase saturated cores fault current limiter

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**Abstract.** A novel saturated-cores Fault-Current-Limiter (FCL) configuration is described. This FCL is based on two parallel planes of iron rectangular cores, on which three-phase coils are mounted and connected in series to the grid. Two DC coils are mounted in between the planes on perpendicular core limbs connecting the two AC planes. The DC coils are set to magnetically saturate the AC cores. The transition to three-dimensional, double-storey design enables handling three-phase symmetrical faults while offering better decoupling between the AC and DC circuits. At the same time, it shortens the AC limb lengths and enables deeper magnetic saturation levels in comparison to other saturated cores FCL designs. Hence, this FCL configuration exhibits lower insertion impedance and higher ratio of fault to nominal state impedance in comparison with other designs.

## 1. Introduction

Recent installations of saturated cores fault current limiters (SCFCL) by Zenergy Power [1], InnoPower [2], Applied Superconductivity Ltd. [3] and GridOn [4] in live networks have made the SCFCL a leading candidate for limiting fault currents in medium to high-voltage networks. While the above installations are expected to provide data about the operation of the SCFCLs in various grid conditions, a continuous search for improved SCFCL designs and for better understanding of the underlying processes of the SCFCL mechanisms takes place. In a recent work, Aracil *et al.* analyzed the electromagnetic forces of an SFCL design and pointed to the differences between such forces in transformers and SCFCL [5]. Nikulshin *et al.* analyzed the dynamics of the transition between the saturated and non-saturated core states and suggested the “effective core length” concept as means for comparing different SCFCL designs and performances [6].

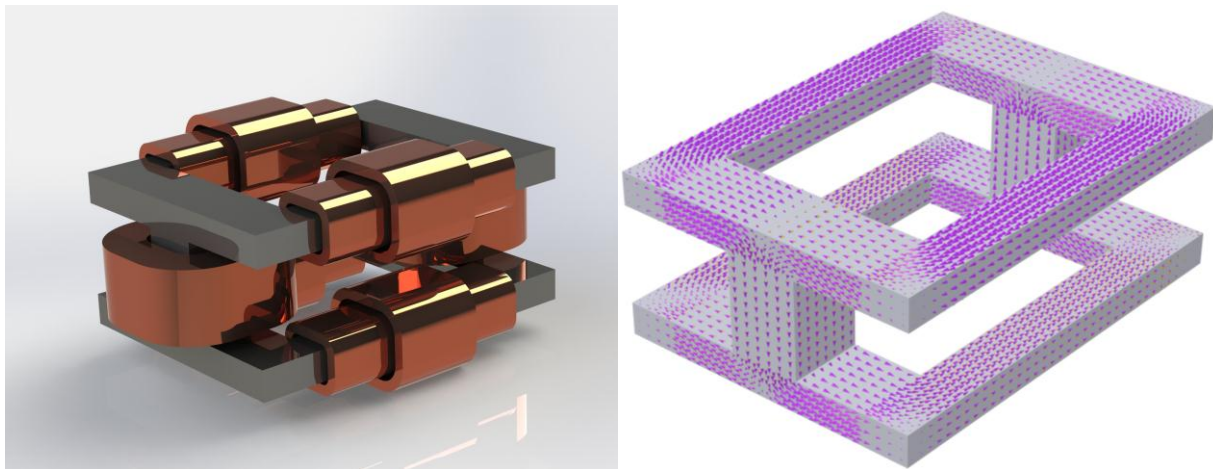
In this work we describe a novel, three-phase SCFCL design first suggested in a patent application [7]. This SCFCL “double-storey” concept is described here and its performances are studied for a bench model design. Insertion impedance lower than 1% is obtained for the nominal state and fault current clipping over 50% can be obtained for single-phase faults and over 30% for three-phase symmetrical faults. The advantages of this SCFCL concept are described below.

## 2. “Double-storey” SCFCL design

Figure 1a. exhibits a 3D CAD model of the “double-story” design. Two rectangular electric steel core frames are placed to form two parallel planes. Each frame contains two parallel long limbs connected by two short limbs with a 50% larger cross section. The AC coils of the three phases are mounted on the long limbs. Two further limbs are placed vertically between the horizontal planes connecting them magnetically and supporting the two planes. DC bias coils are mounted on these vertical limbs in opposing directions namely, the current circulates in the coils in reversed directions.

The flow of the DC flux lines generated by the DC coils is displayed in figure 1b. In the absence of current in the AC coils, flux lines generated in the DC coils point upwards in one DC limb, enter the upper frame and then split and flow along both AC limbs to the opposing DC limb. DC magnetic flux then flows downwards and closes by splitting again in the lower AC limb. The DC flux path forms a closed magnetic circuit. The two steps variation of cross sections between core limbs is introduced to ensure maximal transfer of DC flux to the AC core limbs for achieving deep saturation levels.





