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Saturated Core Fault Current Limiters in a Live Grid

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***Abstract*—With two recent successful installations in a U.K. live grid, the saturated core fault current limiter (SCFCL) has become one of the leading candidates for commercial fault current limiting devices. In this work, we review the concept developed at Bar-Ilan University, which was later adapted by GridON, for a novel compact SCFCL. This SCFCL utilizes a superposition of a closed dc magnetic circuit and an open ac magnetic circuit to overcome the intrinsic problem of transformer coupling found in traditional SCFCL designs. It also allows the use of a single magnetic core for a full ac current cycle limiting. In addition, the relatively short path for the dc magnetic circuit supports copper coils as an alternative to superconducting bias coils, allowing easier market penetration. The performances of the SFCL devices installed in live grids are described.**

***Index Terms*—Fault current limiter, magnetic cores, smart grid.**

I. INTRODUCTION

THE continuous growth in electricity demand and generation, as well as the tendency to parallelize network segments, results in increased fault currents in the grids. Therefore, an intense worldwide effort takes place aiming at a solution to the fault current problem so that replacing existing circuit breaker infrastructure can be avoided or postponed. One such solution is the Saturated Cores Fault Current Limiter (SCFCL). The device is basically a variable impedance reactor connected in series with the grid. Under nominal grid operation, its impedance is low and the device is practically "transparent" to the grid. However, when a fault occurs, its impedance increases significantly preventing the short currents from rising to the full level. Ideally, faults should be limited by about 50% to allow holding to existing infrastructure on one side, yet to allow breakers to clear the fault.

Already back in the 80's, Raju *et al.* [1] built and tested an SCFCL based on low temperature superconductors (LTS). An LTS coil was used for saturating a magnetic core in a magnetic amplifier-like design. An AC coil, wound on the core and connected in series with the grid, presents low impedance to the grid when the current is within its nominal range. During a fault event the rising current in the AC coil generates an AC magnetic field, which opposes the DC bias field. It drives the core out of the saturation state, leading to increased permeability of the core section under the coil and hence increased impedance and limited fault current. Though Raju *et al.* proved the feasibility of the concept to limit fault currents, drawbacks of the design became evident and prevented further commercialization of the SCFCL: First, the AC coil opposes the DC bias field only during half-cycle of the AC current. In the other half-cycle its impedance does not increase and the fault is not limited. As a result, two cores per phase are necessary for limiting the full fault cycle and the SCFCL becomes large in dimensions and mass, and increased cost. Second, when de-saturated, the magnetic core couples the AC and DC coils and high voltage is induced on the DC coil. This transformer coupling forces the use of special protection means, which decrease the device efficiency and increase both cost and design complexity. Third, the use of cryogenic technology in high-voltage environment generates a serious barrier of entry for utilities when considering the integration of new technology such as the Fault Current Limiter (FCL) in the grid.

High-temperature superconductivity (HTS) renewed the interest in SCFCL. Zenergy Power in Germany [2] and InnoPower in China [3] used a geometry variation of the design suggested by Raju *et al.* and placed an HTS coil at the center limb of a 6-cores design. Zenergy built a 13.8 kV SCFCL and installed it in the grid for tests. A 35kV/90MVA and a 220 kV/300 MVA SCFCL manufactured by InnoPower were installed and operated in live grids. InnoPower designs now an even larger prototype, namely a 500 kV/1800 MVA single phase SCFCL.

In Iran, simulations of the modified Raju *et al.* design have been recently performed [4]. An MgB_2-based SCFCL is being developed in Australia [5]. Researchers from India have analyzed different core materials for SCFCL [6]. Simulations of the SCFCL were performed by Fajoni *et al.* in Brazil [7]. Murta-Pina *et al.* in Portugal developed a methodology for modeling the performance of SCFCL designs based on their characteristics [8], [9].

Despite the above-described worldwide effort, most of the studied designs still suffer from one or more of the drawbacks which were present in the original design. Ways to overcome these drawbacks are still searched for. In this paper we review the work at Bar-Ilan University, later adopted and further developed by GridON, which resolved the above-described issues. The performance of 11kV/10MVA and 11kV/30MVA SCFCL devices installed in the UK grid are described.

