Investigation of the Performances of a Permanent Magnet Biased Fault Current Limiting Reactor with a Steel Core

INVESTIGATION OF THE PERFORMANCES OF A PERMANENT MAGNET BIASED FAULT CURRENT LIMITING REACTOR WITH A STEEL CORE

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Abstract- There is an increasing need in power system applications for fault current limiter, to limit the fault current in semiconductor devices and switchgear. These fault current limiters must be reliable, compact and inexpensive. This paper reports the result of an investigation of the characteristics of a Fault Current Limiter (FCL) consisting of a steel core and permanent magnet. Design criteria are presented. The FCL characteristics are simulated using a Tableau approach and the simulation results have been compared with experimental result.

Keywords : Fault current limiter, permanent magnet, steel core, tableau approach.

I. Introduction

FCLs are required to limit the first peak of the fault current while minimizing energy losses and harmonics in the normal state. In addition, the impedance should be low in the normal state and change gradually to a high value in the fault state[1]. Fail-safe operation and compactness are also considered desirable objectives.

Two approaches to fault current limiting have been considered in the past: a superconducting fault current limiter[2] and a dc saturated reactor[3]. The superconductor approach has the following limitations: a limited maximum operating current, the need for a refrigeration system and the need for a reset time subsequent to fault clearing. The latter two limitations will affect the reliability of the system. The dc-saturated reactor approach may also be unreliable because it requires a separate winding and a dc supply to bias a magnetic core. Recent investigations have identified a new approach that uses a permanent magnet to bias a magnetic core into saturation[4], eliminating the need for a separate winding and power supply and thus addressing the issue of reliability. In this paper we describe an improved core structure which has a sharper normal-to-fault transition characteristic. Two of these structures are connected in series and with opposing magnetomotive forces so as to achieve bipolar current limiting. The improved transition sharpness should lead to a lower loss device.

II. FCL Configuration

A bipolar current limiter consists of two magnetic devices connected in series and with opposing magnetomotive forces (MMF). Each magnetic device consists of a high saturation flux density steel core and a permanent magnet (PM) as shown

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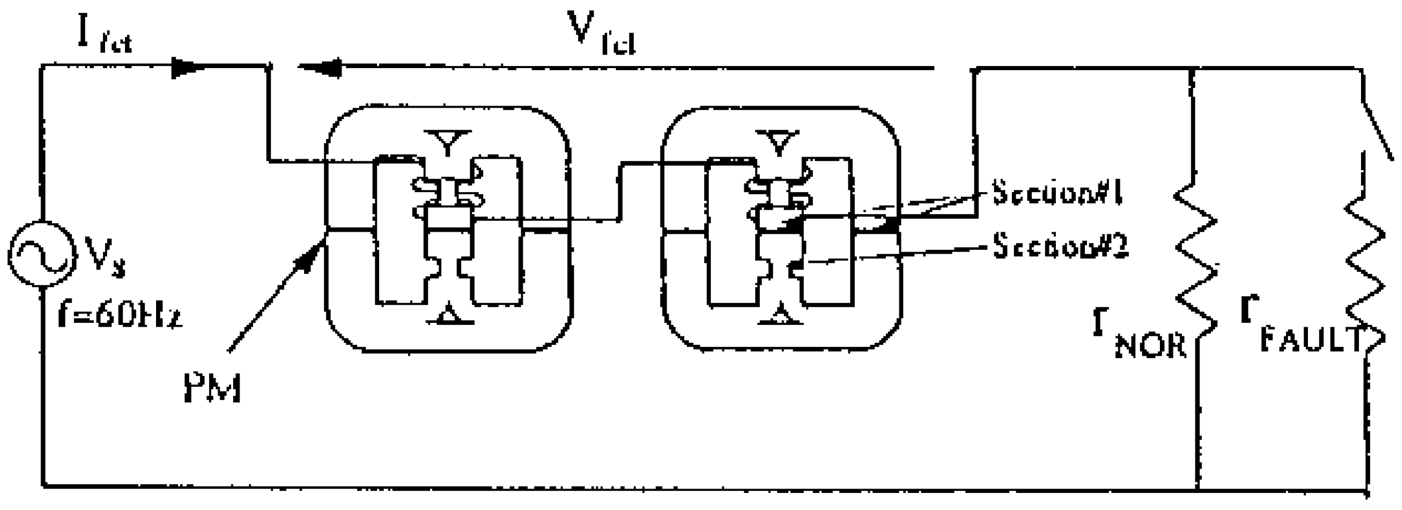


Fig 1. A fault current limiter in power system network.

in Fig.1. The polarity of the coil connections is such that at any instant in the ac cycle the mmf from the ac source and permanent magnet mmf assist in one core and oppose each other in the other. The new structure of the device is shown in Fig.2. This design is better than that of previous ferrite core limiter for the following reason: the core material has a higher saturation flux density than the magnet's remanence flux density and therefore the material can provide both a controlled path for lines of flux (i.e., a large cross-sectional area) and a saturable region (i.e., a reduced cross-sectional area).

