DESIRABLE PARAMETER IDENTIFICATION FOR THE IMPLEMENTATION OF IDEAL PASSIVE FAULT CURRENT LIMITER FOR THE PROTECTION OF POWER SEMICONDUCTOR DEVICES

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ABSTRACT - Compact and small size, reliable and fail-safe operation and low cost featuring fault current limiter causing the designer to take a close look into the use of passive fault current limiter(FCL) for the protection of power semiconductor devices in power electronic systems. This paper has identified the main parameters responsible for the development of ideal passive magnetic current limiter. The effect of those parameters on the range of operation and the voltage-current characteristics of the magnetic current limiter has been studied using tableau approach. Desirable characteristics are discussed and the simulation results are presented.

1. INTRODUCTION

Limiting the flow of enormously large value of current during fault, short-circuit or any other abnormal operating conditions in power electronic systems is the paramount important task of the designer. Lot of researches are still going on till date in the search of an ideal fault current limiter, the requirements of which are described in [1]. A comparative features of the traditional methods of circuit protection which include circuit breaker, high impedance transformers, current limiting fuses, air-core reactors, system configuration such as splitting of buses etc., are given in [2]. The research on superconductor based fault current limiter are in full swing. Though the superconducting fault current limiter has the drawbacks of the requirements of cooling arrangement, control circuit and maintenance, with the availability of high temperature superconducting materials it will be possible to develop fault current limiter for large power system applications. We have reported the passive fault current limiter based on permanent magnet and saturable cores [3, 4]. In this paper we have identified the desirable material requirements and constraints for the implementation of high performance passive magnetic current limiter using the simulation results by tableau approach. Fig.1 shows an use of FCL in a typical power electronic system.

2. DESIRABLE CHARACTERISTICS AND IDENTIFICATION OF MAIN PARAMETERS

Basically the FCL behaves as an inductor. The inductance value is very low at low values of current. But it increases abruptly to a large value during fault condition. The inductance values are designated as L_s and L_u respectively. The basic requirement of a passive fault current limiter is to offer an negligible voltage drop across it under normal operating condition and a large voltage drop during large

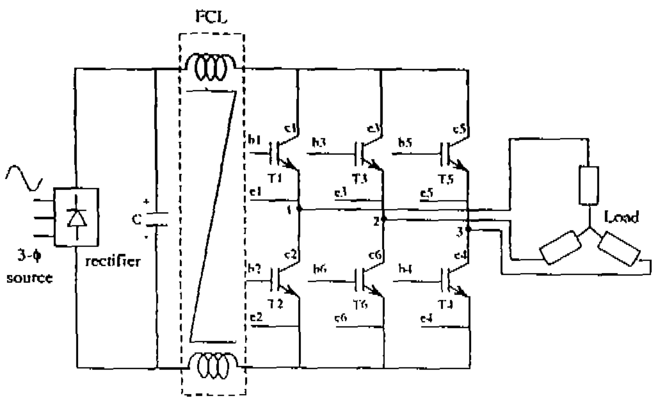

Fig. 1 FCL in typical power electronic systems.

value of current with the capacity of limiting the first peak value of the fault current. The basic configuration of FCL is shown in Fig.2 and the experimental waveforms for a typical fault condition of a small scale system is shown in Fig.3.

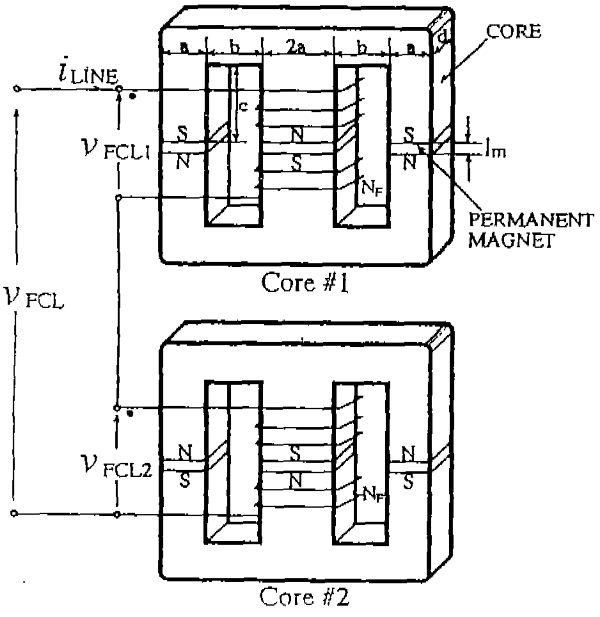

Fig. 2 Basic configuration of FCL

The desirable voltage-current characteristics of the FCL is shown in Fig. 4.