II. THE OPEN CORE SCFCL

Fig. 1 exhibits SCFCL known as an open core SCFCL, designed by Friedman *et al.* [10]. In this design, the magnetic core is reduced to two limbs; on each an AC coil is mounted to form

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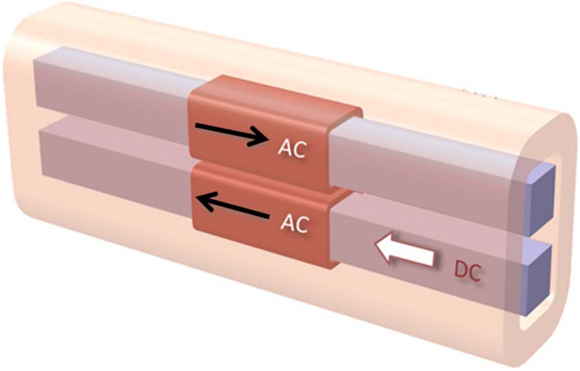

Fig. 1. CAD model of the open core SCFCL. Black arrows denote the direction of the ac magnetic field, and the white arrow denotes the dc field.

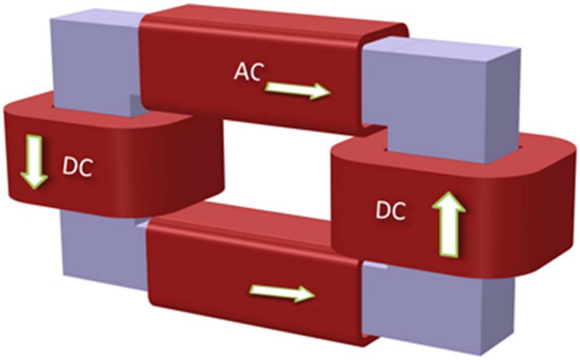

Fig. 2. CAD model of the open–closed SCFCL design. Arrows denote the direction of the ac and dc field lines.

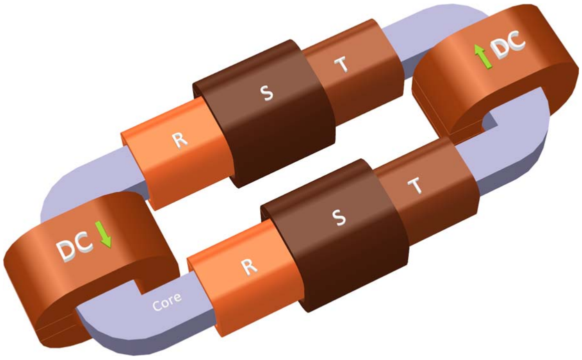

Fig. 3. CAD model of the open–closed three-phase SCFCL design.

an open magnetic circuit for the AC magnetic flux. The DC coil encloses both core limbs and magnetizes both in the same direction forming an open magnetic circuit for the DC flux as well. The AC coils are mounted in an opposing way so that for each half-cycle of the AC current one of the AC coils generates magnetic flux in a direction which counters the DC flux. Thus, the open core design eliminates the need for two window shape cores per phase for limiting the full fault current cycle. In addition, some of the AC-DC transformer coupling is reduced due the opposing AC coils arrangement and because the AC flux lines are closing partially within the DC coil. However, the open DC magnetic circuit requires high Ampere-turns in the DC coil to be able to deeply saturate the core region underneath the AC coils. For the same reason, high instantaneous fault currents are necessary to fully de-saturate the core, hence the open core configuration suffers from relatively low fault current clipping ratio.

We note that Zenergy Power has adopted the open core SCFCL configuration and realized it in a three-phase 11-kV SCFCL [11]. Applied Superconductor Ltd. (ASL) continued to develop Zenergy's open core SCFCL and installed another 11 kV device in the grid for tests [12]. As expected, clipping ratios for the device were about 25%.