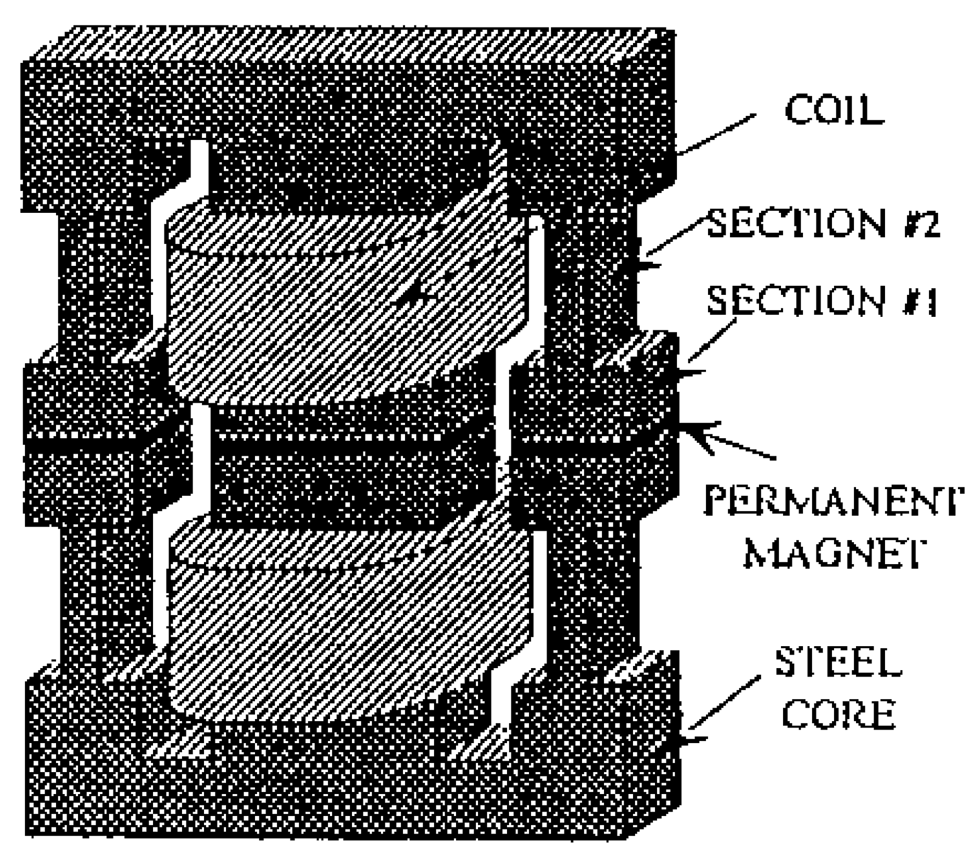


Fig. 2. New structure of FCL.

III. Design Criteria and Equations

In designing the device it is important to establish the flux versus current relationship. This is accomplished by starting with Ampere's law for the magnetic circuit represented by

$$H_m l_m + H_1 l_{i1} + H_2 l_{i2} = Ni \qquad (1)$$

where H is the magnetic field intensity and l is the flux-path length . The suffix "m" denotes PM, "i_1" and "i_2" denote section#1 and section #2 of the steel core respectively; N is the number of turns of main winding around each core and i represents the current.

