FULL-SCALE 11KV FAULT CURRENT LIMITER FOR THE DISTRIBUTION GRID BASED UPON ZERO POWER CONSUMPTION CERAMIC FERRITE PERMANENT MAGNETS

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ABSTRACT

This paper describes the development of circuit parameters to predict the performance of a new permanent magnet biased Fault Current Limiter (FCL) surge protection device being developed for application in the 11kV for the power distribution network. The permanent magnetic biased saturated iron core FCL has benefits of a completely passive, autonomous system which requires no external power, back-up or control, and recovers automatically when the fault is cleared. Low cost ceramic ferrite magnets are employed to bias a structure of distributed saturated iron core inductors in a single device which operates on all three phases. A variety of scenarios have been examined to assess the thermal and current limiting behaviour of the FCL across a range of nominal and fault currents and power factors. A comparison is made with a conventional Current Limiting Reactor fixed inductance to show the power transfer advantage which can be gained using the pre-saturated FCL for the commercial power class of 20MVA, 11kV.

INTRODUCTION

Growth in demand for power and an increasing contribution on the connection of renewable energy as a part of the generation mix, much of which is geographically distributed and fed into local distribution network operators' networks rather than the primary transmission grid, is raising the fault current level of existing networks. [1]

Fault Current Limiters offer a cost-effective opportunity to reinforce existing networks without costly and lengthy need to replace major elements of the distributed system, allowing increased normal power transmission and fault headroom. 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 unduly the normal operation of the network in which it is inserted.

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.

An initial feasibility study reported in [2] has been developed into a full scale, 3-phase FCL which will be demonstrated in the 11kV network. A specification for the likely requirements for a 20MVA, 11kV FCL in the network was carried out for the up-scaling of the magnetic core to meet such a requirement. In this paper we will present the results of studies to evaluate the thermal behaviour and current limiting capability across a range of operating scenarios which are envisaged to be encountered in a network situation.

FERRITE MAGNET BIASED 11KV, 20MVA PROTOTYPE

A full-scale 20 MVA prototype has been designed and is under constructed to demonstrate the concept for a distributed ceramic ferrite magnet biased saturated core FCL. The overall dimensions of the 3-phase device are approximately 3m x 3m x 3m, and a total weight of 55 tonnes. The completed structure, including external cladding and base frame, is shown in Figure 1.

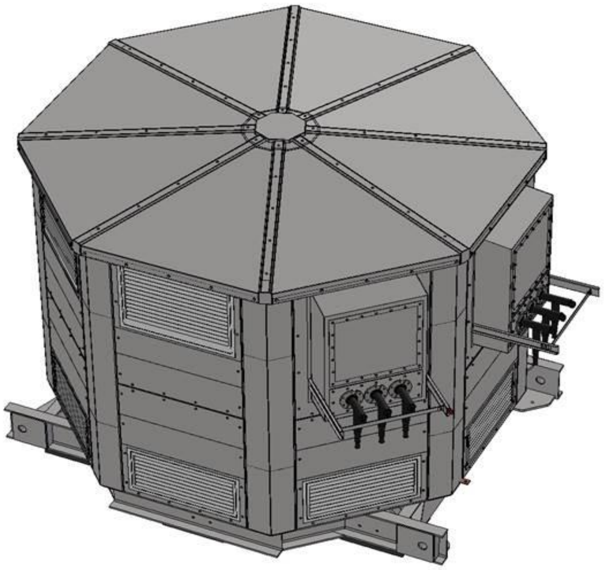

Figure 1. Illustration showing configuration the external view of the permanent magnet Fault Current Limiter. External wiring connections, cladding, base frame and natural ventilation louvers can be seen in the figure.

The octagonal structure is built up in three layers with individual inductors biased in pairs to allow the FCL to act on the initial peak of the fault current waveform irrespective of polarity. Windings for all three phases have been incorporated onto a single structure which comprises 24 iron core limbs encompassed by dry insulated windings. The prototype has been designed to operate with a normal current up to 525 Amps and a prospective, initial peak offset fault current of around 24000 Amps. Static magnetic fluxes are introduced at each end of each inductor limb from stacks of ceramic ferrite magnets housed in discrete nonmagnetic containers. The structure is shown in Figure 2 without the external cladding in which the windings, core limbs and magnets can be seen.

