Design of Nonsuperconducting Inductive Fault Current Limiter

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Abstract: **One type inductive fault current limiter has been explained in this paper. Its principals of operation and method for calculation have been proposed. Finite element method (FEM) simulation of fault current limiter has been presented. Comparison between calculation and result of measurements has been presented.**

Keywords: ***inductive fault current limiters, finite element method***

I. Introduction

The growth of today's utility systems is causing fault currents to exceed the ampere rating of installed circuit breakers and other equipment at existing stations [6,8]. The connection of new and larger generating stations and strengthening of the distribution system to meet the growth in demand, the magnitude of the fault current has also grown [3,4]. The mathematical forecasts indicate that this trend will continue at an accelerated rate [2,7,10,11]. In order to correct this problem, a fault current limiter (FCL) can be used [1,9]. A lot of realizations of FCL are known [8,11]. One of them is inductive fault current limiter (iFCL).

II. Clasification

There are different classifications of known FCL. According to CIGRE WG A3.10, FCL are passive or active depending on the ways of their equivalent impedance changing. Depending on the type of used materials, FCL are two types - FCL made of conventional materials and FCL using superconducting materials. Depending on the equivalent impedance, the FCL are two types – inductive type and resistive type. Of course, there are other types of FCL such as semiconductor FCL - they possess nonlinear inductances or resistances and power semiconductors ensuring appropriate operation of the device.

For each of these types FCL is inherited one or other advantage or disadvantage [4,5,6].

III. Principle of Operation

The iFCL has two operation modes – on standby –waiting for fault current, second one - limitation mode. In standby mode iFCL non affect to the network. In limitation mode the device significantly increase his impedance and limit the current. The iFCL use non-linear depending L = f (μ) characteristic. The value of the magnetic induction and the magnetic permeability has a maximum extreme. The operating point is at maximum value of μ in limitation mode.

A. *Known Solution of iFCL*

In order to ensure a low value of μ in a standby mode a part of manufacturer of iFCL keep core saturated [3]. They use superconductive materials for get this done [2]. These devices are type 1 iFCL (Fig1).

In this paper has been reviewed limiter type 2. In standby mode the device is not saturated. For his manufacture are used conventional materials.

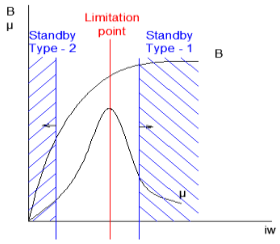

Fig. 1. Principal of limitation on iFCL

B. Proposal Solution

Control coil is connected to short circuit by switch S, on standby mode fig.1 [4]; Magnetic flux density is low and specific magnetic permeability has a minimum value. Reactance in this mode is negligible.

When fault current appears the control coil is being opened by commutating element. The magnetic flux density is being increased and the specific magnetic permeability is being increased too. In this way inductance is being increased and it limits fault current to acceptable value. Schematic of test iFCL is shown in fig.2.

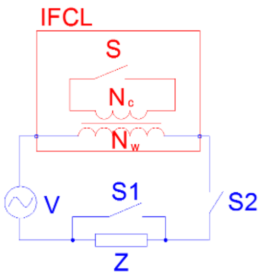

Fig. 2. Principle of operation on iFCL

In accordance with the law of full current applied to the magnetic circuit, the equivalent inductance of the coil is (1)

$$L = \mu_0 \mu_r \frac{w_1^2 S_a}{l_a + \delta \mu_r} \qquad (1)$$

Where S_a is the cross-section of the core; l_a - Average length of the magnetic line; δ - air gap; μ_0 - magnetic permeability of vacuum; μ_r - specific magnetic permeability. The variation of equivalent reactance was due to change of specific magnetic permeability.

IV. Design of Inductive Fault Current Limiter

Main voltage supply U_n, normal current of short circuit, inductance of iFCL at limitation mode Lo and parameters of the switch are set. At the designing of the magnetic circuit dissipation of magnetic flows are neglected. The engineering design of inductive iFCL includes the following steps:

A. Define the Maximum Value of Magnetic Flux Dentisy – Bmax;

Depending on the parameters of used electrical steel the values of the maximum magnetic flux density are selected and the magnetic intensity too. The main consideration is that at the limitation mode the magnetic permeability μ must have a maximum value.

B. Geometric Size of IFCL

Dimensions of the core - Sa, la, δ and the number of coil turns of the main coil w_1 are selected by (2):

$$w_1 = \sqrt{\frac{l_a + \delta \mu_r}{\mu_o \mu_r S_a} L_o} \qquad S_a = \frac{U_n}{4{,}44\, f w_p B_{m,1}} \qquad (2)$$

C. Design of main coil

The main coil is sized as taking into account parameters of using switch S (3):

$$w_2 = \frac{w_1}{n} \frac{I_{2S}}{I_{kc}} = w_1 \frac{U_{2S}}{U_n} \qquad (3)$$

where n is turns of control coil.