The B-H characteristic of the PM is represented as

$$H_m = -H_r + B_m/\mu_m \qquad (2)$$

The steel core B-H characteristic is represented as

(in the unsaturated state) $B_i = \mu_u H_i$ (3)

(in the saturated state) $B_i = B_k + \mu_s (H_i - H_k)$ (4)

where H_r is the coercive force of the PM, and B_k and H_k are the steel core's flux-density and magnetic field intensity at the current knee point respectively.
Expressing (1) in terms of flux and reluctances we obtain the following relationship for operating flux assuming no current is applied.

$$\phi_0 = \frac{\left[H_r l_m + \phi_k \cdot (R_{2s} - R_{2u})\right]}{R_1 + r_m + R_{2,u}} \quad (5)$$

ϕ_0 must be greater than ϕ_k if section#2 is to operate into saturation where ϕ_k, the knee point flux of section #2, is given by

$$\phi_k = B_k * S_2 \quad (6)$$

of the steel core. S_2 is the area of section #2 of steel core. R denotes reluctance and the suffix "s" and "u" correspond to saturated and unsaturated state respectively.
The operating inductances in the saturated and unsaturated state of each core are expressed by (7) and (8) respectively.

$$L_u = \frac{N^2}{R_{i1} + r_m + R_{i2,u}} \quad (7) \qquad L_s = \frac{N^2}{R_{i1} + r_m + R_{i2,s}} \quad (8)$$

L_s should be very small and L_u should be designed to limit the fault current.
The volume of the PM for a specific application is given approximately by

$$V_m = S_m l_m \approx \frac{L_u \cdot I_{knee}^2}{\mu_m \left(H_r - \frac{B_K}{\mu_m} \cdot \frac{S_{i2}}{S_m} \right)^2} \quad (9)$$

where I_{knee} is the value of the fault current at which the transition from the saturated to unsaturated state occurs.

IV. SIMULATION

A Tableau method was used to analyze the circuit of the FCL. This method is suited for solving transient response problems in coupled electric and magnetic circuits [5, 6]. The electromagnetic circuits are evaluated by using the nodal analysis method and are stated in the following form.

$$T * X = b \quad (10)$$

where T represents the Tableau matrix, X represents the unknown variables and b represents constants. The Tableau equation incorporates the external electrical circuit, magnetic circuit model and eddy current related effects. The equivalent magnetic and electric circuit for the structure shown in Fig.1 is shown in Fig.3 where △ is used to represent branches and ○ is used to represent nodes[5]. R and r_m represent the reluctance of the core and PM respectively. U and U_m represent the mmf of the ac source and PM respectively. e_d represents the induced eddy voltage while r_d represents the resistance to the eddy current path.