Following four important parameters are considered here.

i) the slope, S_1, at normal operation

ii) the slope, S_2, at fault condition

iii) the ratio of S_2 to S_1 or L_u to L_s

iv) the knee point, k.

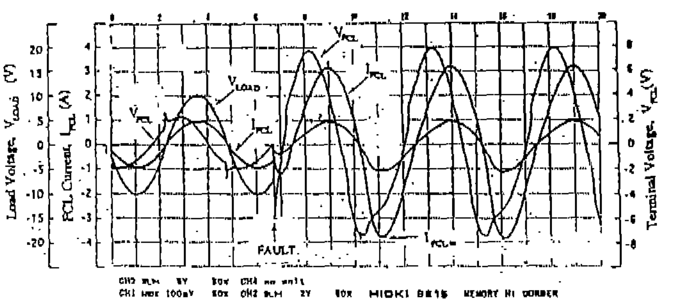

Fig. 3 Experimental waveforms for a typical fault condition.

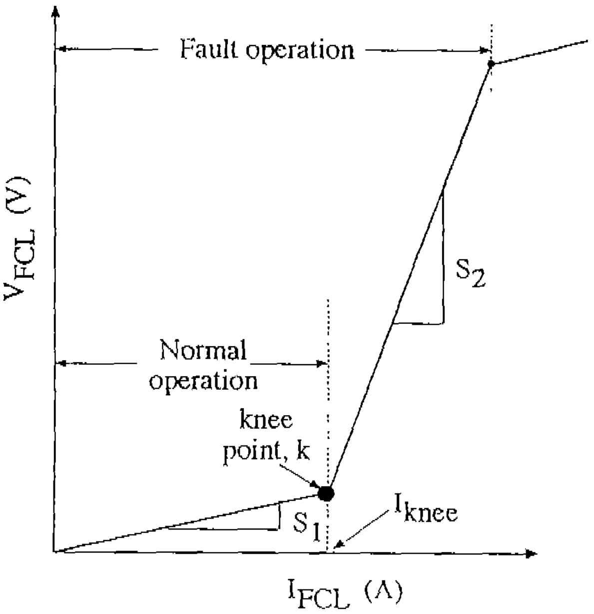

Fig. 4 Desirable volt-current characteristics

The slope, S_1, is the ratio of the voltage across FCL to the current flowing through it during low value of current and it depends on L_s, the saturated inductance of FCL.

Now

$$L_s = \frac{N_F^2}{R_m + R_s} \qquad (1)$$

where R_m and R_s are the magnetic reluctances of the permanent magnet and the core at saturation respectively.

N_F is the number of turns of the coil in each core.
Designing $R_s >> R_m$, we have

$$L_s \approx \frac{N_F^2}{R_s} = \frac{N_F^2 \mu_s S_{core}}{l_{core}} \qquad (2)$$

where μ_s is the saturated permeability of the core, l_{core} and S_{core} are the length and area of the core in saturation respectively.

A low value of L_s can be achieved by

(1) reducing the number of turns of the coil, N_F
(2) using core of having very low value of μ_s
(3) smaller area of the core, S_{core}
(4) larger length of the core, l_{core}.

The slope, S_2, is the ratio of voltage across FCL to the current flowing through it during large value of current and it depends on L_u, the unsaturated inductance of FCL.

$$L_u = \frac{N_F^2}{R_m + R_u} \qquad (3)$$

where R_u is the magnetic reluctance of the core at unsaturated state.