D. Define magnetic flux density and inductance

Magnetic flux density and inductance are defined by (4) in standby mode

$$B_{m,1} = \frac{2{,}55 I_{kc}}{4{,}44\, f S_a} \frac{l_a}{l_a + \delta \mu_r} z_{20} \left(\frac{w_1}{w_2} \right)^2 \qquad (4)$$

where z20 is all resistance on main coil,

$$z_{20} = \sqrt{(R_2 + R_{2S})^2 + (X_2 + X_{2S})^2}$$

R_2, X_2, R_{2S}, X_{2S} are active resistance and reactance on control coil and switch. Maximum value of magnetic flux density has to be less than 0.1T. If the magnetic flux density is higher the geometric sizes have to be corrected.

E. Define Overheating and Losses

Depending on construction of iFCL are created equivalent circuit which consist of heat resistances of the main coil, the control coil and the core. By this circuit is calculated heating of coil in standby mode.

F. Define Time for Turn off

This time has to satisfy of two contradictory conditions. Time has to be less than time of achievment maximum value of short current and to limit current of dinamic and termal satbility. In that time iFCL has to wait sensors in the relay protection to detect fault current. This detection is neccesary for main signal to open the circuit braker. Investigation about turn-off time and using of different commutation switches for control coil are presented in [12]

V. Modeling of Fault Current Limiter by FEM

For calculation and modeling of iFCL by finite element method (FEM) is used software product Comsol Multiphysics v.4.4.

A. Electromagnetic Task

For calculation magnetic field in iFCL is used part of “AC/DC” modul - „Magnetic Field”. 3D primitives are used for designing the geometric size.They are embedded in the program. All part is defined with relevant material. Whole volume is divided into finite elements - 133 348 tetrahedron .

Applied is Amper`s law in following form (5)

$$\left(j\omega\sigma - \omega^2 \varepsilon_0 \varepsilon_r \right) A + \nabla \times \frac{B}{\mu_0 \mu_r} - \gamma v \times B = J_e \qquad (5)$$

Where ε_o is the permittivity of vacuum; ε_r - relative permittivity; μ_o - permittivity of vacuum; μ_r - relative permeability; J_e - externally generated current density.[13]

IV. RESULTS

An inductive fault current limiter is calculated by explaned methodology and FEM. Its consist of EI core with two concentricity coils in the middle core and connection armature. The main coil is outer and it is made of wire with section 1.5mm^2 and 150 turns. The control coil is iner and it is made of wire with section 72mm^2 and 15 turns. To verify result form calculations had been made labrotory model with same constructive parameters (fig. 3).

Fig.3. Model of iFCL

Compare between explened methodology, FEM method and measurement result from laboratory model is made. The investigations are made on metal short current when there isn`t resistance to limit fault current.

Distribution of magnetic flux density calculated by FEM method is shown on fig.4 and fig.5. The main coil current is 5.6A.

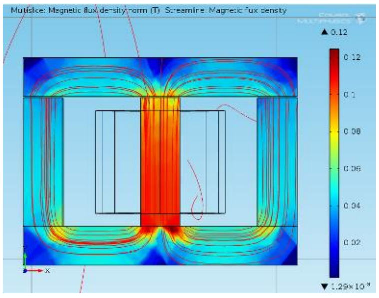

Fig. 4. Distribution of magnetic flux density on stand by mode L=0.58mH

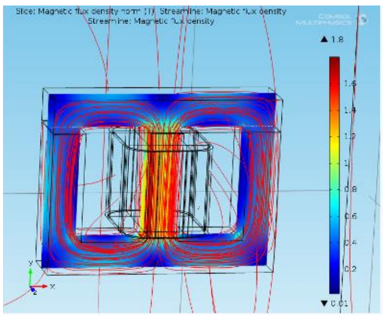

Fig. 5. Distribution of magnetic flux density on limit mode L=55mH

The measurement value from laboratory model on standby mode is 0,64 mH, and on limit mode is 69,9 mH.

The changing of inductance from normal state to limitation state for different current on simulated model and real model are presented on Fig. 6.

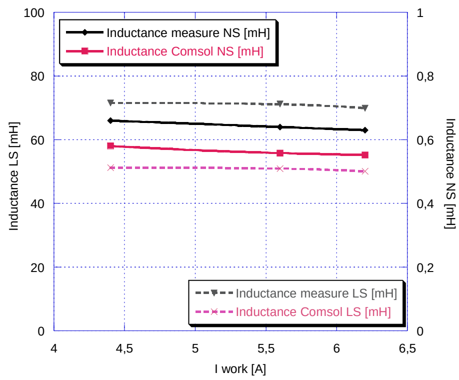

Fig.6. Changing of inductance

Using different values of mail coil currents the coil electrical losses are calculated, simulated and measured. The results are shown on fig.7.

