FAULT CURRENT LIMITER SURGE PROTECTION DEVICE FOR THE POWER GRID BASED UPON ZERO POWER CONSUMPTION CERAMIC FERRITE PERMANENT MAGNETS

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ABSTRACT

This paper describes the development of a new Fault Current Limiter (FCL) surge protection device for the power grid based upon zero power consumption permanent magnets. FCL components will be vital to prevent grid damage and to facilitate the safe connection between renewable energy generators and the power grid, particularly the emerging smart grid. The technology behind the new FCL has been achieved from a combination of magnetic engineering insights, including: using low cost ferrite magnets to saturate an iron inductor; a configuration providing efficient magnetic coupling; achieving a high level of protection against demagnetisation damage from the huge current surges during a fault. This technology results in a completely passive, autonomous system which requires no external power, back-up or control, and recovers automatically when the fault is cleared. The key challenge is magnetic scalability and manufacturability using cost efficient permanent magnets. The paper describes how a proof-of-concept project using high cost rare earth magnets was adapted and developed to provide an economically feasible solution using ceramic ferrite magnets, ultimately leading to the development of the FCL for the commercial power class of 20MVA, 11kV.

INTRODUCTION

With an increasing emphasis on renewable energy as a part of the generation mix, much of the geographically distributed new generation is more economically fed into local distribution network operators' networks rather than the primary transmission grid. Continuing growth in power demand, the use of intelligent/active networks and the addition of distributed generation, all require tighter interconnections. All of these tend to raise the fault current level of existing networks. [1]

An ideal Fault Current Limiter (FCL) is an automatically re-settable device which limits (rather than interrupts) the fault current in a branch of a circuit on occurrence of a fault condition so as to prevent any components in the circuit from being overloaded, and moreover does not generate significant losses or influence the normal operation of the network in which it is inserted.

FCLs can help networks to limit this rise. A suitably priced reliable FCL that could be introduced into existing power grids could minimise the costs of upgrading or reinforcing components to handle fault conditions while allowing increased normal power transmission.

A new magnetic structure has been conceived and developed, based on the idea of interacting AC and DC fluxes in a device comprising commercially available permanent magnets and soft magnetic alloy cores in a novel, highly efficient arrangement to render the composite core electrically invisible under normal conditions but able to respond quickly with a high impedance to limit damaging fault currents.

A programme has been undertaken commencing with building and testing a small physical prototype biased with high energy rare earth Samarium Cobalt Sm_2Co_{17} magnets developed using a 3D FEM simulation tool. The general concept was then adapted to operate with ceramic ferrite permanent magnets as the bias source. At this stage particular emphasis was placed on ensuring sufficient saturation of the soft iron limbs and examining the likelihood of demagnetisation of the ferrite magnets. A specification for the likely requirements for a 20MVA, 11kV FCL in the network was carried out prior to the final stage reported in this paper for the up-scaling of the magnetic core to meet such a requirement.

RARE EARTH MAGNET BASED PROTOTYPE

A small, bench-top prototype was built to demonstrate the concept for a distributed magnet, orthogonally biased FCL. The test was designed to compare the current limiting capability of the FCL with an air-cored coil of similar dimensions. The prototype was designed to operate with a normal current of around 3 Amps and a prospective fault current of around 30 Amps.

Prototype core configuration

The prototype design incorporated Sm_2Co_{17} magnets and M4 grain oriented electrical steel wound toroids which were cut and assembled in six equally sized sections. The toroidal cores had overall dimensions of i/d 90mm, o/d 110mm and width (each) of 10mm. The magnets had an inner arc length of 30mm and height 30mm. A relatively large number of electrical windings (800 turns – sufficient to allow a lab based power supply to energise the core up to a limit of 30 Amps) were wound in an evenly distributed fashion. A second, 800-turn "air-cored" coil was fabricated using a core made from a non-magnetic, non-conducting material with a similar cross section and circumferential length.

