Core losses of the ‘saturated core’ FCL

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Abstract. One of the important parameters determining cost efficiency of a ‘saturated core’ Fault Current Limiter (FCL) is the energy losses, consisting of copper losses and core losses, in normal regime. In this paper we analyze only the core losses during FCL functioning in the normal regime and at a fault. In the normal regime the core (usually made of silicon steel) is saturated and therefore endures very small losses. More precisely, their smallness is due to a small voltage drop on FCL (about 4% of the grid voltage). Because FCL works in the normal regime more than 99% of its time this what defines its cost efficiency. On the contrary, at a fault the core losses become significant: a larger part of the grid voltage falls on the FCL causing a large change in the magnetic flux and as a consequence, large eddy-current losses in the core. In conclusion it is argued that *cheap low-carbon steel* magnetic core causes but inessential increase of the losses in the normal regime. At the same time an increase of the losses at fault (amounted to several orders of magnitude) gives an additional FCL impedance and leads to the increase of the time constant of the device, thus reducing the first peak of the current.

1. Introduction

FCL is one of the most attractive applications of HTS in the power systems, which has no classical equivalent [1]. The most attractive, a so-called ‘resistive’ FCL is under intensive development [2,3]. Precise possible locations of a FCL inside the network dictate very different boundaries of such FCL characteristics as recovery time, limitation current etc. This invites FCL designs based on other (than ‘resistive’) concepts [4]. A so-called ‘saturated core’ FCL has two important advantages over the others: it is based on existing technology and materials and its operation is not concerned with transition of the superconducting element (coil) to the normal state (its recovery time is zero) [5]. The main obstacles to the development of the ‘saturated core’ FCL are considered to be the mass and core losses [4]. In this paper we estimate the core losses for the magnetic cores made of different materials.

2. Silicon steel core losses

Silicon steel is a traditional material for manufacturing of magnetic cores. First we examine their state at different regimes (normal and fault) and then proceed to analyze the losses at both. A normal regime is the state when an amplitude of the AC current does not exceed a double nominal amplitude I_m. A fault arises at the moment of a short circuit.

Fig. 1a shows an equivalent circuit of the network with a ‘saturated core’ FCL. Two cores have a common bias coil connected to a DC power supply with a bias current I_b which has to be large enough to ensure that in the normal regime both FCL cores are in saturation state (see Fig. 1b).

