Magnetic Fault Current Limiter Operation Analysis Using 3-Dimentional Finite Element Method

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Abstract— Daily increasing number of consumers and power network expansion leads to an increase in short circuit current, which makes the need of short circuit current limiter to be of great importance. One type of fault current limiters is passive magnetic which consists of iron core (magnetic shield) and magnet that is used in low voltage distribution networks. Their major features are high speed, consecutive operation capability and not meeting the need of fault diagnosis circuit and command circuit for limitation, simultaneous start of current limitation and fault occurrence. In this paper, magnetic fault current limiter is simulated using the Finite Element Method with COMSOL software in a 3-dimantional environment and simulation results are compared with laboratorial results of 2kVA passive FCL in Kanazawa University.

Keywords- fault current limiter; saturated core limiter; finite element analysis; COMSOL

I. Introduction

Network connections are becoming more complicated and broader to promote reliability especially in city centers which leads to increase of short circuit probability. Current limiter equipments are applied for protection against over current and short circuit current. The advantage of fault current limiters (FCL) against fuses in power quality improvement is providing source voltage in short circuit condition, more immediate preventing of sudden current increase and consequently sudden voltage variation decrease which is vital for some consumers. Each FCL should have features such as limitation of fault current first peak, low impedance and low power loss in normal conditions (without short circuit), not harmonic making, automatic operation without needing control and complicated sensors, few volume, gradual and continuous variation from normal state to error state and vice versa.

Applied methods in limitation of fault current consist of using switches, resonance circuits, fuse and ultra conductors. Using switches in limitation of fault current is usually in transmission system and requires fault diagnosis sensor [1]. Resonance limiters are usually used accompanying thyristor and require sensor and digital controller which decreases system’s reliability [2, 3]. Fuse limiters are used with parallel resistor and by disappearance of the fuse, current will pass through the resistor [1]. For manufacturing limiters, Superconductive materials are also used which have the ability of being applied in high voltage and high power but their cooling and maintenance cost is high [4, 5, 6 and 7].

The operation of a passive magnetic fault current limiter which consists of iron core (magnetic sheet) and magnet in low voltage distribution network is studied in this paper which is investigated in several references [8, 9, and 10]. The mentioned limiter is not usable in high voltage and high power because of limited low capacity of magnet in producing bias magnetic flux in iron core while its topology and structure need optimization. In this paper, a 2KVA passive FCL manufactured in Kanazawa University is considered and agents that lead to operation restriction and efficiency reduction are examined by performing practical examinations.

II. TOPOLOGY AND OPERATING PRINCIPLE OF MAGNETIC FCL

FCL is placed in series in the circuit, like Fig. 1. In Fig. 2, mode of operation is shown. In normal state when the current level is not more than the rated value, voltage drop on limiter is negligible, but if fault current occurs, limiter’s impedance will increase instantaneously and limits the current.

Limiter with parallel structure is illustrated in Fig. 3 and 4. Magnet installed in center leg is for producing a strong magnetic field in iron core such that in normal state limiter core is in magnetic saturation. Two lateral stalks are applied alternatively in positive and negative cycles to restrict fault current. In normal conditions, magnetic field on lateral coil is not strong enough for the iron core to remain in saturation; therefore the limiter will be like a coil with void core (air) the corresponding impedance of which will be subminiature. However, at the moment of fault current incidence, lateral stalks will periodically unsaturate in positive and negative half-cycles and will pose a high impedance in the current path which impedes the escalation of fault current. If the fault current increases continuously and reaches a very high level, the iron core may go to reverse saturation and the limiter loses its limiting capability [8].
current is higher than $I_{\text{link}}$, voltage drop on the limiter increases abruptly.

Fig. 5 and 6 demonstrate expected waveforms of current and voltage drop on the limiter. In normal conditions, system current is lower than line current, $I_{\text{link}}$, boundary level. However, currents higher than $I_{\text{link}}$ lead to core unsaturation and consequently higher impedance which results in line current decrement. As shown in fig.6, in $\theta_k < \theta < \pi - \theta_k$, where the
III. 2 KVA DESIGN AND TEST OF CORE-TYPE FCL MAGNETIC PRODUCT CLASS

Dimension and structure of device magnetic core is demonstrated in Fig.3 and magnet and magnetic shield characteristics are given in Table I. Number of turns of coils on each lateral stalk is 150 and on each core stalk a search coil with 10 turns is installed. The mentioned device is designed to limit the current within 10(A) in distribution system with low voltage of 100(V).

