Journal of Magnetism and Magnetic Materials 390 (2015) 100–106

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Performance analysis of saturated iron core superconducting fault current limiter using Jiles–Atherton hysteresis model

D. Sarkar [a,*], D. Roy [a], A.B. Choudhury [a], S. Yamada [b]

[a] Indian Institute of Engineering Science and Technology, Shibpur, (Formerly Bengal Engineering and Science University Shibpur), Howrah 711103, West Bengal, India
[b] Institute of Nature and Environmental Technology (K-INET), Kanazawa University, Kanazawa, Japan

ARTICLE INFO

Article history:
Received 15 January 2014
Received in revised form
9 June 2014
Accepted 20 April 2015
Available online 23 April 2015

Keywords:
Jiles–Atherton
Hysteresis
J–A model
Fault Current Limiter
Saturated Core
FCL
Superconducting coil
Shorted ring

ABSTRACT

In this paper study of the Saturated Iron Core Superconducting Fault Current Limiter (SISFCL) has been carried out. Since in an SISFCL, the iron core plays a key role in distributing the magnetic flux, the hysteresis property of the core material has been introduced in a mathematical model to get a more accurate result. In this paper the Jiles–Atherton hysteresis model has been used for modeling the core. The equations are solved through numerical method and performances of SISFCL are analyzed for both normal and fault conditions. On further analysis it is observed that for suppression of higher value of fault current a high voltage develops across the DC source. Hence there is a chance of the DC source being damaged by the rise in voltage under fault condition. In order to protect the DC source, a shorted ring is introduced in the SISFCL circuit and its effects have been analyzed. It is noticed that the shorted ring has successfully reduced the voltage across the DC coil during fault condition while the performance of the limiter remains the same.

1. Introduction

With the increase in size of the power system network it is becoming an increasingly difficult task to mitigate the fault current. All devices designed to withstand the mechanical and thermal stresses have to be upgraded to cope up with the increased fault level. Solutions to counter the problem of excessive short circuit current have become an important issue for the power system operators both at transmission as well as at distribution levels. With this objective in mind, several fault limiting techniques have been proposed. Researchers are looking for a device that would not affect the system during normal operation and will only come into effect during fault condition. Several concepts of fixing the fault current problems are put forward and can somewhat establish their capability in dealing with the problem. But most of these solutions have brought many negative effects along with them such as high transmission loss, harmonic problems and lower grid stability. Saturated core FCLs has existed as a concept since the late 1970s; however, significant research and development on these devices did not begin until after the discovery of High Temperature Superconductors (HTS). Various types superconducting fault current limiter have become popular in the recent decade [1–3] of these the Saturated Iron-Core Type High-Temperature Superconducting Fault Current Limiter (SISFCL) has been discussed here.

Unlike resistive and shielded-core Superconducting Fault Current Limiters, which rely on the quenching of superconductors to achieve increased impedance, SISFCLs utilize the dynamic behavior of the magnetic properties of iron to change the inductive reactance on the AC line. Keeping this in mind Saturated Iron Core Superconducting Fault Current Limiter (SISFCL) has emerged as a probable solution in the near future. It shows a lot of attractive features as low steady state loss, immediate current limiting and fast recovery and has high power quality and reliability. The main structure comprises of two iron cores, superconducting coil for DC biasing, DC current source and AC coils. During normal operation the DC bias current flowing in the DC coil forces the core to saturation and the permeability μ becomes low. This decreases the effective impedance of the device and the voltage drop across the SISFCL is negligible under normal operating condition. But during fault, the high AC current causes high amount of AC flux to flow through the core. As the setup is such that the two AC coil turns are wound in opposition, flux produced by one adds to the flux produced by the DC coil whereas the flux produced by the other opposes it. The latter case reduces the flux in that core such that it goes out of saturation and the permeability μ increases which in

---

[*] Corresponding author.
E-mail address: debraj.sarkar25@gmail.com (D. Sarkar).

http://dx.doi.org/10.1016/j.jmmm.2015.04.071
0304-8853/© 2015 Elsevier B.V. All rights reserved.

