Field-Circuit Coupling Applied to Inductive Fault Current Limiters

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Abstract: Fault Current Limiters (FCLs) are expected to play an important role in the protection of future power systems due to the rising levels of the short-circuit currents. The inductive FCLs, comprising magnetic cores and one or more dc and ac windings, are particularly interesting because they inherently react on the fault. The so-called open-core FCL configuration ([1]) employs only one magnetic core for both directions of the line current, reducing significantly the amount of magnetic material. However, due to its specific flux distribution during operation, the derivation of the accurate analytical model is rather difficult. This paper presents the simulation model of the FCL, created in Comsol Multiphysics. It describes the implementation of a coupling technique for the magnetic field and the exciting electrical current applied to the two-dimensional transient model. The model developed is a valuable tool for the modeling and optimization of the inductive FCLs. Lab experiments are performed in order to verify the FEM model. The comparison of the results is presented.

Keywords: magnetic field, electrical circuit, finite elements, inductance, fault-current limiter.

1 Introduction

The ever increasing demand for power delivery leads to the installation of the new generating units and new interconnections between the power grids. In the case of a fault, such as a short circuit (see in Fig.1), the amount of power captured by the short circuit is enlarged and, therefore, the peak values of the fault currents are increased. It is expected that the physical limits of the current protection equipment (such as the Circuit Breakers, CBs) are going to be reached in the near future. Therefore new ways of protection of the power grids are required. This makes the use of the Fault Current Limiters (FCLs) inevitable [2].

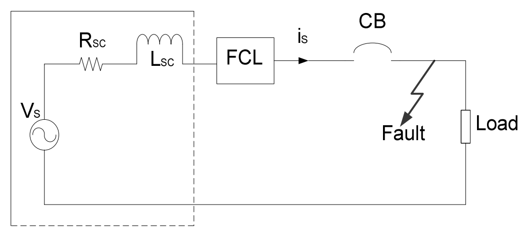

Figure 1: Single-phase equivalent circuit

The installations of the distributed generators (DGs) in different locations in the power grid increases the level of the fault currents to even higher values. The contribution of DGs to the fault can be seen in Fig.2. The DGs installed in the $feeder2$ contribute to the system fault current flowing toward the faulted place in the $feeder1$. In this situation both $CB1$ and $CB2$ would be tripped and the DGs would be disconnected from the grid even though the fault source is in the $feeder1$.

FCLs are expected to provide an uninterrupted flow of the limited fault current (so called follow current) until the fault is cleared or interrupted by CBs. The duration of the fault limiting period is very important for the coordination of the other protective equipment in the power system. Coordination provides possibility for protective units to determine the exact location of the fault source or to burn the intermittent faults into permanent one in order to determine their location. This could, for instance, prevent undesired disconnection of the unfaulted DGs from the power grid and, at the same time, interruption of the faulted one.

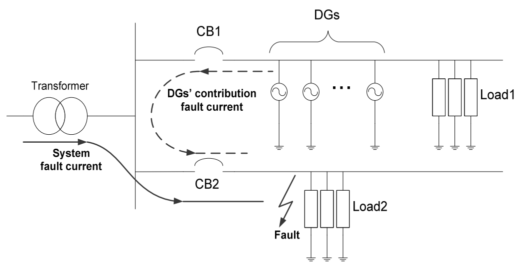

Figure 2: Example of the DG contribution to the fault current

A number of different FCL configurations have been proposed so far in the literature [3]. They implement one of the two limiting principles: insertion of a resistive or inductive impedance in series with the line, upon the fault inception. The most important task of the FCL is to restrain the first fault current peak, since it causes large mechanical stress to all parts of the power system. The inductive FCL based on the core saturation effect are particulary interesting due to the fact that they do not have any reaction delay. They inherently react on the fault, requiring no control circuit; hence, the first fault current peak is completely restrained.

Several configurations of the inductive core-saturation FCL have been proposed [1]-[8]. The so-called open-core FCL type ([1]) is particularly interesting because it uses only one magnetic core for the full operation (limiting of the fault current in the both directions).

Due to its specific way of operation (described later) it is rather difficult to derive the valid analytical model which would enable modeling and design of the device.

The objective of this paper is to derive the model of the open-core FCL in Comsol Multiphysics. The model is expected to provide the possibility of accurate and reliable design not only of the open-core FCL but also of the other inductive FCLs' types and power transformers. The implementation of a coupling technique for magnetic field and the exciting electrical circuit is described. In order to verify the Comsol Multiphysics model, a lab experiment is performed. The paper presents the comparison of the results.