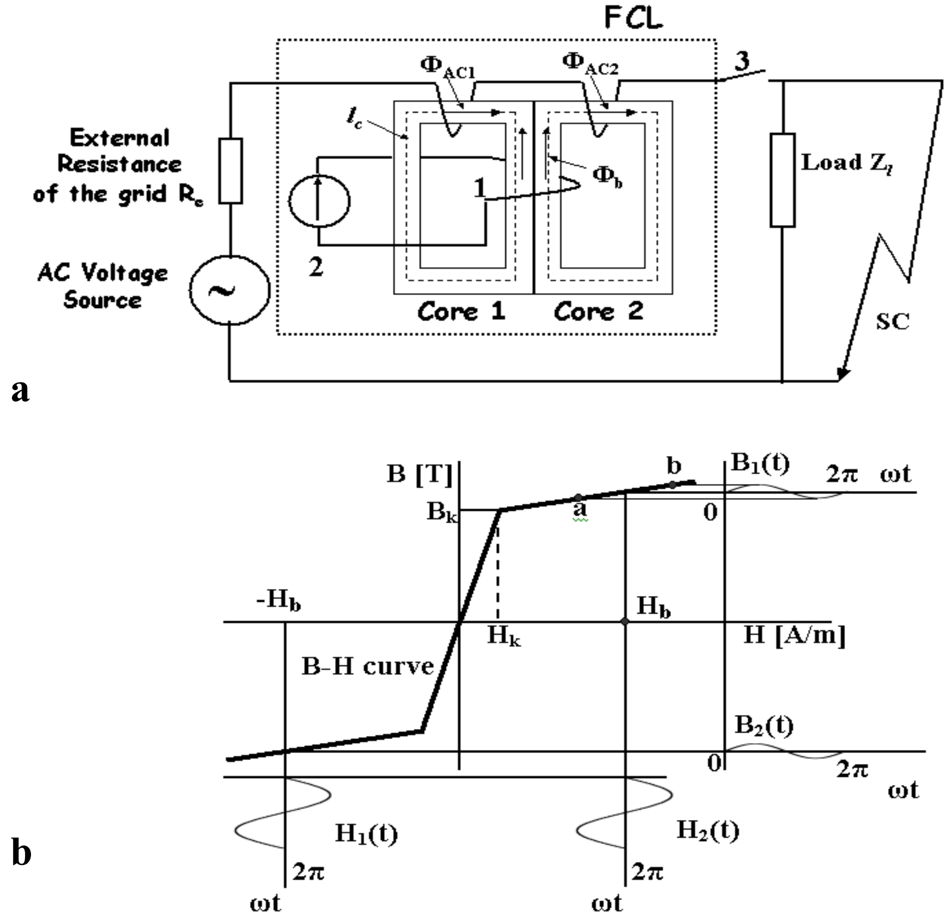

Figure 1. a. An equivalent circuit of the network with a 'saturated core' FCL. Zigzag line SC shows a place of the short circuit. b. Example of plotting of H(t) and B(t) for both FCL cores at nominal AC current.

Magnetic field strength in the core *H(t)* produced by nominal AC current $I(t) = I_m \sin\omega t$ is

$$H_{1,2}(t) = \pm H_b + H_m \sin\omega t; \; H_m = I_m n_{AC} / l_c \qquad (1)$$

where n_{AC} is the number of AC coil turns and l_c is the average length of the magnetic circuit of the core. At the moment of AC current turns zero the field in the core is defined by the bias coil: $H(0) = H_b = I_b n_b / l_c$, where I_b and n_b are the current and the number of AC coil turns.

Graphs of $H_1(t)$ and $H_2(t)$ in cores 1 and 2 are shown in fig. 1b. Magnetic induction *B(t)* in the cores is the sum of the constant bias value B_b and variable component proportional to differential magnetic permeability of the core.

$$B_{1,2}(t) = \pm B_b + \mu_s \mu_0 H(t)$$

where $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is magnetic permeability of vacuum and μ_s is a core permeability in saturated state.

Table 1. Parameters of the FCL and core materials

Parameter	Silicon steel	Low carbon steel
Core permeability in saturated state, μ_s	6.5	6.5
Steel conductivity σ, $(\mathrm{Ohm.m})^{-1}$	$1.67.10^6$	7.10^6
Steel plate thickness, mm	0.35	5
Frequency f, Hz	50	
Nominal current I_{nom}, kA	0.786	
Nominal voltage V_{nom}, kV	4.24	
Load impedance Z_l, Ohm	5.4	
Voltage drop on FCL ΔV_{FCL}, V	190	
Mass of the core, kg	4000	
Bias field strength H_b, kA/m	20	
Amplitude of the magnetic field strength H_m, kA/m	10	

We use further a piecewise-linear approximation of the B-H curve for the steel. Such approximation works well enough when we focus on the part of the B-H curve close to the full saturation region.

We compute the core losses for a one phase 'saturated core' FCL with nominal power 1.67 MVA [4]. We consider first a standard silicon steel core with sheet thickness 0.35 mm and then cheap low carbon steel core with plate thickness 5 mm. The parameters of the models for losses calculations are shown in Table 1.

Simplifying the problem, core permeability in a saturated state, μ_s, was taken as a root square average in the interval 10-30 kA/m and used as a characteristic of saturated part of the approximated B-H curve.