Nomenclature

μ_0	Magnetic permeability in vacuum [henry/m]
μ_r	Relative permeability [-]
M	Magnetization [A/m]
H	Magnetic field intensity [A/m]
B	Magnetic Flux density [wb/m^2]
H_e	Effective magnetic field intensity [A/m]
M_s	Saturation magnetization [A/m]
M_{an}	Anhysteretic magnetization [A/m]
a	Shaping coefficient [A/m]
M_{irr}	Irreversible magnetization [A/m]
M_{rev}	Reversible magnetization [A/m]
k	pinning coefficient [A/m]
I_d	Constant DC current [A]
V_s	Source voltage [V]
i	Instantaneous current [A]
t	Time [s]
l	Mean magnetic length [m]
A	Cross-sectional area [m^2]
φ	Magnetic flux [wb]
e	Instantaneous induced electromotive force [V]
u	Instantaneous Voltage across windings [V]
w_d	Number of turns in the DC winding [-]
w_c	Number of turns in the AC winding [-]

Subscript

0	Air
r	Relative
e	Effective
sat	Saturation
rev	Reversible
irr	Irreversible
an	Anhysteretic
1	Core 1
2	Core 2
c	AC
d	DC
o	Source
s	Shorted ring

turn increase the impedance of the equipment limiting the current. With every cycle each core alternately goes out of saturation and thus the current limiting is successfully carried out [4]. A schematic diagram of the SISFCL has been shown in Fig. 1.

2. Hysteresis model

Many devices used in power systems contain magnetic cores as it acts as a medium for the flow of magnetic flux. But the flux response is not linear, which makes it very difficult for the modeling of the device. Linearized modeling, which is often adopted to ease the calculations, is of course an approximation. But for the analysis of the dynamic responses and transient phenomena an accurate hysteresis model is essential. Many concepts are put forward to resolve this problem of which two techniques have been popular for the hysteresis modeling viz. Presaich's model and Jiles–Atherton's (J–A) model of which the J–A model is considered for the present discussion.

2.1. Anhysteretic magnetization

The behavior of a saturable magnetic core is typically described in terms of its magnetic flux density (B) vs. magnetic field intensity (H). The relationship between these quantities is shown in the following equation:

$$B = \mu H = \mu_0 \mu_r H = \mu_0 (H + M) \tag{1}$$

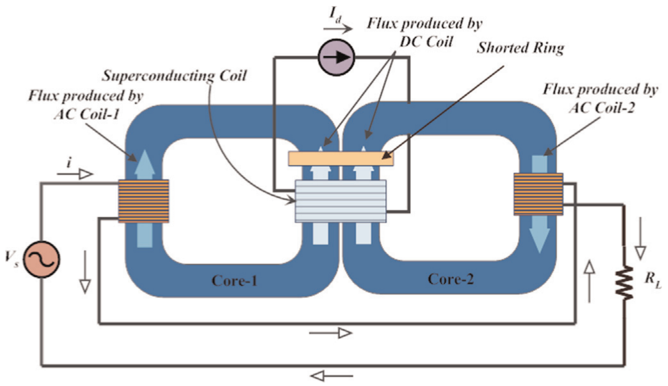

Fig. 1. Schematic Diagram of SISFCL with shorted ring.

The parameter M in the equation refers to the magnetization or field intensity within the material that is developed by the magnetic domains. However on domain basis examination the differential field strength on each domain is found to be larger than expected due to the effect of surrounding domains. This phenomena is represented by the equation $H_e = H + \alpha M$, where H_e is termed the effective field intensity and α, the scaling coefficient.

If a magnetic material was able to return all of the magnetic energy that was input, the resulting magnetization curve would take the form of a single valued sigmoid. This curve, referred to as the anhysteretic magnetization curve, represents the ideal or lossless magnetization of a material. The parameters used to calculate this quantity are the effective field strength (H_e) given by the above equation, the saturation level (M_{sat}), and the shaping coefficient a, which adjusts the slope of the curve according to the magnetic hardness of the material. The phenomenological representation of anhysteretic magnetization (M_{an}) proposed by Langevin [5] is defined by the equation,

$$M_{an} = M_{sat}\left(\coth\left(\frac{H_e}{a}\right) - \frac{a}{H_e}\right) \tag{2}$$

2.2. The Jiles–Atherton's hysteresis model

The Jiles–Atherton model [5,6] is a physically based model that includes the different mechanisms that take place at magnetization of a ferromagnetic material. The theory is based on the existence of magnetic domains, which are separated by domain walls. The magnetization M is represented as the sum of the irreversible magnetization M_{irr} due to domain wall displacement and the reversible magnetization M_{rev} due to domain wall bending.

$$M = M_{rev} + M_{irr} \tag{3}$$

The rate of change of the irreversible part of the magnetization is given by,

$$\frac{dM_{irr}}{dH} = \frac{M_{an} - M_{irr}}{k\delta - \alpha(M_{an} - M_{irr})} \tag{4}$$