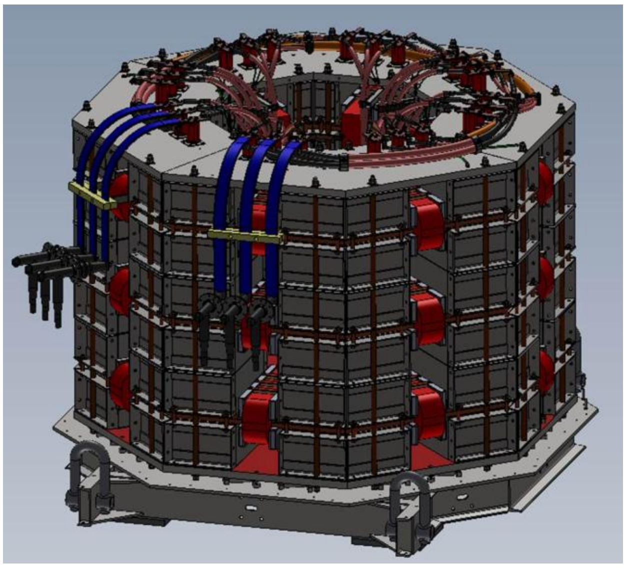

Figure 2. Illustration showing the internal structure of Fault Current Limiter with exterior cladding removed.

A high degree of magnetic coupling has been achieved through careful consideration of component geometries. In order to avoid permanent demagnetisation of the ferrite magnets, three-dimensional finite element modelling has been utilised to ensure peak field values corresponding to electrical currents during a fault event in the AC windings on the inductor limbs do not exceed coercive field values in the vicinity of the magnets. (The details of the magnetic modelling are not reported in this paper.)

ELECTRICAL BEHAVIOUR EVALUATION OF THE 11KV, 20MVA FCL

Electrical circuit parameters

A nodal parameter based electrical circuit simulator has been developed using VisSim software package [3]. This has been used to estimate short-circuit fault current limitation of the FCL. The circuit containing the 3-phase source, FCL, load and short-circuit switch is shown below as a schematic diagram in Figure 3.

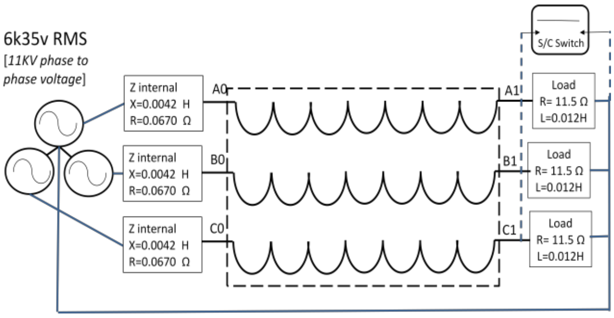

Figure 3. Test circuit for FCL under load and short-circuit conditions

The effect of the permanent magnet FCL has been compared in each case to the situation with no current limiter connected in circuit where the full unrestricted current is allowed to flow, and also in comparison with an equivalent air-cored current limiting reactor (CLR) inductor substituted in circuit for the permanent magnet biased FCL.

Using this model it has been possible to estimate (i) the current limitation of the FCL in a short circuit situation (ii) the sensitivity to changes in power factor from 0.8 to 1.00, (iii) the power delivery advantage of the FCL over the air-cored CLR over a range of nominal operating currents from 100 to 525 Amps, (iv) the temperature rise of the FCL under the most extreme nominal operating current case of 800 Amps and the advantage afforded by specification of dry winding insulation.

The circuit parameters were calculated for the source and load using a simple Excel spreadsheet. To derive the transient source parameters at 11kV and 10MVA the regulation, impedance and X/R of the source were specified to produce resistance and inductance values of the supply transformer. To specify the load current the ratio of inductive and resistive components in the load were used to give the load impedance as lumped parameters. The VisSim simulator uses lumped values and inserts the FCL between the source and load. It extracts the current flowing through each phase (indicated as phases A, B and C in Figure 3) and the voltage across the inductive and resistive components of the impedance of the FCL. The inductive component represents the series reactance which exists under the non-fault current limited condition. The increased reactance during fault current limitation is clearly a significantly non-linear quantity as would be expected from the non-linear profile of the induction curve for the steel core as it is driven out of saturation during a fault current event. The resistive component of the FCL indicates the power dissipation which occurs in the machine itself.

Results

The effect of the FCL on restricting the short circuit current was evaluated with initial current of 525 Amps and a power factor of 0.95. Figure 4 shows the current flow without the FCL connected in the circuit. The short circuit switch was closed at the arbitrary time of .04 seconds and the current increased sharply and then passed through the characteristic sub-transient period until it reached a steady state. At a time 0.4 seconds later the switch was opened and the current returned to the load-restricted value.