**Figure 1.** (a) - Left panel: Computer aided model of the “Double storey” SCFCL design. (b) - Right panel: Flow of DC magnetic flux lines in the core in the absence of AC currents.

The AC coils shown in figure 1a. are mounted on the AC limbs in a way that for each phase the coils are split and inversely connected in series across opposing limbs so that in the absence of DC bias their flux adds up. As described in ref [8], asymmetry between phase coils is a built-in feature of this design and achieved by varying the phase coil diameter, number of turns and/or the position along the AC limb. The amount of asymmetry is carefully selected to allow a net field vector sum high enough to drive the AC limb out of saturation in the event of a three-phase symmetrical fault, yet small enough to keep the negative sequence during normal grid state below allowed standards [7]. The model is designed for a 230 V/phase grid voltage and nominal current of 6.5 A namely, this model is rated at 4.5 kVA. The physical parameters of the core sections and coils are displayed in tables 1 and 2 correspondingly. The grid impedance is 1.5 ohm resulting in 154 A<sub>RMS</sub> prospective current in the absence of the SCFCL.

**Table 1.** Dimensions of the core limbs.

	W [mm]	D [mm]	H [mm]
Vertical limb	60	62	90
Short horizontal limb	180	62	30
Long horizontal limb	354	40	30

**Table 2.** Coil parameters.

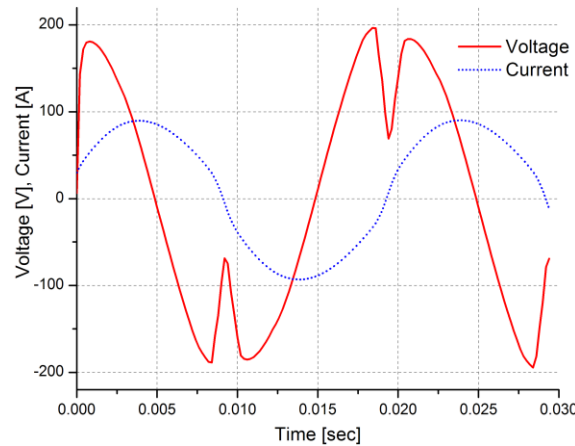
	Length [mm]	Turns	Inner cross- section [mm <sup>2</sup> ]	Coil thickness [mm]
DC coil	70	300	76x76	40
AC R-phase	85	95	46x36	10
AC S-phase	90	95	66x76	10
AC R-phase	85	95	46x36	10

### 3. Results

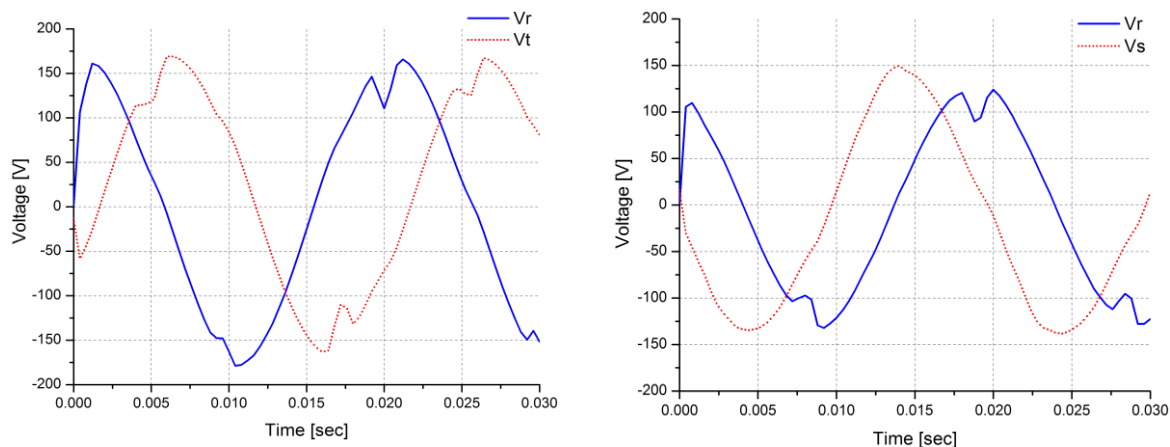
The performances of the “double-storey” model described above have been studied using static and transient COBHAM Vector Fields Opera simulation tools. All current and voltage waveforms obtained for nominal grid operation are sinusoidal and the current amplitude is practically identical for all three phases. The voltage amplitude is higher for the S phase in comparison to R and T phases. This is the result of the S coils having a larger inner cross-section. The normal state impedance obtained for the S phase is 0.59 Ω (1.66%) and 0.32 Ω (0.9%) for phase R. The relatively low impedance value obtained for phase R is the result of the “double-storey” design, which enables shortening the AC limbs length thus increasing saturation depth. The normal state impedances may be further reduced by increasing the DC bias field.