Usually $R_m >> R_u$ and we can write

$$L_u \approx \frac{N_F^2}{R_m} = \frac{N_F^2 \mu_m S_m}{l_m} \qquad (4)$$

where μ_m is the permeability of the permanent magnet, l_m and S_m are the length and area of the permanent magnet.

To limit the peak value of fault current a high value of L_u is desirable. Assuming the value of μ_m as constant, a high value of L_u can be achieved by

(1) increasing the number of turns of the coil, N_F
(2) larger area of the magnet, S_m
(3) smaller length of the magnet, l_m.

The ratio L_u to L_s is given by

$$\frac{L_u}{L_s} \approx \left(\frac{\mu_m}{\mu_s}\right) \cdot \left(\frac{S_m}{S_{core}}\right) \cdot \frac{1}{\left(\frac{l_m}{l_{core}}\right)} \qquad (5)$$

A large value of L_u to L_s ratio is desirable and this can be achieved by choosing a higher value of (μ_m/μ_s) and (S_m/S_{core}) and a lower value of (l_m/l_{core}).

The knee point is dictated by the following equation.

$$N_F I_p < H_r l_m - H_c l_{core} \qquad (6)$$

Neglecting the magnetizing force required by the core, we can write

$$N_F I_p < H_r l_m \qquad (7)$$

where I_p is the peak value of the coil current under normal operating condition and H_r is the coercive force of the permanent magnet.

From the above equation it can be said that the range of operation(i.e. large value of normal operating current) can be extended by

(1) reducing the number of turns of the coil, N_F
(2) using the permanent magnet of having higher coercive force, H_r,
(3) larger length of the magnet, l_m.

From the above discussion it is seen that $\{N_F, \mu_s, l_{core}, S_{core}, l_m, S_m$ and $H_m\}$ are the important parameters. By careful selection of the above parameters a desirable characteristics may be achieved.

3. MODIFICATION OF CHARACTERISTICS

Initially, assuming $S_m = S_{core}$, we have

$$\frac{L_u}{L_s} \approx \left(\frac{\mu_m}{\mu_s}\right) \cdot \frac{1}{\left(\frac{l_m}{l_{core}}\right)} \qquad (8)$$

Usually, $\mu_s/\mu_m \sim 10$ to 100.

Designing, $l_{core}/l_m \sim 100$ to 1000, L_u/L_s may be obtained of the order of 10.

It is seen that to obtain large ratio of L_u/L_s, a very low value of μ_s is desirable.

The area of the permanent magnet, S_m may be greater that the core area, S_{core}.

$S_m/S_{core} > 1$ has the effect of

1) improvement of the L_u/L_f ratio,

2) allow the use of core material having saturation flux-density larger than that of the residual flux density of the permanent magnet.

The above configuration of one half of the assembly is shown in Fig.5. Now only section#2 will operate in saturation in the normal condition. So l_{core} will be the length of the section#2 only. As a result the value of the ratio l_{core}/l_m will reduce.

The modified volt-current characteristics are shown in Fig.6. By increasing the value of H_r the knee point can be extended. The slopes S_1 and S_2 remain unchanged in this case. If either by increasing l_m or by reducing N_F, the knee point is extended, it will decrease both the slopes S_1 and S_2. Though the reduction of S_1 is desirable but reduction of S_2 will lead higher values of fault current. By selecting the parameters carefully the characteristics close to ideal one can be obtained.

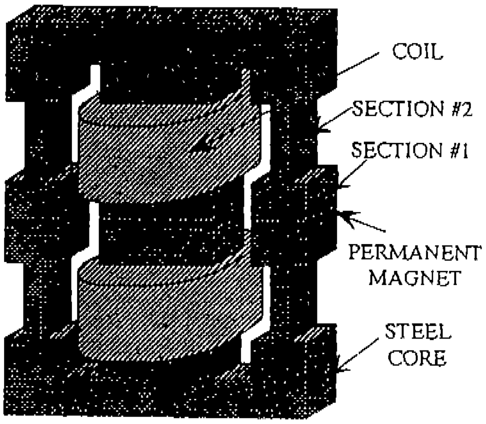

Fig. 5 Alternative configuration of FCL

4. SIMULATION METHOD

The simulation of the performance characteristics of the fault current limiter has been carried out by tableau method which can take into account the combination of electric and magnetic circuit. The circuit configuration for the simulation is shown in Fig.7 and the corresponding equivalent circuit is shown in Fig.8 including the effect of eddy currents in the permanent magnet. The basic equations are written in Eqs.(9) to (19). The details of the parameters have been explained in reference(6). By choosing a suitable time step the equations are solved by Newton-Raphson and iterative method to obtain the solution[5].