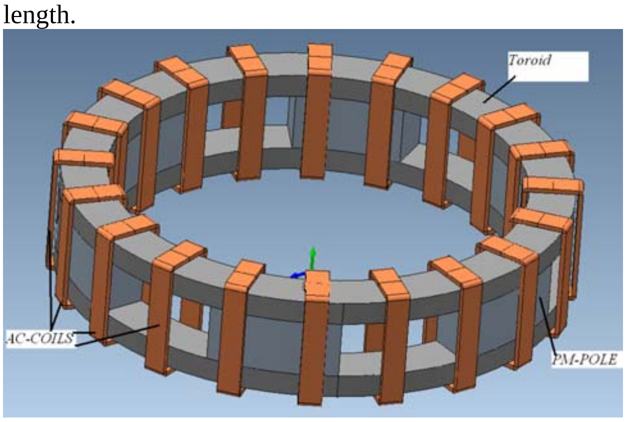

Figure 1. Schematic showing configuration of toroidal iron cores with Sm_2Co_{17} biasing magnets and AC coil windings.

FEM modelling

A 3D FEM tool was used for the design and simulation of the device. A commercial non-linear magnetostatic solver was used to optimise the magnetic circuit and a time-step non-linear transient solver was used to simulate the dynamic behaviour of the device. The output of the transient solver was coupled to a defined model of the electrical circuit to calculate the instantaneous current profile.

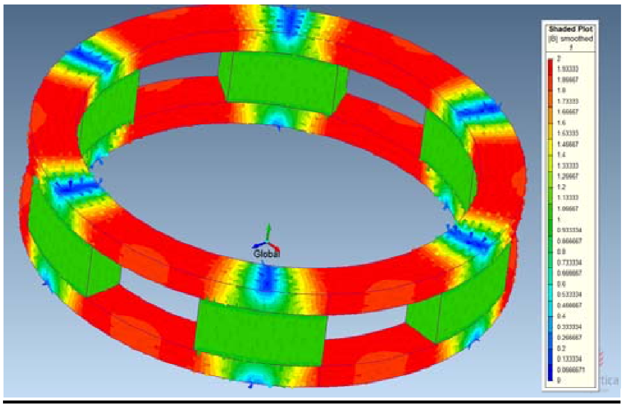

Figure 2. Flux density distribution for coil current = 0A

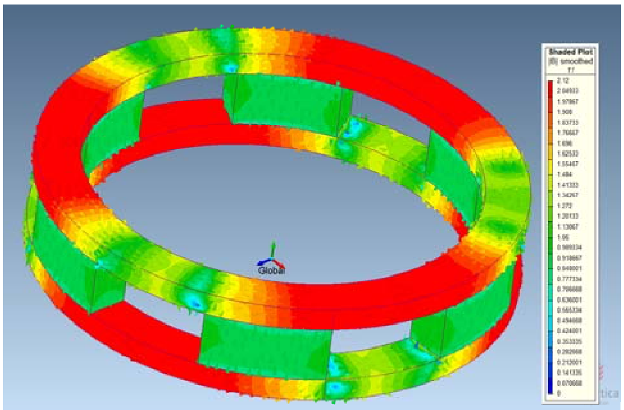

Figure 3. Flux density distribution for coil current = 30A

Test method

A test circuit was set up consisting of laboratory based power supply (max current 30 Amps) and a load resistor with a short-circuit switch connected in parallel. The FCL core was connected in series with the power supply and the load resistor. The current through the FCL was recorded for a range of supply voltage when the load resistor was briefly shorted. The test was then repeated with the FCL replaced by the air-cored coil. The resistance of each coil was measured and shown to be similar. (Note that this method differs from the typical comparison of comparing an FCL with a short-circuit containing no inductive current limiting element, since it was not possible to produce a short circuit current limited only by source impedance in the laboratory.)

Results

Simulation results obtained from the 3D FEM transient solver comparing the current allowed to flow through the FCL and air cored coil only are shown in Figure 4 below.