Power losses in the core are the sum of eddy current losses P_{ed} and hysteresis losses (which we further neglect [6]). Eddy current losses for the unit mass P_0 can be calculated by formula

$$P_0 = P_{ed} / m_c = \sigma\omega^2 B_m^2 d^2 / 24\rho \quad W/kg \tag{2}$$

where ρ is the mass density of the steel.

Formula (2) can be used when the steel plate has a thickness d that satisfies condition $d/\Delta \le 1/2 \div 1/3$ where Δ is skin layer depth. Substituting the data from table 1 into (2) we obtain the value of P_0=2.14.10^{-2} W/kg. Total losses in two cores are P_{ed}=0.86 W, i.e. negligible quantity. This last value shows that increase of the losses by two or three orders of magnitude (up to 0.1% of the total power) can be admissible as compared to the losses in transformers and therefore allows making the core of a cheaper steel.

The use of a cheap low carbon steel thick plate increases eddy current losses due to an increase in values of d and $B_m=\mu_s\mu_0 H_m$. Let us estimate the losses under these conditions. The skin layer thickness in this case is

$$\Delta=\sqrt{2/\omega\mu_0\mu_s\sigma} \tag{3}$$

which leads to $\Delta =$ 10.6 mm. We can take the sheet as thick as 5mm. Using (2) we receive eddy current losses P_{ed} = 714 W, which is less than 0.1% of the rated power.

3. Power losses during the fault.

Duration of the short circuit regime depends on the operating speed of a breaker connected with FCL in series and does not exceed 100 ms. Total time of the short circuit regime is small and power losses during short circuit have no influence on economical efficiency of the device. But we found that power losses, which can be regarded as additional resistance connected with the AC coils in series, can influence on the main characteristics of FCL. Behavior of the 'saturated core' FCL during short circuit strongly depends on the moment of its occurrence. If it occurs at the moment when V=0 the first peak of the current achieves its maximal value and we concentrate on considering such short circuit. To estimate the losses we consider first transient behavior of the device. This behavior is illustrated on Fig. 2 as relationship of the total magnetic flux linkage of both cores Ψ_Σ and AC current I. The total flux linkage (of both cores) can achieve its maximal possible value if the short circuit occurs at the moment when the voltage of the grid V=0. The maximal total flux linkage value corresponds to the maximal possible current value and this case will be considered. Dependence of the total flux linkage on time after short circuit can be described by formula

$$\Psi_\Sigma(t) = \Psi_{\Sigma m}\exp(-t/\tau) - \Psi_{\Sigma m}\cos\omega t \qquad (4)$$

where $\Psi_{\Sigma m}$ is an amplitude of the total flux linkage, τ is a time constant of the full grid including FCL. The first aperiodic term of the formula damps with a time constant $\tau = L_\Sigma/R_\Sigma$, where L_Σ and R_Σ are inductance and resistance of full grid including FCL. At the end of first cycle flux linkage achieves its maximal value (point A) that corresponds to maximal current in the circuit (point B).

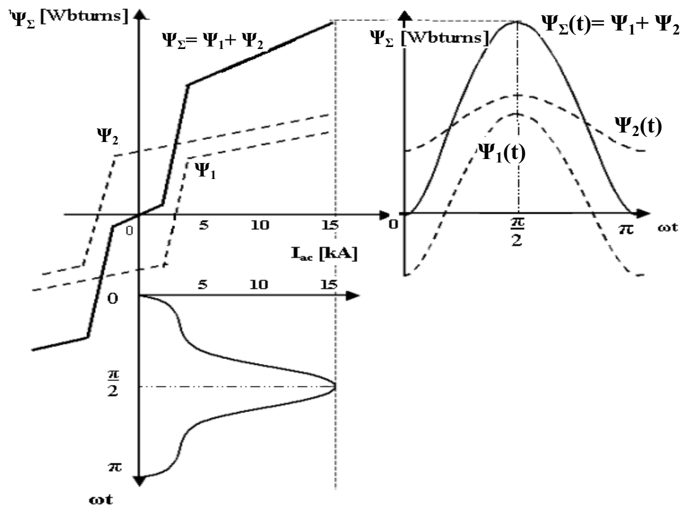

Figure 2. Plot of the flux linkage vs. AC current and plotting of the first peak of the flux linkage in both cores according formula (4) and first peak of the current at fault occurred at the moment when V=0