IV. FINITE ELEMENT ANALYSIS

COMSOL finite element software environment provides an appropriate tool named Multiphysics which is useful for such equipment whose operations need simultaneous consideration of various physics such as electrical, thermal and magnetic [11]. In other words, while it is possible to simulate physical dimensions of studied device, there exists the possibility of defining electrical circuit having source, load, impedance and switch in system’s magnetic model and unlike other finite element software programs, separate generation of electrical waveform is not required.

V. COMPARISON OF SIMULATION RESULTS WITH TEST RESULTS

The manufactured device in 100(V), 100(Hz) low voltage network is put in the circuit according to Fig.3 and the limiter is examined by changing the resistance of RL.

Fig.8 illustrates the magnetic FCL three-dimensional model. Fig.9 represents the distribution of magnetic flux density in the FCL core before fault occurrence. As can be seen on the figure, in the normal condition lateral stalks are in saturation state and the value of limiter Inductance is very low and does not have much impact on circuit current.

### TABLE I

<table>
<thead>
<tr>
<th>Properties of magnet materials (Nd-Fe-B) and core</th>
<th>( B_r )</th>
<th>( B_k )</th>
<th>( \mu_{ru} )</th>
<th>( \mu_{rs} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic flux density of magnet</td>
<td>1.29 [T]</td>
<td>1.50 [T]</td>
<td>4800</td>
<td>100</td>
</tr>
<tr>
<td>Relative unsaturated permeability coefficient</td>
<td>( B_k )</td>
<td>( \mu_{ru} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative saturated permeability coefficient</td>
<td>( \mu_{rs} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saturation magnetic flux density of core</td>
<td>( \mu_{ru} )</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In case an error occurred, according to the increase of circuit current, AC coils current on lateral stalks will augment and the result flux causes one of the lateral stalks to unsaturate as seen in Fig.10.

Figs. 11, 12, 13 and 14 illustrate waveform of the limiter current and voltage drop in normal and fault condition, respectively. In the normal condition when the line current is less than 13.3 (A), the voltage drop on limiter coils is very low, such that the line current will not be affected by the limiter which is in series with the voltage source and load. On the other hand, when the current is more than 13.3 (A), the voltage drop on the limiter will increase and will impede sudden augmentation of the current, and also in comparison with the state of not having limiter it will debilitate the current.

As it is shown in Fig.13, in fault current positive half cycle, the magnetic flux produced by coils on the left stalk disaccord with the magnetic flux produced by the magnet and the left stalk unsaturates leading the increase of the corresponding voltage drop \( V_{FCL+} \), while the right stalk goes to a deeper saturation. Similarly, in fault current negative half cycle, the right stalk unsaturates and the voltage drop \( V_{FCL-} \) increases. \( V_{FCL+} \) and \( V_{FCL-} \) measured waveforms correspond with theoretical analysis shown in Figs.5 and 6.

Fig.14 demonstrates the fault current before and after limitation. According to Fig.14, the saturated core limiter limits the 160(A) fault current into about 40(A) that is 75% limitation and the results obtained match with test results in Fig.13.

Fault current limiting capability is defined by \( \lambda \) as follows Eq. (1).

\[
\lambda = \frac{I_{\text{nonfcl}}}{I_{\text{withfcl}}} \tag{1}
\]

Where \( I_{\text{nonfcl}} \) is the current without FCL and \( I_{\text{withfcl}} \) is the line current when the limiter exists in the circuit.

Fig.15 displays the FCL voltage drop according to corresponding \( \lambda \) limiting ratio which is derived from practical results and simulation results respectively in which the conversion from low impedance state to high is observed about 14(A) and is approximately equal to the designed value. Fault current limitation ratio also reaches 15(A) which corresponds to the load current 22(A) and shows the device efficiency in fault current attenuation.
Fig. 9: Flux density distribution before fault occurrence (3-dimensional)

Time = 0.083
Surface: Magnetic flux density norm (T)

Fig. 10: Flux density distribution after fault occurrence

Fig. 11: Voltage and current waveforms in normal conditions from practical test

Fig. 12: Voltage and current waveforms in normal conditions from simulation

Fig. 13: Voltage and current waveforms in fault current conditions from practical test
VI. CONCLUSIONS

This paper investigates the operation of a magnetic FCL, core saturation manner and the role of magnetic field in limiting. Simulations are done using COMSOL software and a finite elements model. Results are compared with laboratory test results which shows flux density distribution manner in critical moments of limiter operation and development of proper inductance for limitation.

REFERENCES