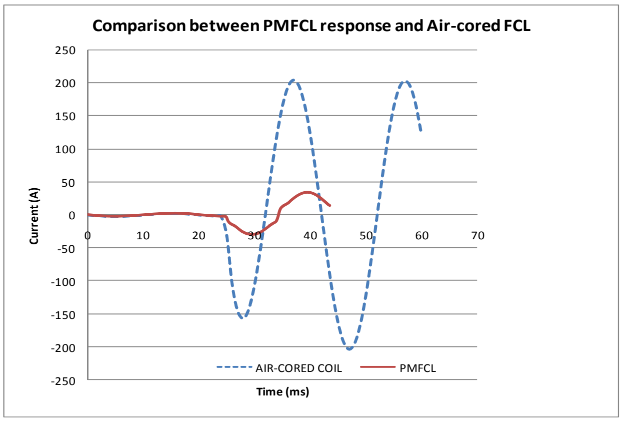

Figure 4. Snap shot of the transient current profile following a simulated fault in the Sm_2Co_{17} biased FCL FEM model and air cored coil.

Figure 5 shows a graph of current when the load resistor is shorted versus the applied supply voltage for the physical prototype. In order to compare the effects of the magnetism in the FCL at 30 Amps, the linear data for the air cored coil is extrapolated, as shown by the red line.

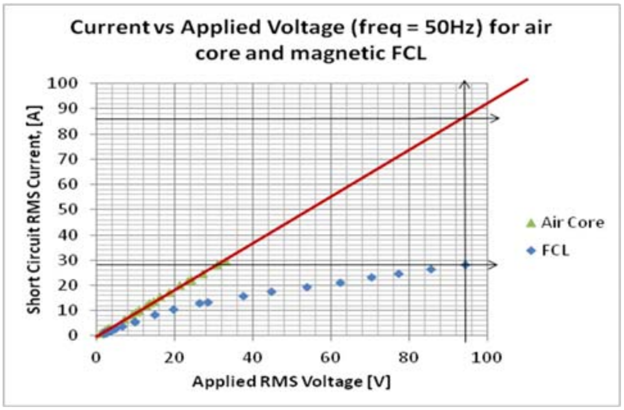

Figure 5. Current vs applied voltage for Sm_2Co_{17} biased FCL and air cored coil.

Discussion

At the “normal” current of 3 Amps, there is a small difference between the FCL and air-cored coil. Under these conditions, the magnetic field set up by the winding is not sufficient to de-saturate the toroidal cores, as intended, and the relative permeability of the core remains low. At higher currents, it can be clearly seen that the FCL is acting to limit the short-circuit current relative to the air-cored coil. Here, the effect of the magnetic field driving the toroid sections out of saturation, leading to an increase in core permeability and hence inductance is demonstrated.

For a current of 28 Amps, the impedance of the FCL is shown to be around 3 times that of the air-cored coil. In the FEM simulation at 30 Amps a change in current limitation was found to be approximately 4.5 times. Given unavoidable differences between the models (such as the assumption of isotropic permeability for highly anisotropic grain oriented steel and reluctances introduced by small air gaps between the wound toroidal cores and the pole faces of the magnets), this is a reasonable comparison and gives confidence to the use of the FEM method with this highly non-linear magnetic design problem.

The performance of the core was found to be repeatable, showing no degradation of the permanent magnets following a “fault event”, again as predicted by the above-mentioned FEM simulation.

From the study with the rare earth magnet biased FCL prototype it could be concluded that:

(i) Current limiting capability has been demonstrated in a toroidal core, distributed magnet, orthogonally biased permanent magnet FCL.
(ii) The validity of the FEM approach to designing and analysing the highly non-linear behaviour of a saturated inductance is demonstrated.
(iii) Within the range tested, the permanent magnets were not subjected to permanent demagnetisation by the orthogonal magnetic field due to the 30 Amp “fault” current.

FERRITE MAGNET BASED PROTOTYPE

Rationale for hard ferrite magnets

The cost of rare earth permanent magnet materials is currently around 10-50 times that for ceramic ferrite materials. Hard ferrite possesses reasonable characteristics in recoil capability and offers the prospect as a cost-effective substitute.

The challenge presented by adopting ferrite magnets as the bias source is the substantial scaling up in the size of the magnets. The volume of magnetic material necessary to provide sufficient magnetomotive force to drive the iron core into saturation necessitates substantially larger magnets. With magnets coupled with highly saturated iron, flux leakage into directions other than the desired paths through the iron cores becomes increasingly problematic with size. The challenge is met by careful consideration of the relative geometries of the soft and hard components in the FCL core and the possibility to distribute the static magnetomotive force sources around the low reluctance closed ring structure.