To calculate the losses in this case we have to know amplitude of the magnetic induction B_m that can be different in cores 1 and 2. Graphical plotting of flux linkage for two cores (Fig. 2) shows that both Ψ_m and correspondingly B_m are small in one core because this core is saturated, and for the second core both are high ($B_m = B_s$, B_s is the saturation induction). Furthermore we have to check that the thickness of the steel plate is less than the thickness of the skin layer. To calculate the latter according (3) we use the average permeability μ_{av} that can be received as $\mu_{av} = L_{av} l_c / \mu_0 A n_{ac}^2$.

Here l_c and A are average magnetic circuit length and area, n_{ac} is the number of the AC coil turns.

The best estimation of the L_{av} was found from $L_{av} = \Psi_m^2/2W_m$, where stored energy $W_m = \int_0^{\Psi_m} Id\Psi$ is defined by plot of Ψ_Σ – I (fig. 2). Thus we find $L_{av} = 2.74mH$, $\mu_{av} = 46.5$ and $\Delta = 8mm$. Power losses in the cores made of silicon steel are P_{ed}=0.44 W/kg and total losses are P_{ed} = 880 W.

Table 2. Eddy current losses in the core

			Silicon steel	Low carbon steel
Total core losses	W	Normal regime	0.86	0.714
	kW	Short circuit	0.88	744

For the core made of thick low carbon steel plate formula (2) suggests a considerable increase of the eddy current losses due to increase of the plate thickness and conductivity. In this case P_0=372 W/kg and total losses P_{ed}= 744 kW. Summary data of the power losses are shown in table 2.

The losses in the core can be regarded as an additional resistance in the circuit. Given a fixed have a preset voltage on FCL the correct model is where FCL inductance and resistance are connected in parallel. We use the inductance value for short circuit conditions obtained earlier $L_{av} = 2.74mH$ (ωL_{av} = 0.86 Ohm). The resistance R_{st} caused by eddy current losses is estimated by

$$R_{st} = V_m^2/2P_{ed} = 12.1 Ohm$$

Presence of the big resistance in the circuit has a strong influence on its time constant. To calculate the circuit time constant we have to transform the circuit with parallel connection into the circuit with series connection. The corresponding values of L_{av}^* and R_{av}^* for series connection we receive from:

$$L_{av}^* = L_{av}/1 + (\omega L_{av}/R_{st})^2 \text{ and } R_{st}^* = \omega L_{av}(\omega L_{av}/R_{st})/1 + (\omega L_{av}/R_{st})^2 \quad (5)$$

Substitution $L_{av} = 2.74mH$ and $R_{st} = 12.1Ohm$ into (4) gives us $L_{av}^* = 2.74mH$ and $R_{st}^* = 0.061Ohm$. We neglect the inductance of the external circuit that are much smaller than L_{av}^* and take the resistance $R_\Sigma = R_{av}^* + R_e$=0.068 Ohm ($R_e$ is the estimated external resistance value). As a final result we receive the time constant τ=45ms. The similar calculation for the circuit including FCL with silicon steel cores gives τ=390ms. Estimation of the first current peak by using formula (4) and Fig. 2 gives us the first current peak values 11.5 kA and 14.25 kA, i.e. about 10% decrease caused by the core losses.

Conclusions

We found that power losses in 'saturated core' FCL during normal operation of the grid are very small and have no effect on the economical efficiency of the device. The cost of the magnetic core can be reduced by using cores made of cheap low carbon steel instead of transformer steel. At fault the core losses can be regarded as an additional resistance that decreases the time constant of the circuit. Losses in the core made of low carbon steel are so big that the time constant drops by factor of two, which in turn leads to 10% decrease of the first peak of the current.

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