Analysis of the effects of asymmetric faults in three-phase superconducting inductive fault current limiters

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Abstract. Inductive fault current limiters of magnetic shielding type can be described in terms of the excursion in the plane defined by flux linked with primary and line current, and this methodology has been previously applied to single-phase devices. Practical applications, however, require three-phase limiters, which, for the sake of compactness, may be built by three legged cores, instead of three single phase units. This has the advantage of using well established methods of power transformers industry, but the performance of the devices depends on the type of fault, e.g. phase to ground or phase to phase. For instance, in a three legged core, a phase to ground fault affects healthy phases, and these are the most frequent faults in distribution grids, where such systems are envisaged. The effects of asymmetric faults are analysed in this paper, by means of measured excursions in the linked flux-current plane.

1. Introduction

Most developed topology of superconducting fault current limiters (SFCL) is the resistive one, due to its compactness. Nevertheless, air core reactors are usually added in order to decrease the amount of costly high temperature superconducting (HTS) tape material required to obtain the desired limiting impedance, and thus relatively large installations may result, see e.g. ECCOFLOW project [1]. Inductive SFCLs of the magnetic shielding type are intrinsically less compact, due to the need of a ferromagnetic circuit. Yet, they require only moderate amount of superconducting tape and they are robust against hot-spot formation, which makes them attractive in medium voltage grids with e.g. dispersed generation. After the successful demonstration of a magnetic shielding SFCL by ABB [2], nearly no projects have been developed, due to the need to build relatively large HTS bulk cylinders for secondaries. Recently, some projects appeared where bulk tubes are replaced by BSCCO [3] or coated conductor [4] tapes, which obviate that problem.

Previous work included developing a modeling methodology based on predicting the excursion of the operating point of the SFCL in the linked flux – current (ψ – i) plane [3]. This was first applied to single-phase devices, and to a three-phase limiter in the present work. These are preliminary studies for the development of a medium voltage device for a live grid in Portugal. One concern for utilities regarding the acceptance of SFCLs is their performance under asymmetric faults. Taking this into account, the limiter is tested under several types of short-circuits.
2. Prototype, experimental apparatus and methodology

The SFCL is built by a three legged iron core whose dimensions are shown in figure 1. The device, shown in figure 2, allows choosing 20, 60 or 80 turns in the primaries. These are placed on the bottom of each leg, while dewars with HTS rings made of single turns of Bi-2223 tape are placed on top. Different number of rings may be used (1, 2 or 3). Bi-2223 tape was supplied by Innost, and its critical current is 90 A. The test grid is shown in figure 3 where switches simulate faults, namely phase to ground, phase to phase and phase-phase to ground faults. Line impedances are built by 400 W/1 Ω resistors. Phase to ground voltage in the experiments was 80 V peak.

3. Experimental results

In each experiment, prospective currents were measured, in order to evaluate limitation. The excursion in \( \psi - i \) plane was also plotted. Different numbers of rings were used in the secondaries. The number of turns in the primaries, in the following experiments, was always 20.

3.1. Phase to ground fault

Phase B was short-circuited to ground. Prospective and limited currents are shown in figure 4, and \( \psi - i \) excursion in figure 5. “Healthy” phase A is shown in figure 6. Each secondary had two turns.

3.2. Phase to phase fault

Phase B and phase C were short-circuited in this test. Prospective and limited currents are shown in figure 7, while figure 8 shows \( \psi - i \) excursion. One turn secondaries were used.

3.3. Phase-phase to ground fault

Phases A and B were short-circuited to ground in this test. Currents are shown in figure 9, and \( \psi - i \) excursion in figure 10. “Healthy” phase C is shown in figure 11. Three turns secondaries were used.
4. Conclusions
Taking into account the type of load connection (ungrounded wye) asymmetric faults will obviously always affect current in healthy ones. Nevertheless, when magnetic flux penetrates the core, it links also with the latter, and this has to be taken into account in the models, as different types of faults represent distinct magnetic paths in the core. This can be eliminated by using magnetic circuits of shell type. Limitation efficiency depends on the type of fault, as different electric and magnetic circuits are established (most effective limitation happens with only one turn in secondary). Even slight unbalances in the limiter are reflected in the hysteresis loops, see e.g. last fault. Future work includes designing an SFCL with shell type core as well as analysing grounded unbalanced loads.

Figure 4. Prospective currents (a) and limited currents (b) on a phase to ground fault.

Figure 5. Excursion in the $\psi - i$ planes for phase A (a), phase B (b) and phase C (c).

Figure 6. Evolution of linked flux and current in phase A, namely $\psi_A$ and $i_A$, during the fault.

Figure 7. Prospective currents (a) and limited currents (b) on a phase to phase fault.
Figure 8. Excursion in the $\psi - i$ planes for phase A (a), phase B (b) and phase C (c).

Figure 9. Prospective currents (a) and limited currents (b) on a phase-phase to ground fault.

Figure 10. Excursion in the $\psi - i$ planes for phase A (a), phase B (b) and phase C (c).

Figure 11. Evolution of linked flux and current in phase C, namely $\psi_C$ and $i_C$, during the fault.

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References
[1] Hobl A, Goldacker W, Dutoit B, Martini L, Petermann A and Tixador P 2013 IEEE Trans. App. Supercond. 23 5601804
[2] Paul W, Lakner M, Rhyner J, Unternährer P, Baumann T, Chen M, Widenhorn L and Guérig A 1997 Supercond. Sci. Tech. 10 914-8
[3] Arsenio P, Silva T, Vilhena N, Pina J M and Pronto A 2013 IEEE Trans. App. Supercond. 23 5601004
[4] Usoskin A, Mumford F, Dietrich R, Handaze A, Prause B, Rutt A and Schlenga K 2009 IEEE Trans. App. Supercond. 19 1859-62