The following sections describes the main principle of the FCLs' operation.

2 Inductive Fault Current Limiters

2.1 Principle of Operation

The FCL is required to have no influence on the nominal line current, i.e. to be 'invisible' for the power line during the nominal regime, and to introduce the high impedance during the fault period to successfully restrain the fault current. The inductive FCLs with the magnetic cores use the saturation effect of the BH hysteresis curve in order to provide the appropriate impedance value during both the pre-fault and the fault regimes.

The value of the core permeability μ is very small in a saturation, approximately equal to air permeability μ_0, and the corresponding inductance value of the ac winding is small (1). If therefore the core is saturated during the nominal regime, its influence on the line current will be negligible, i.e.,

$$L_{FCL} = \mu_r \mu_0 \frac{N_{ac}^2 A_c}{l}, \qquad (1)$$

where L_{FCL} is the inductance of the FCL, μ_r and μ_0 the relative permeability of the core and the permeability of air, respectively, N_{ac} the number of ac turns, A_c the cross-section of the core and l the mean flux path length.

As the core is taken back to the linear regime by the fault current, the permeability value increases and so the inductance value. Since the impedance of the FCL is placed in series with the line (see in Fig.1), the fault current is automatically restrained.

The following section describes the operation principle of an open-core FCL.

2.2 The Open-core Inductive FCL Configuration

The open-core configuration is presented in Fig.3. It comprises a single magnetic core, one dc and one ac winding. The dc winding 'sees' the closed core, i.e. the dc flux path closes only through the magnetic core; it drives the core to deep saturation. The dc BH working point is shown in Fig.4. The ac winding, which carries the line current, is wrapped around both vertical legs of the core. In each half-cycle, the ac flux in one leg counteracts the dc flux and takes that leg closer to the linear regime, while it aligns the dc flux in another leg and drives it to even deeper saturation. During the nominal regime, the ac flux is not capable of taking any of the legs out of saturation, as shown in Fig.4. This provides low value of the FCL impedance and, thus, no limiting effect. Upon the fault inception, the rising fault current counteracts completely the dc magneto-motive force and takes alternately one of the legs out of the saturation, causing an increase of the ac winding inductance and limitation of the short-circuit current.

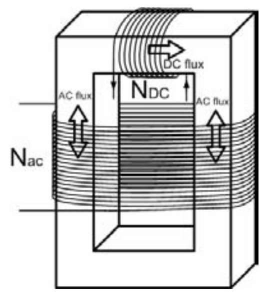

Figure 3: The configuration of the open-core inductive FCL - comprising a magnetic core, a dc and an ac windings

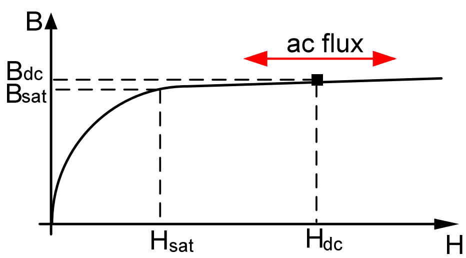

Figure 4: The BH curve - dc working point and the ac flux change during the nominal regime

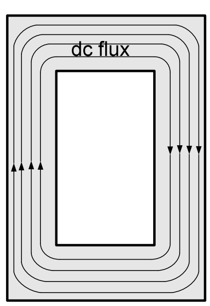

Figure 5: The dc flux distribution

The ac flux lines are shown in Fig.6. As can be seen, the ac flux flows partially through the magnetic core and partially through surrounding air, i.e. the ac winding 'sees' the open core configuration. The flux plot corresponds to the situation in the one half-cycle, whereas the direction of the ac flux lines is opposite in the following half-cycle.