III. THE OPEN-CLOSED SCFCL

A further development of the Bar-Ilan design, aiming to improve the clipping factor of the SCFCL and reduce the Ampere-turns of the DC bias coil, was described in [13]. The design, displayed in Fig. 2, superimposes a closed DC magnetic circuit and an open AC magnetic circuit whereas both coils are orthogonal to each other. The magnetic core is an elongated window core where the AC coils are mounted on the long limbs of the core generating parallel AC magnetic field lines. As a result, the AC fields of both coils cancel each other at the axis of symmetry in between the coils as long as the core magnetization state is identical for both long limbs. The resulting AC magnetic field pattern is therefore of an open circuit with AC flux lines closing through air. This configuration of the AC coils creates a perfect spot for mounting the DC coils on the short limbs of the core at this axis of symmetry so that the DC coils are exposed to minimum net AC flux and the transformer-coupling problem is minimized. The current in the DC coils flows in a direction so that the DC flux of both coils forms a closed magnetic circuit.

The open-closed SCFCL design can be extended to support 3-phase limiting operation with a single core design [13]. Fig. 3 demonstrates such a design, which can handle all fault scenarios, namely single-, 2- and 3-phase symmetrical faults.

Limiting a 3-phase symmetrical fault by a single core SCFCL is a challenge. This is because when all 3-phase coils are mounted on the same core and they undergo an identical increase in current, the vector sum of all magnetic fields generated by the coils is zero, hence the core remains saturated and the current limiting operation fails. To overcome this problem, a built-in asymmetry has been introduced into the design. The R, S &T phase coils are designed to include asymmetry in a way that the vector sum of the magnetic field of all coils is sufficient to de-saturate the core in an event of a 3-phase symmetrical fault. This asymmetry is achieved by mounting the phase coils on different segments of the core limb where the level of magnetic saturation is position dependent, by varying the coil diameters and/or by varying the number of turns between the phase coils. Special care has to be taken when optimizing the asymmetry level so that during nominal grid operation the negative sequence introduced by the SCFCL is low enough and within allowed standards. It is worth noting that the partial cancellation of the coils field during nominal condition helps reducing the device impedance making it even more transparent for nominal current operation.

One important feature of the open-closed SCFCL configuration is its compactness and relatively short DC magnetic path. The superposition of the AC and DC orthogonal coils, allows the core to be compact and as a result, the core can be magnetized using relatively low Ampere-turns. For the first time, it is possible to achieve deep core saturation using normal copper coils for distribution voltage level devices. Perhaps this feature is the one to allow overcoming the barrier of entry for utilities, postponing the introduction of superconducting bias coils to later, larger devices.

In a recent work, Nikulshin *et al.* have explored the transition between the magnetic states of the core in the three SCFCL designs described above [14]; the original design by Raju *et al.*, the open core SCFCL and the open-closed SCFCL. The dynamics of the transition between the saturated and de-saturated core states was analyzed introducing an effective core length—the length of the de-saturated section of the core limb relative to the full limb length. It was shown that during a fault, the de-saturated core section propagates from the limb center towards the limb edges where the dynamics of the increase in the effective core length depends on the SCFCL configuration. In particular, it was shown that the traditional Raju *et al.* design is the first to exhibit finite effective core length with the increase in AC current. This design is the first to de-saturate because its saturation state is the "weakest" of all three since the magnetic path for the flux from the DC coil to the AC coil is the longest hence, the magnetic reluctance is highest.

Last to de-saturate is the "open core" design where deep saturation persists up to about twice the current required to start de-saturation in the "Raju" SCFCL design. The "open-closed" design exhibits an intermediate behavior with the most gradual growth of the effective core length. The different SCFCL concepts may therefore be selected for various installation locations depending on the specific requirements.

IV. LIVE GRID INSTALLATIONS

GridON Ltd. has further developed the SCFCL initially developed at Bar-Ilan University. In 2013, the company has built and installed an 11 kV/10 MVA SCFCL in the Newhaven substation of a distribution network of Power Networks UK [15]. Due to the commercial nature of the SCFCL technology, details about the specific device design are not described here.