The most common fault scenario is a single-phase fault. Figure 2 displays the voltage and current curves for a fault in R-phase. The voltage curve is typical of SCFCL fault curve exhibiting the “split-peak” fingerprint of the rapidly varying coil impedance near zero AC current [7]. The voltage drop

across the R coils is 133.05 Vrms namely,  $\sim 57\%$  clipping. The calculated fault impedance is  $1.95 \Omega$  representing over 6-fold impedance increase over the normal state impedance.



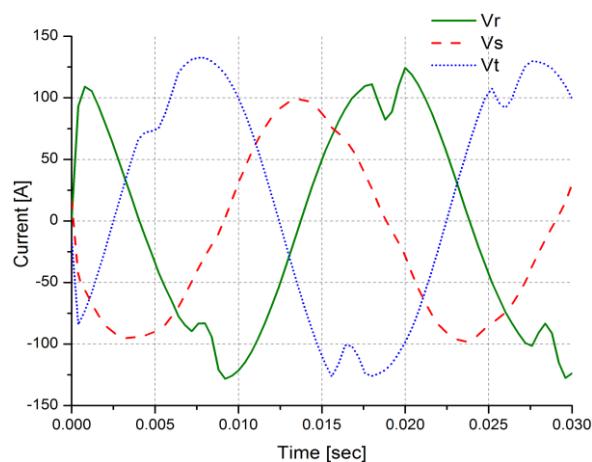
**Figure 2.** Voltage (red) and current (blue) curves for R-phase in the event of single-phase fault of phase R.



**Figure 3. (a)** - Left panel: Voltage waveforms obtained in the two faulted phases: R (blue), S (red). **(b)** - Right panel: Voltage waveforms obtained in the two faulted phases: R (blue), S (red).

A less common fault scenario involves a fault between two phases. We describe here two different cases of such faults: R-S and R-T faults. In both cases the faulted phases become directly connected to the ground. Figures 3a and 3b display the voltage curves correspondingly for the R-S and R-T fault scenario. The R-T fault scenario is described in figure 3a. Since the R and T phase coils are distanced from one another relative to their distance to the S coil, the obtained voltage curves are more “traditional” and both exhibit the “split-peak” feature. Voltage drop across each phase is about 113 V namely, about 49% clipping. It is interesting to note that the partial overlap between the R and S coils causes a strong coupling between them when the core is de-saturated resulting in the alteration of the “split-peak” feature in the voltage curve (figure 3b.). The voltage drop measured on each phase is 85.6 V and 98.3 V for phases R and S, respectively and their impedances are  $0.83 \Omega$  and  $1.09 \Omega$  namely, about 37% and 43% clipping in phases R and S, respectively.

The most challenging scenario is the three-phase symmetrical fault. For a single core SCFCL this is a serious challenge as the vector sum of the magnetic fields created by 3 coils wound on the same core shifted in phase by 120 degrees, cancels out when the vectors are identical. The built-in asymmetry of the phase coils in this design overcomes this challenge. In this example, the asymmetry introduced by the S coils is sufficient to drive the whole core out of saturation and provide current limiting protection. Figure 4 exhibits the voltage curves in this case.



**Figure 4.** Voltage waveforms obtained in the event of a three phase symmetric fault: R (green), S (red), T (blue).

Clearly, a significant part of the grid voltage still falls on the SCFCL coils. The voltage across R, T phases is about 88 V ( $\approx 38\%$  clipping) and about 69 V ( $\approx 30\%$  clipping) for the S phase. In most cases such levels of clipping for a three-phase symmetrical fault are sufficient, therefore making the double-storey SCFCL design an interesting and promising candidate for future FCL implementation.

#### 4. Summary

A new SCFCL design has been described. The model composed of two parallel core frames on which three AC phase coils are wound with a built-in impedance asymmetry. Two vertical DC core limbs connect between the AC core frames and generate the required saturation in the AC limbs. This out-of-plane placement of the DC and AC core sections results in a low coupling between the two closed AC and DC magnetic circuits. The results obtained for this design in various normal and fault state scenarios show strong clipping ability during a single-phase fault and fair clipping ratios for two and three-phase faults while maintaining low insertion impedance during normal grid operation. Further investigation of this design is taking place for comparing the dynamics of its de-saturation process with other SCFCL designs. The results will be published elsewhere.

#### Acknowledgments

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