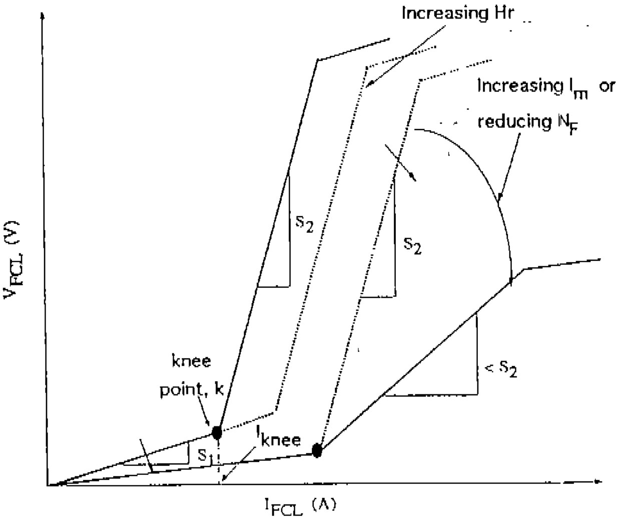

Fig. 6 Modification of characteristics

Electric Circuit # Main

$$Z_r i_e - Y_e v_r = W_1 \qquad (9)$$

$$v_e - A'_e v_{cr} + C'_{e1}\frac{\partial}{\partial t}\Phi_1 + C'_{e2}\frac{\partial}{\partial t}\Phi_2 = W_2 \qquad (10)$$