FEM model

The aim of the study was to design and test a ferrite magnet biased FCL under similar electrical conditions used for the previous Sm_2Co_{17} biased toroidal core. To ensure validity in the simulation a 3D FEM model was required [2]. A simple, square sided shape was conceived to allow a sub-section of the model to be solved more efficiently.

The following data was selected for the simulation: Arnold Magnetics Inc ceramic ferrite CM-8 with a relative permeability = 1.069, H_c = 240000kA/m and with the knee of the B-H curve set to 0T in the data used in the model; M4 grade electrical steel.

A schematic of the full model is shown in Figure 6. The dimensions for the iron limbs were overall length = 300mm, width = 60mm and build-up of each core = 5.7mm. The dimensions of the magnets were height = 140mm, length along limb direction = 100mm, width as for the iron limbs. Each of the four coils consisted of 200 turns with each located centrally along the limbs.

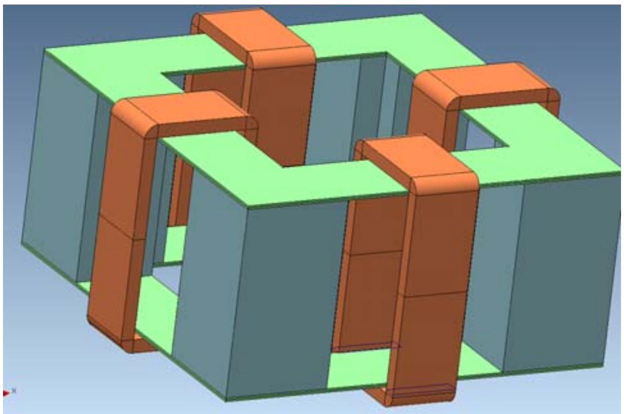

Figure 6. Schematic showing configuration of FCL core with ferrite biasing magnets and AC coil windings.

Results

Magnetic saturation of iron cores

The magnetic flux density in a quarter-section of the core is shown in Figure 7 for a coil current of 0A. The data in Figure 8 shows the saturation state for a contour along the length of the iron core from the corner to the mid-point of the limb. The region within the coil is shown to be saturated at around 2.0T.

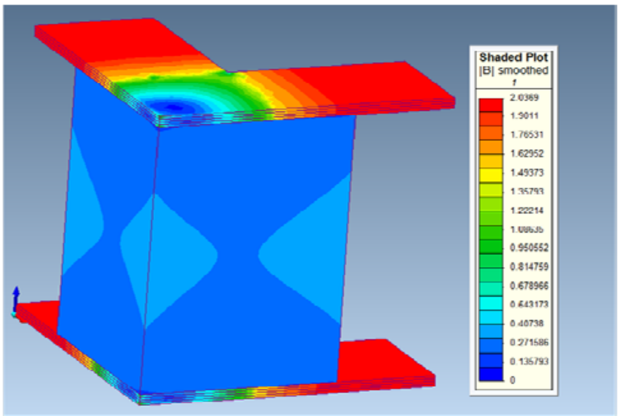

Figure 7. Flux density distribution in ferrite magnet FCL for coil current = 0A

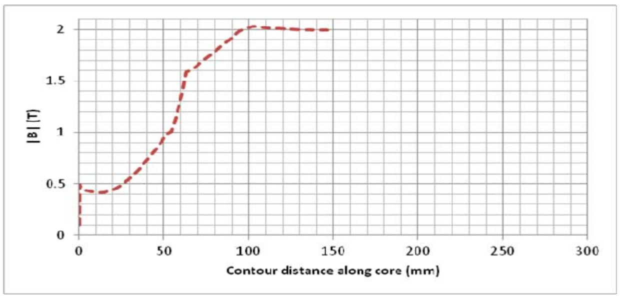

Figure 8. Flux density contour along length of iron limb in the ferrite magnet FCL model.