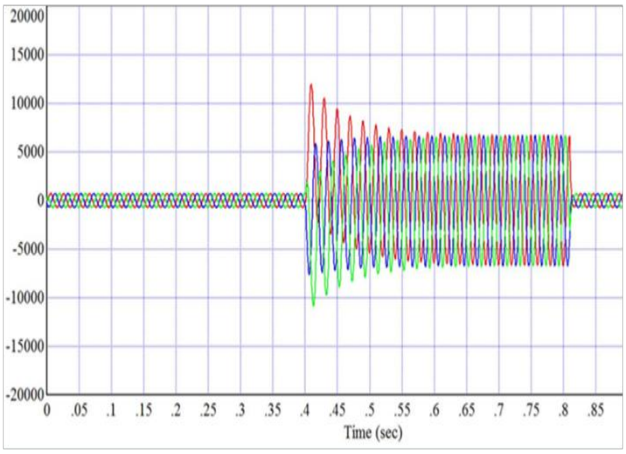

Figure 4. Short circuit current (Amps) without FCL. The three phases are shown in red, green and blue.

Figure 5 shows the short circuit current when the FCL in circuit, with the same initial values for current and power factor, with the short circuit condition effected over the same time period. The current limitation can be seen with the reduced initial peak current compared to results shown in Figure 4.

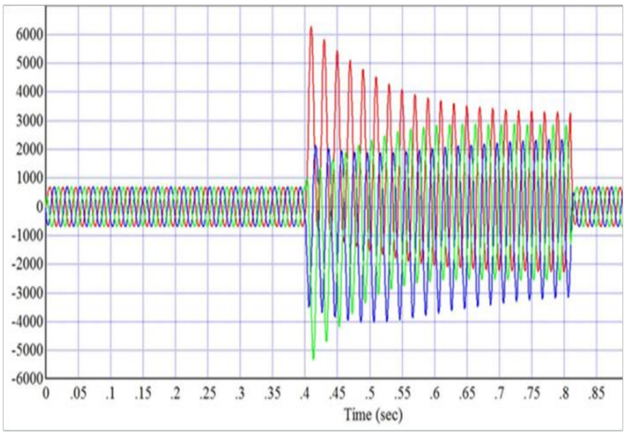

Figure 5. Short circuit current (Amps) with FCL connected

The sensitivity of the FCL to changes in power factor from 0.8 to 1.00 is illustrated by its effect on the percentage reduction in initial current shown in Figure 6.

The effect on the current limitation is shown subsequently in Figure 7. The power delivery advantage of the FCL over the air-cored CLR, over a range of nominal operating currents from 100 to 525 Amp (with power factors = 0.95), is shown in Figure 8.

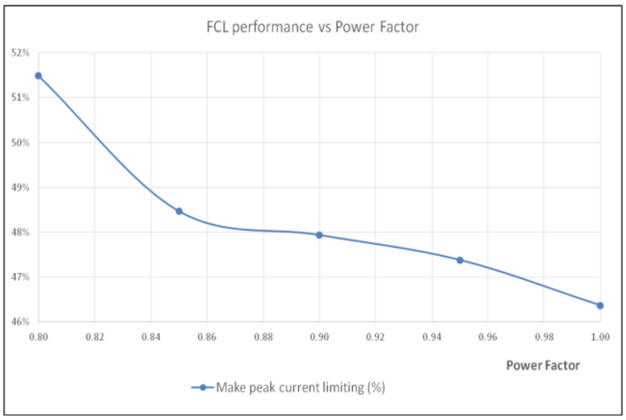

Figure 6. Effect of power factor on initial ('make') current limitation with the FCL connected

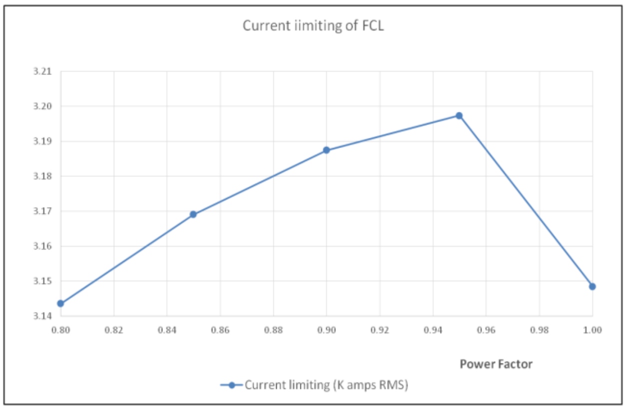

Figure 7. Effect of power factor on RMS 'break' short circuit current with the FCL connected

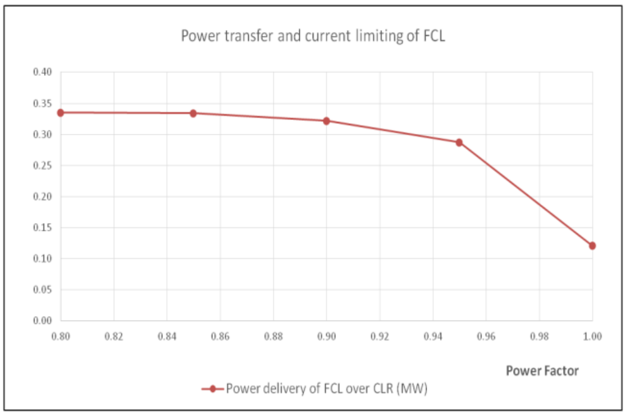

Figure 8. Power delivery advantage in MW of the FCL compared with an air-cored Current Limiting Reactor

THERMAL MANAGEMENT OF FCL

In order to evaluate the temperature rise caused by the dissipation of resistive losses in the FCL, calculations were performed at nominal current flow values of 100 to 525 Amps and for the extreme case of 800 Amps. The machine was specified to exceed H class insulation. The results are presented in Figure 9 below.