$$A_r i_e = 0 \qquad (11)$$

Magnetic Circuit # Core 1

$$R_{m1}\Phi_1 - A'_{m1}u_{e1} - C_{e1}i_e - C_{d1}i_{d1} = 0 \qquad (12)$$

$$A_{m1}\Phi_1 = 0 \qquad (13)$$

Eddy Current Circuit# PM 1

$$Z_{d1}i_{d1} - A'_{d1}u_{d1} + C'_{d1}\frac{d\phi_{12}}{dt} = 0 \qquad (14)$$

$$A_{d1}i_{d1} = 0 \qquad (15)$$

Magnetic Circuit# Core 2

$$R_{m2}\Phi_2 - A'_{m2}u_{e2} - C_{e2}i_e - C_{d2}i_{d2} = 0 \qquad (16)$$

$$A_{m2}\Phi_2 = 0 \qquad (17)$$

Eddy Current Circuit # PM 2

$$Z_{d2}i_{d2} - A'_{d2}u_{d2} + C'_{d2}\frac{d\phi_{22}}{dt} = 0 \qquad (18)$$

$$A_{d2}i_{d2} = 0 \qquad (19)$$

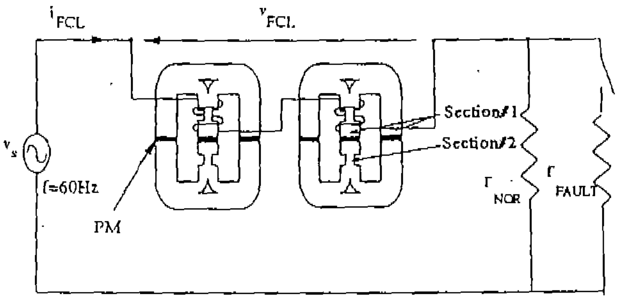

Fig. 7 Circuit configuration for simulation

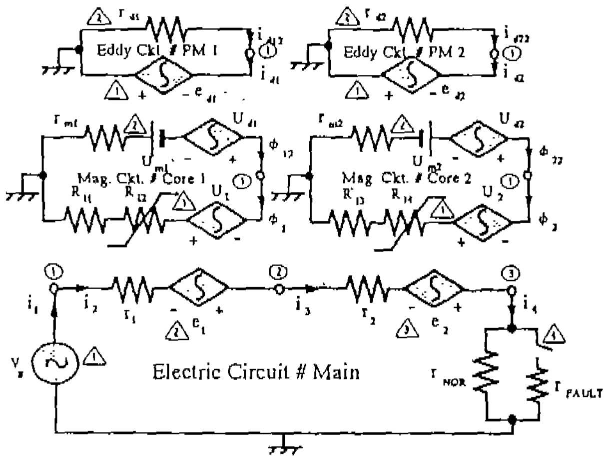

Fig. 8 Equivalent circuit representation

5. SIMULATION RESULTS

It is clear from the above discussions that this type of fault current limiter is not suitable to limit very large current. Rather it can be used very effectively for few tens to a few hundred amperes of current. We have simulated the performance of a system of 100V, 10A capacity. The basic design parameters used are listed in Table 1.

Fig.9 shows the characteristics of transient current with and without FCL in the circuit. It is seen that the FCL limits the current instantaneously and effectively.

Fig.10 shows the rms values of the volt-current characteristics of the FCL. The voltage as well as the current loose the sinusoidal nature during fault condition. So instead of rms values the characteristics based on the

Table I Parameters used for simulation

Permanent Magtet	Nd-Fe-B magnet
Length (l_m)	1.5 mm
Area (S_m)	30 cm^2
μ_m	1.1 μ_0
H_c	0.6x10^6 A/m
Saturable Core	Steel Core
μ_u	10000 μ_0
μ_s	50 μ_0
B_s	1.61 T
Section#1	
Length	20 mm
Area	30 cm^2
Section#2	
Length (l_{core})	105 mm
Area (S_{core})	6 cm^2

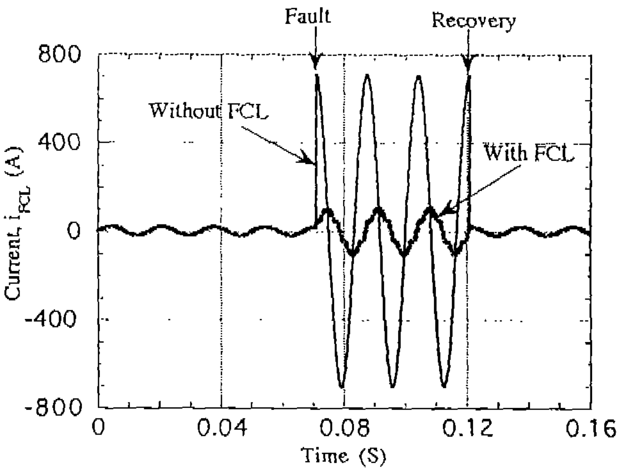

Fig. 9 Transient current waveforms with and without FCL.

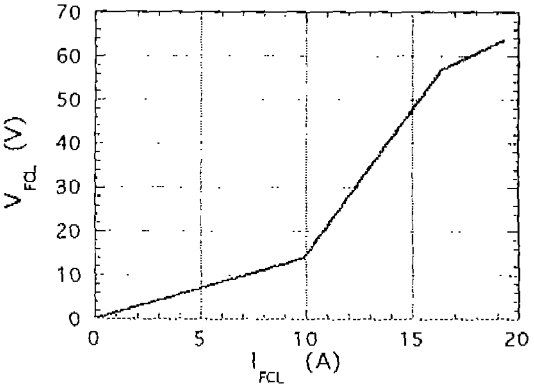

Fig. 10 Volt-current characteristics of FCL (RMS values).

peak values will be more relevant. Fig.11 shows the variation of the peak voltage of the FCL as a function of the peak current through FCL. Fig.12 shows the transient voltage across one half of the assembly and that of across FCL. It is seen that the voltage shoots up abruptly during fault and comes back to the normal state instantaneously at recovery. During normal operation the voltages are sinusoidal in nature and v_{FCL1} is half to that of v_{FCL}.

The above characteristics confirmed the validity of the proposed device as fault current limiter.