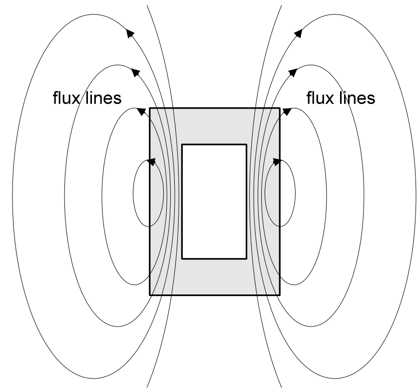

Figure 6: The ac flux path in one half cycle

On the basis of the magnetic flux distribution (Fig.6), it can be concluded that the open-core can be modeled as a solenoid. The simplified Ordinary Differential Equation (ODE) model for the solenoid of the length ℓ, the cross-section A, the number of turns N_{ac} around ferromagnetic core with permeability μ, given $\psi(t = 0) = \psi_0$, is as follows:

$$\frac{d}{dt}(L\,I) + R\,I = V(t) \tag{2}$$

$$\psi = L\,I \Leftrightarrow I = \frac{\psi}{L(\psi)} \tag{3}$$

$$\frac{d\psi}{dt} + \frac{R}{L(\psi)}\psi = V(t), \tag{4}$$

where L is the solenoid inductance, R the winding resistance, ψ the magnetic flux and V the voltage induced across the winding as consequence of the flowing current through the solenoid.

The BH curve of the core material is used to find μ as a function of ψ.

For a long solenoid, the inductance L can be calculated from (1). The long solenoid assumption means that the length of the core of the solenoid l is much larger than the diameter of the core. Such an assumption cannot be made for the studied case, and the mentioned equations do not give the correct result.

Being unable to derive the correct expression for the inductance L as a function of ψ for the analysis purpose of the open-core FCL, the finite element (FE) model of the FCL has been created in Comsol Multiphysics. As the first step, a lab experiment is performed in order to get the background for validation of the FCL FE model. The results obtained in Comsol Multiphysics, where the model has the same system characteristics as those from the experiment, are compared with lab results.

3 Experimental Results

To verify the data obtained through the modeling in Comsol Multiphysics, the lab experiment with the open-core FCL configuration is done. The experimental electrical circuit is shown in Fig.7. The triggering circuit enables manual inception of the fault in desired moment during the power voltage period.

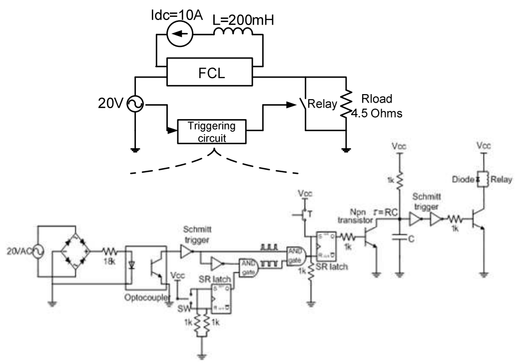

Figure 7: The electrical circuit used in the open-core FCL experiment

The characteristics of the electrical circuit and current values are presented in Table 1.

Parameter	Value
Voltage value, V_{line}	$28V$
Load resistance, R_{load}	4.5Ω
Nominal current, I_{nom}	$5A$
Limited fault current, I_{lim}	$10A$
Unlimited fault current, I_{fault}	$28A$

Table 1: Electrical circuit parameters

The magnetic core used in the experiment (available in that moment in the lab) is shown in Fig.8, with designated ac and dc windings. The parameters of the FCL are given in Table 2.

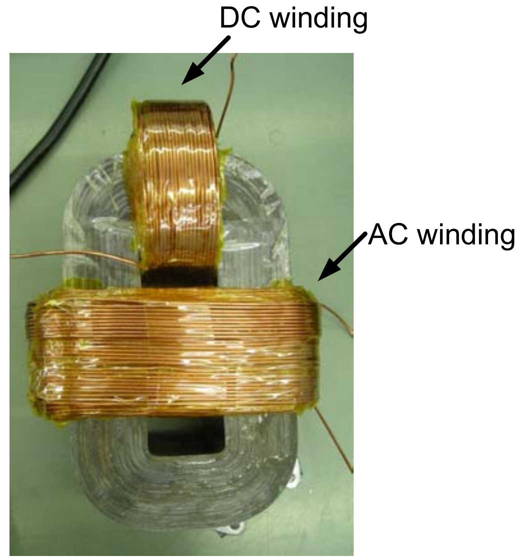

Figure 8: The core and the windings used in the open-core lab experiment

Parameter	Value
Number of ac turns, N_{ac}	200
Number of dc turns, N_{dc}	250
DC current value, I_{dc}	$10A$
Cross section of the core A_c	$12.625cm^2$
Mean ac flux path length, l_{ac}	$15.3cm$
Mean dc flux path length, l_{dc}	$30.2cm$
Winding resistance, R_{wind}	1.2Ω

Table 2: FCL design Parameters

Fig.9 presents the waveform of the measured line current for the pre-fault and the fault state. It can be seen that the current is limited up to 10A, where the fault is triggered in $5ms$ relatively to the zero-crossing of the voltage.