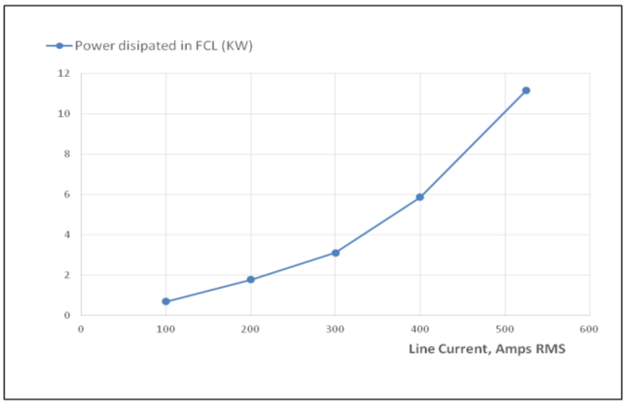

Figure 9. Power dissipated in the FCL due to resistive losses at various nominal non-fault current values

The incorporation of dry winding insulation using a commercial silicone elastomer Sylgard 160 [4], and natural air ventilation, the windings could withstand a steady state temperature of 200 C. An oil-immersed winding insulation design, by comparison, may allow for only a 100 C maximum operating temperature. It is estimated that an additional 20% of copper would have been required in the addition of further winding turns in the case of an oil based insulation system.

The FCL design incorporates the inductor windings in discrete distributed packages, each encapsulated with the Sylgard 160 elastomer insulation. The combination of the dry winding insulation specification and the distributed design of the inductors in the FCL structure has enabled a thermally efficient design to be realised without the requirement for forced (and powered) ventilation systems to be incorporated.

CONCLUSIONS

A 3-phase circuit model has been used to evaluate the performance of a permanent magnet biased FCL containing multiple, distributed saturated iron cores in an 11 kV system. The power delivery advantage has been shown in comparison with an air-cored CLR. The resistive losses have been calculated and it has been shown that a dry type silicone elastomeric winding insulation is suitable for this application. The current limitation capability has been calculated in comparison with no FCL and the performance of the FCL has been evaluated over a range of nominal non-faulted currents and power factors.

FUTURE WORK

3-port connection

Due to the flexible nature of the multiple, distribution inductor windings in the single FCL structure, it is possible to consider a 3-port connected FCL for a combined incomer connection and bus tie scenario.

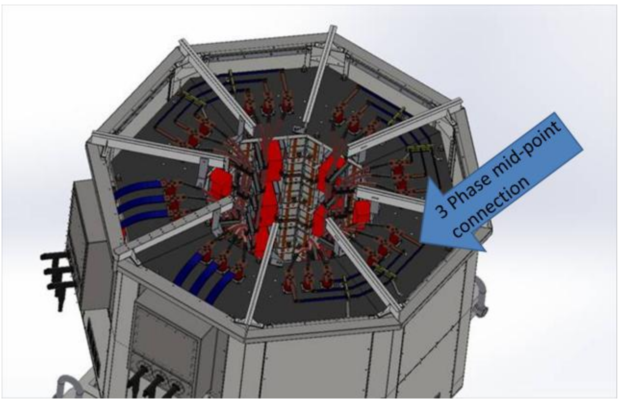

Figure 10. Illustration shows the mid-point winding connection in the FCL structure

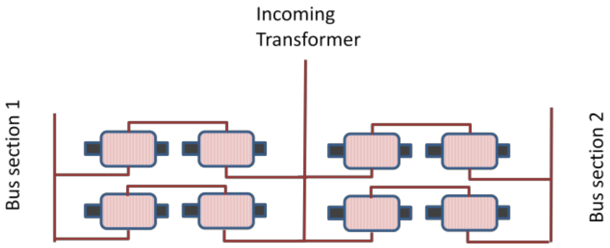

Figure 11. 3-port FCL configured as bus-tie centre fed by the incomer connection (per phase view)

Compared with a conventional 2-port connection, the 3-port configuration has been found to give an additional 10% of fault current limitation, with resistive losses in windings at around 40%. A programme of work will be undertaken to study in detail the 3-port configuration under a wide range of applications scenarios.

REFERENCES

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[4] Dow Corning Corporation, *Sylgard 160 silicone elastomer, Form No. 11-3179A-01*, Feb 17 2014