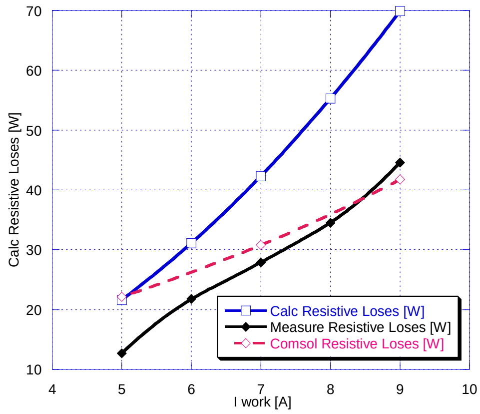

Fig.7. Electrical losses in mail coil

The error on calculation method is bigger than FEM method. By FEM modeling we can obtain result which is near to real model.

The distribution of temperature is shown in fig.8. The simulation is made using Comsol in standby mode. The main coil current is 4.7A.

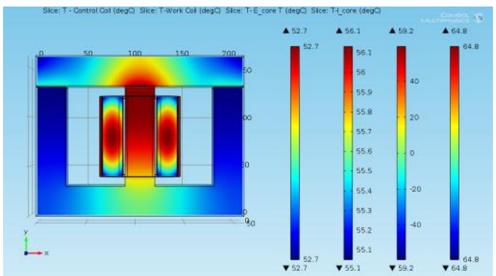

Fig. 8. Distribution of temperature in iFCL

The temperature changing in the main and control coils by calculation, modeling and measurement are shown in fig.9

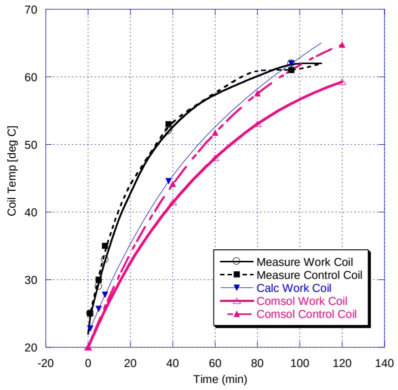

Fig. 9.The heating vs time.

The limitation factor is 2.5 times when load is 15.7ohm. The transition process calculated by Comsol is shown in Fig. 10. The rate current in work coil is 3.5Amp and after 25ms is limited to 1.4Amp.

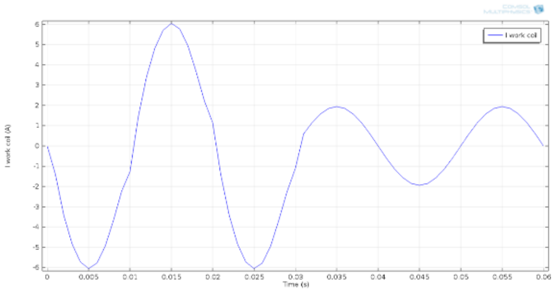

Fig. 10. Transient process by Comsol

The transition process for laboratory model is measured by using power quality analyzer Metrel MI2192 (Fig. 11). Current transformer is used for this experiment and the measured values have to divide by 10. The limitation factor will increase if the load resistance decreases and could reach to 10.

Changing of equivalent inductance of the laboratory model is around 100 times. The limitation factor reaches 10.7 times, because of usage the real supply transformer.

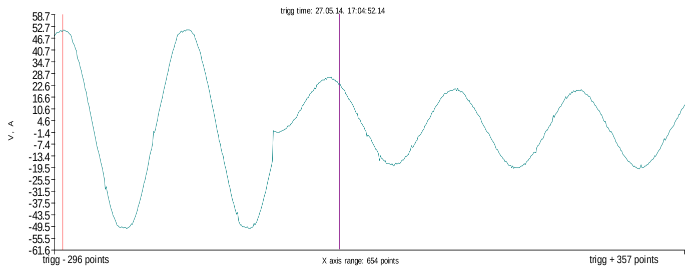

Fig 11. Measurment transient process by Metrel

VI. Conclusions

A new topology for FCL based on iFCL is introduced in this paper. Analytic analysis for the proposed structure is performed carefully and simulations are presented using Comsol Multi-Physics software.

Inductance in standby mode is same as conventional concrete reactors. This device could limit the fault current up to 10 times.

This type iFCL has low cost, because is using a non-superconducsting inductor.

In general, we could conclude that the studied device has good capability for fault current limiting.

VII. References

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