Proximity to demagnetisation of ferrite magnets

A post-processing solver was used to investigate the likelihood of demagnetisation of the ferrite magnets. In this approach the knee of the ferrite was defined to be 0T. (In fact, the knee for the real material lies just below this value in the third quadrant of the BH curve.) Figure 9 shows a snap shot of the demagnetisation state of the ferrite magnet for a peak coil current of 56A. A value below zero indicates no risk of demagnetisation in the magnet. The magnitude of the negative values in the figure indicates the degree of proximity away from the specified zero point of the knee of the BH curve.

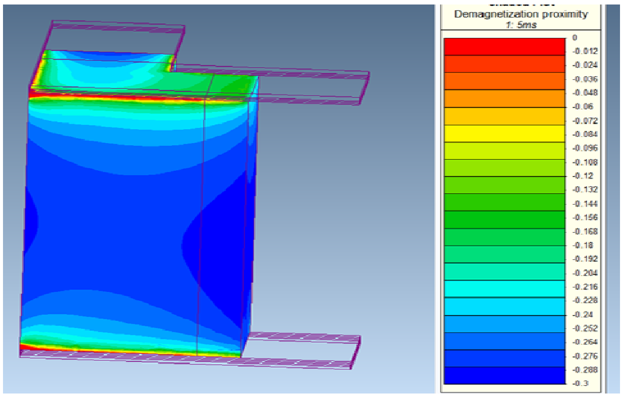

Figure 9. Proximity to demagnetisation of the ferrite magnet at coil current = 56A.

20MVA FERRITE MAGNET FCL

A preliminary electrical specification has been developed to inform the non-linear inductive performance of the FCL. For a device rated at 20MVA in the 11kV network, the inductance profile shown in Figure 10 was found to be appropriate. In order to meet this specification in a full-scale device, an FCL core incorporating CM-8 ferrite magnets with the M4 grade electrical steel cores was conceived to be assembled from a multiplicity of standard sized closed ring cores. Each core had the following dimensions: height of core (magnet plus build-up of iron limbs) = 0.6m, overall diameter = 2.6m, width of steel = 0.57m.

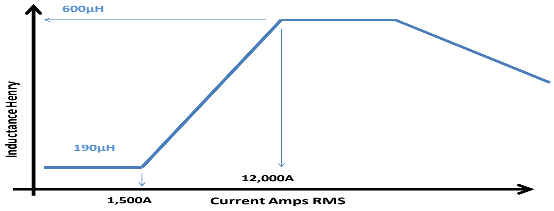

Figure 10. Required inductance vs current for a full scale 20MVA rated FCL device in the 11kV network.

Results

A single FCL with the above-mentioned dimensions containing 16 turns was modelled using the 3D FEM tool. A time-step solver was used to calculate the absolute inductance vs current profile which is shown in Figure 11 below. Inductance was found to increase by approximately 2.8 times across the range between normal and possible fault current levels. The full device would contain multiple core structures of this size in series per phase which offer an inductance range of from 1.9mH to 4.5mH with a 1% voltage drop at 1250A and 30% current reduction at 21kA fault level.

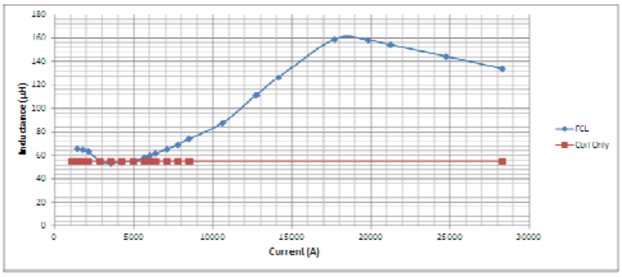

Figure 11. Absolute inductance vs current for a single FCL core structure with 16 turns within a 20MVA rated device.

REFERENCES

[1] CIGRE Working Group A3.23, 2012, "Application and Feasibility of Fault Current Limiters in Power Systems", CIGRE Technical Brochure, ISBN 978-2-85873-189-3

[2] D. Cvoric, 2010, *Novel Topology of a Saturated-core Fault Current Limiter*, Technische Universiteit Delft