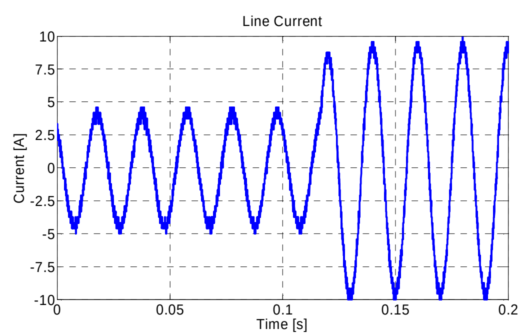

Figure 9: Measured waveform of the limited current for pre-fault and fault period

The obtained current waveform is sufficient for validation of the Comsol Multiphysics FCL model.

The following section presents the model of the FCL, where the magnetic field - electrical circuit coupling technique is explained.

4 Magnetic Field-Electrical Circuit Coupling

The developed mathematical model consists of a partial differential equation (PDE) for the magnetic field, generated by the FCL, coupled with a circuit relation for the current in the ac coil. Both the dc and the ac coils are modeled as multi-turn windings implying that the individual turns are homogenized; the appearance of a skin effect is avoided by setting the electrical conductivity in the coils equal to zero. The physics of the electric and magnetic effects are coupled by the magnetically induced voltage in the ac coil that counteracts its source. More specifically, the following PDE for the z-component of the magnetic vector potential is applied

$$-\frac{\partial}{\partial x}\left(\nu\,\frac{\partial A_z}{\partial x}\right)-\frac{\partial}{\partial y}\left(\nu\,\frac{\partial A_z}{\partial y}\right)=J_z\,, \quad (5)$$

where $J_z = \pm N_{ac}\frac{I(t)}{S}$ is the current density in the coils and N_{ac} and S the number of coil turns and the cross-sectional area, respectively. The circuit relation for the current in the ac coil is an algebraic relation that ensures that at all times the sum of resistive and induced voltage V_{ind} is equal to a given, externally applied voltage, i.e.,

$$R\,I + V_{ind} = V_{applied}\,. \quad (6)$$

In this relation V_{ind} can be either computed as N_{ac} times the time variation of the magnetic flux through the cross-section S of the core in the xz-plane at $y = 0$, i.e.,

$$V_{ind} = N_{ac}\frac{d}{dt}\int_S B_y\,d\Omega\,, \quad (7)$$

or through the average induced voltage in the ac winding. Denoting by $S_{cl,1}$ and $S_{cl,2}$ the left and right cross-section of the ac winding in xy-plane, the latter alternative gives

$$V_{ind} = V_{ind,1} - V_{ind,2}\,, \quad (8)$$

where the minus takes the direction of the current into account and where

$$V_{ind,i} = \frac{N_{ac}\,\ell_z}{S_{cl,i}}\int_{S_{cl,i}} E_z\,d\Omega. \quad (9)$$

The fault is modeled by allowing the value of $R(t)$ to suddenly drop to a very low value at a particular time instance.

The model is realized by using the perpendicular current quasi static application mode. The circuit relation is implemented using the ordinary differential setting. The PDE and ODE are coupled using an integrating coupling variable V_{ind}, representing the induced voltage.

5 Results

In this section the representative numerical results are presented. In order to make the experimental and the simulation results comparable, the characteristics of the physical setup (see in Table 1 and Table 2) are used for Comsol model.

Fig.10 shows the current waveforms with and without limiting effect.

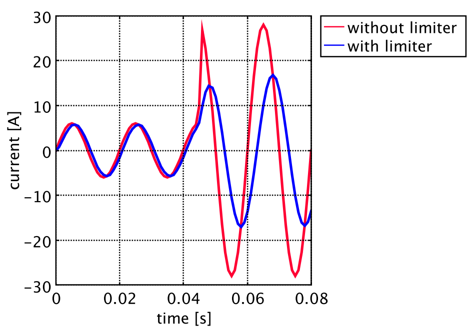

Figure 10: The waveforms of the line current, with and without FCL placed in line

It can be seen that the fault current is limited to the value of $17A$. In the experiment, this value is equal to $10A$ (see in Fig.9). The difference in the results implies that the $2D$ model is not sufficiently accurate. Namely, when creating the $2D$ model, it is assumed that the $z-$dimension of the model is infinitely long. Since this assumption cannot be applied to the FCL model, the $z-$dimension is manually adjusted to the real value (equal to that of the experimental core). However, the model is still incomplete, since the front and back faces are not resembling those in the real situation (front and back parts of the windings are missing). Thus, the development of the full $3D$ model is necessary, and is appointed as the next step in the research.