Shown in Fig. 4 is the prospective fault current for a 2-phase fault in the grid. Fig. 5 displays an event of such 2-phase fault recorded on the SCFCL installed in the substation. As is clear from the figure, after about 0.7 seconds this event evolved into a 3-phase fault, which was successfully limited by the device. The fault current is limited by about 50%.

The data presented here is representative. During almost two years of operation in the Newhaven substation, GridON's SCFCL has successfully handled and limited fault current scenarios of all types: single-, two- and three-phase faults some of which with multiple occurrences after breaker reclosure. In the time of writing this paper, GridON has completed the installation of a second SCFCL, 11 kV/30 MVA at Western Power Distribution's primary substation in Castle Bromwich, Birmingham, U.K. To this end, no fault events have been recorded yet.

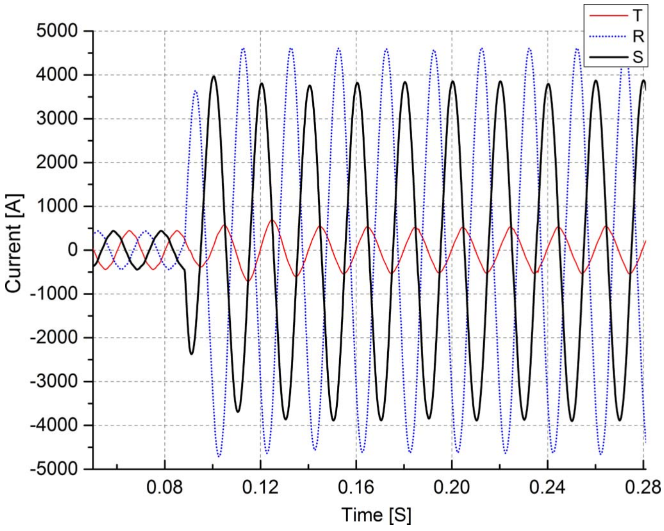

Fig. 4. Prospective fault currents in two phases R and T for the 11-kV/10-MVA SCFCL installed in Newhaven, U.K.

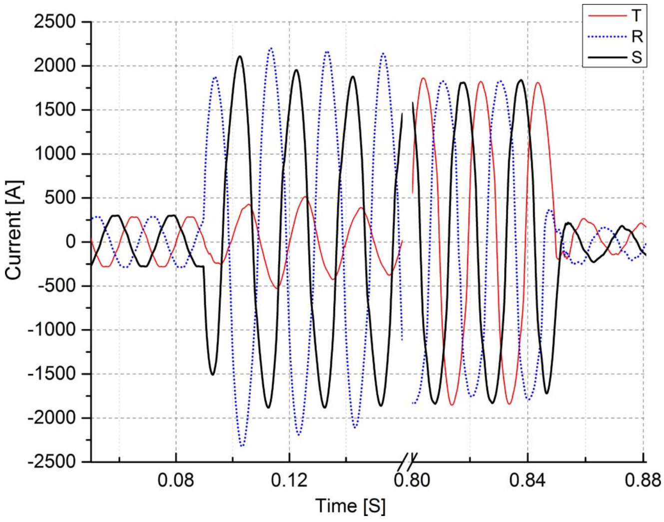

Fig. 5. Two-phase fault event evolving into three-phase fault. Recorded in Newhaven substation, U.K., for GridON's 11-kV/10-MVA SCFCL.

V. SUMMARY

SCFCL concepts suggested by Bar-Ilan University and further developed by GridON Ltd. have been reviewed. This development has led to an installation of 11 kV/10 MVA SCFCL in a live grid in UK, which was proven successful under various scenarios of single-, two- and three-phase fault events. The success of the SCFCL has led to a second installation in a live grid in UK and paved the way to more commercial installations to come. The SCFCL seems to provide the necessary solution to the fault current problem and thus allows adding generation resources to distribution networks and connecting network segments in parallel.

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