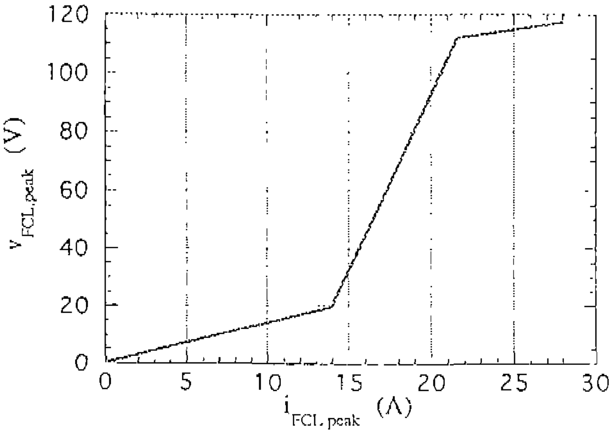

Fig. 11 Volt-current characteristics of FCL (Peak values).

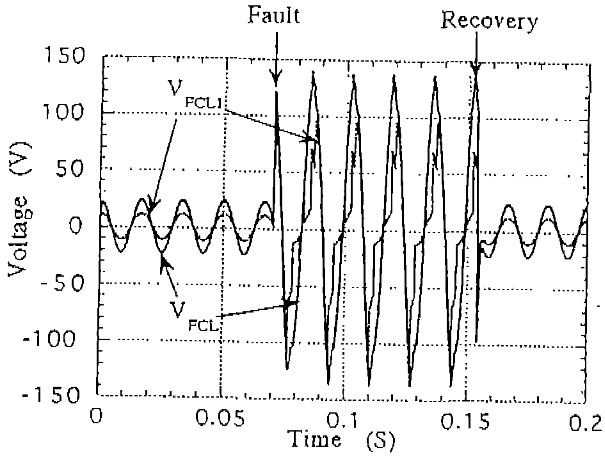

Fig. 12 Transient voltage waveforms across FCL.

6. CONCLUSIONS

In this paper we have identified the main parameters for the development of high current magnetic current limiter based on permanent magnet and saturable core. The effects of these parameters on the performances on FCL have been discussed and the simulation results using tableau method are presented. Based on the simulation results the followings are concluded.

(1) The coercivity of the permanent magnet should be as large as possible. A value of 0.6MA/m or more is highly desirable.

(2) The area of the permanent magnet to be taken slightly more than that obtained from the calculation.

(3) The unsaturated permeability of the core need not be very large. A relative permeability value of 1000 or more is sufficient.

(4) The saturated permeability of the core should be as low as possible. A relative permeability value equal to that of air or equal to that of permanent magnet is highly desirable.

(5) The area of the core to be less or equal to that of permanent magnet from leakage flux consideration.

(6) The core length is obtained from the ratio of unsaturated inductance to saturated inductance. The value of core length increases with saturated permeability. The increase value of core length increases the leakage flux.

REFERENCES

[1] B.P.Raju, K.C.Parton and T.C.Bartram, "A Current Limiting Device using Superconducting D.C. Bias - Applications and Prospects", IEEE Transc. on Power Apparatus and Systems, Vol. PAS-101, No.9, September 1982, pp 3173-3177.

[2] E.Leung, "Surge protection for power grids", IEEE Spectrum, July 1997, pp 26-30.

[3] M.Iwahara, S C.Mukhopadhyay, S.Yamada and F.P.Dawson, "A Full Passive Fault Current Limiter Using the Permanent Magnet for the Burden Critical Equipments", Journal on Non-linear Electromagnetic Systems, IOS Press, 1998, pp 349-352.

[4] S.C.Mukhopadhyay, M.Iwahara, S.Yamada and F.P.Dawson, "Investigations of Performances of PM Biased Current Limiting Reactor using Steel Core", Presented in 7th joint MMM-Intermag conference, SanFrancisco, USA, January 6-9, 1998, to be published in IEEE transc. of Magnetics, July 1998 issue

[5] M.Iwahara and E.Miyazawa, "A Numerical Method for Calculation of Electromagnetic Circuits using the Tableau Approach", IEEE Transc. on Magnetics, Vol.19, No.6, Nov. 1983, pp 2457-2459.