Fig.11 shows the time change of the magnetic flux density B. It can be seen that the left and right core legs are driven alternatively in and out of saturation, upon the fault inception. Thus, at any moment one of the legs is de-saturated, restraining the fault current.

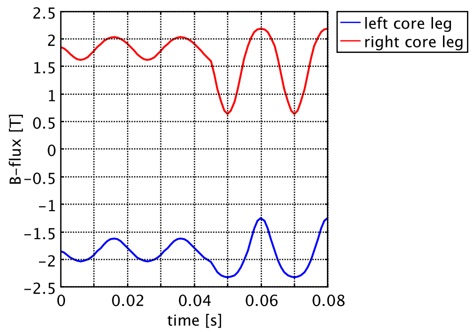

Figure 11: Magnetic flux waveform

Fig.12 presents how the induced voltage increases when the fault occurs. This is consequence not only of the rising current but also of the increasing FCL's impedance. The induced voltage, as already mentioned, is used as a link between the magnetic field and the electrical circuit, providing possibility to model the change of the FCL's impedance. In this way, the use of any mathematical (analytical) expression for the L_{FCL} is avoided. As stated in Section 2.2, these analytical expressions do not give accurate results.

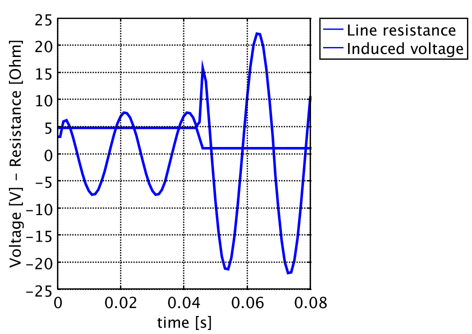

Figure 12: Induced voltage waveform

The asymmetry in the flux paths, on which the working principle is based, is further illustrated in Fig.13 and Fig.14. It can be seen that the core right leg is driven out of saturation, where the magnetic field is generated outside of the core. These results confirm the situation presented in Fig.6, where the ac flux flows through surrounding air.

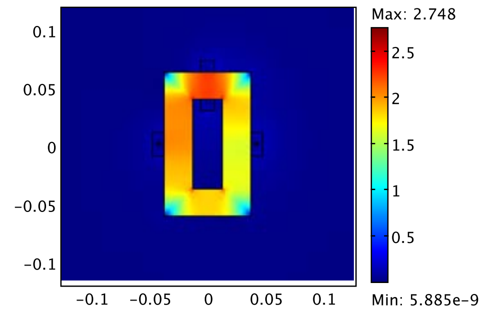

Figure 13: Snapshot of the magnitude of the magnetic flux density

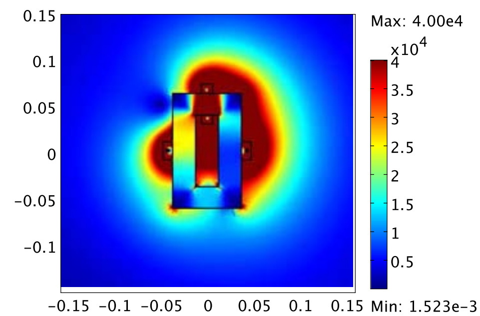

Figure 14: Snapshot of the magnitude of the magnetic field

The results presented in this section show that the created two-dimensional model is not able to capture the three-dimensional aspects of the inductive FCL. It motivates the extension of this work to a three dimensional model.

6 Conclusion

In work a magnetic field - electrical circuit coupling technique for the modeling of an inductive Fault Current Limiter is successfully developed. The model is a valuable tool for the modeling and optimization of the inductive FCLs. In model, the induced voltage is used to link the magnetic field to the electrical circuit, providing the expected change of the FCL's impedance upon the fault inception. In this way, the use of analytical expression for the L_{FCL} is avoided.

The comparison of the experimental and simulation results (see Fig.9 and Fig.10) shows that the $2D$ model is not accurate enough. The development of the full $3D$ model is necessary, and is going to be the next step in this research.

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