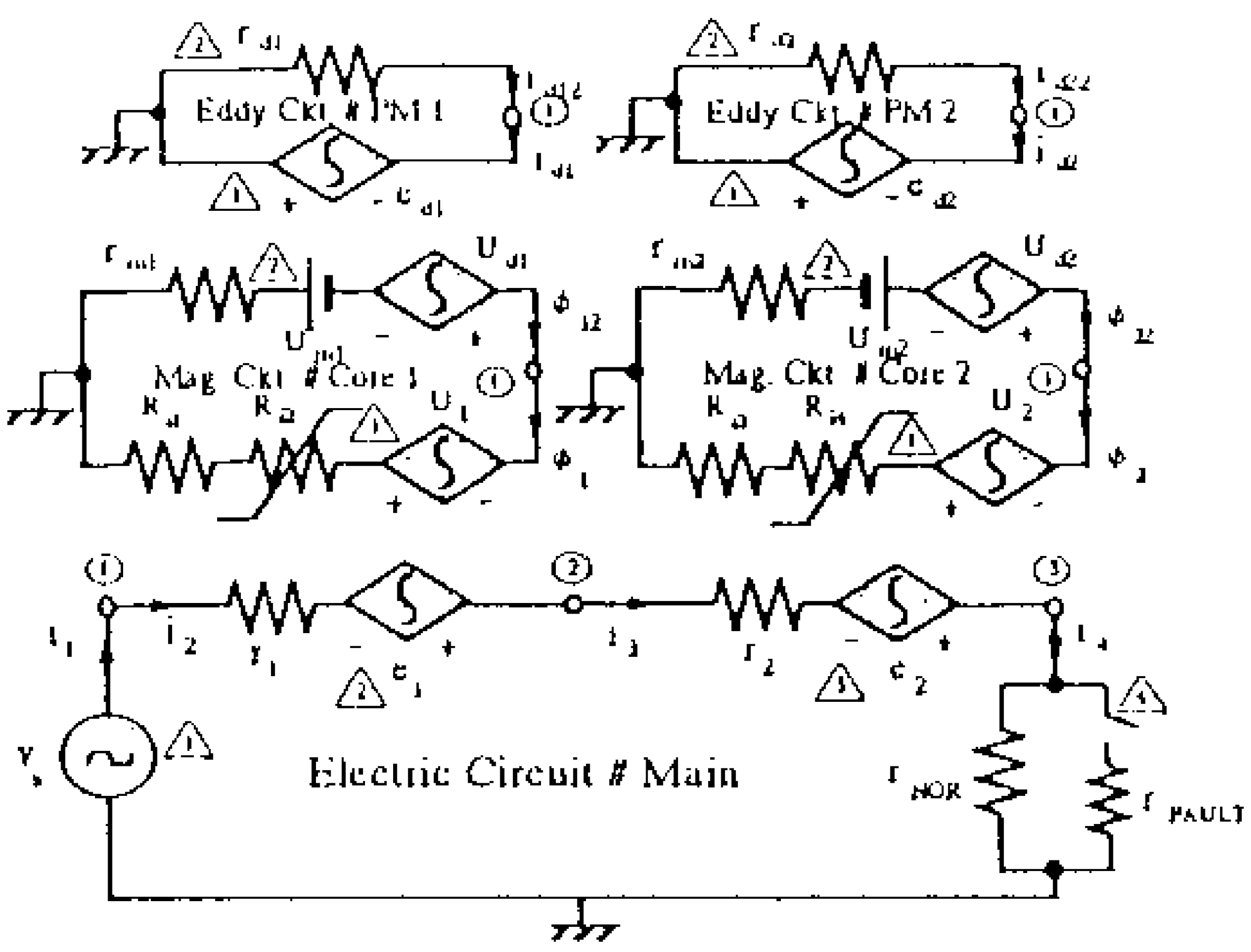


Fig. 3. Equivalent circuit configuration of Fig. 1.

The governing equations of the FCL are described as follows.
Electric Circuit # Main

$$Z_e i_e - Y_e v_e = W_1 \quad (11)$$

$$v_e - A_e^t v_{ce} + C_{e1}^t \frac{\partial}{\partial t} \Phi_1 + C_{e2}^t \frac{\partial}{\partial t} \Phi_2 = W_2 \quad (12)$$

$$A_e i_e = 0 \quad (13)$$

Magnetic Circuit # Core 1

$$R_{n1} \Phi_1 - A_{m1}^t u_{c1} - C_{e1} i_e - C_{d1} i_{d1} = 0 \quad (14)$$

$$A_{m1} \Phi_1 = 0 \quad (15)$$

Eddy Current Circuit # PM1

$$Z_{d1} i_{d1} - A_{d1}^t u_{d1} + C_{d1}^t \frac{d\phi_{12}}{dt} = 0 \quad (16)$$

$$A_{d1} i_{d1} = 0 \quad (17)$$

Magnetic Circuit # Core 2

$$R_{n2} \Phi_2 - A_{m2}^t u_{c2} - C_{e2} i_e - C_{d2} i_{d2} = 0 \quad (18)$$

$$A_{m2} \Phi_2 = 0 \quad (19)$$

Eddy Current Circuit # PM2

$$Z_{d2} i_{d2} - A_{d2}^t u_{d2} + C_{d2}^t \frac{d\phi_{22}}{dt} = 0 \quad (20)$$

$$A_{d2} i_{d2} = 0 \quad (21)$$

A suitable time step dt for the transient solution was chosen

A backward Euler method was used to approximate the derivative term. The Newton-Raphson method and Gaussian Elimination methods were used to obtain a solution to (10). The system was solved for the loading condition shown in Table 1. Fig.4 shows the variation of rms voltage across FCL as a function of the line current which is maintained sinusoidal. At low values of current, the rms voltage across the FCL increases slowly as a function of current. Above a current value of 5 amperes, the FCL rms voltage increases more rapidly as a function of current. Fig.5 shows the line current, FCL voltage and load voltage before, during and subsequent to a fault.

Table 1 : Core materials and dimensions

Material	Specific Data	Dimension
Steel Core B_k H_k $\mu_{ru} = \mu_u/\mu_o$ $\mu_{rs} = \mu_s/\mu_o$	 1.62 T 30 A/m 2500 100 5	Coil Turns, NF=36 Section#1 Area =1500 mm^2 Length=165mm Section#2 Area =300 mm^2 Length=50mm
Permanent Magnet B_r H_r μ_m	NdFeB (EPSON Electric Co. Ltd) 1.1 T 0.35 MA/m $1.4 \cdot 10^{-6}$ H/m	l_m = 1.0 mm

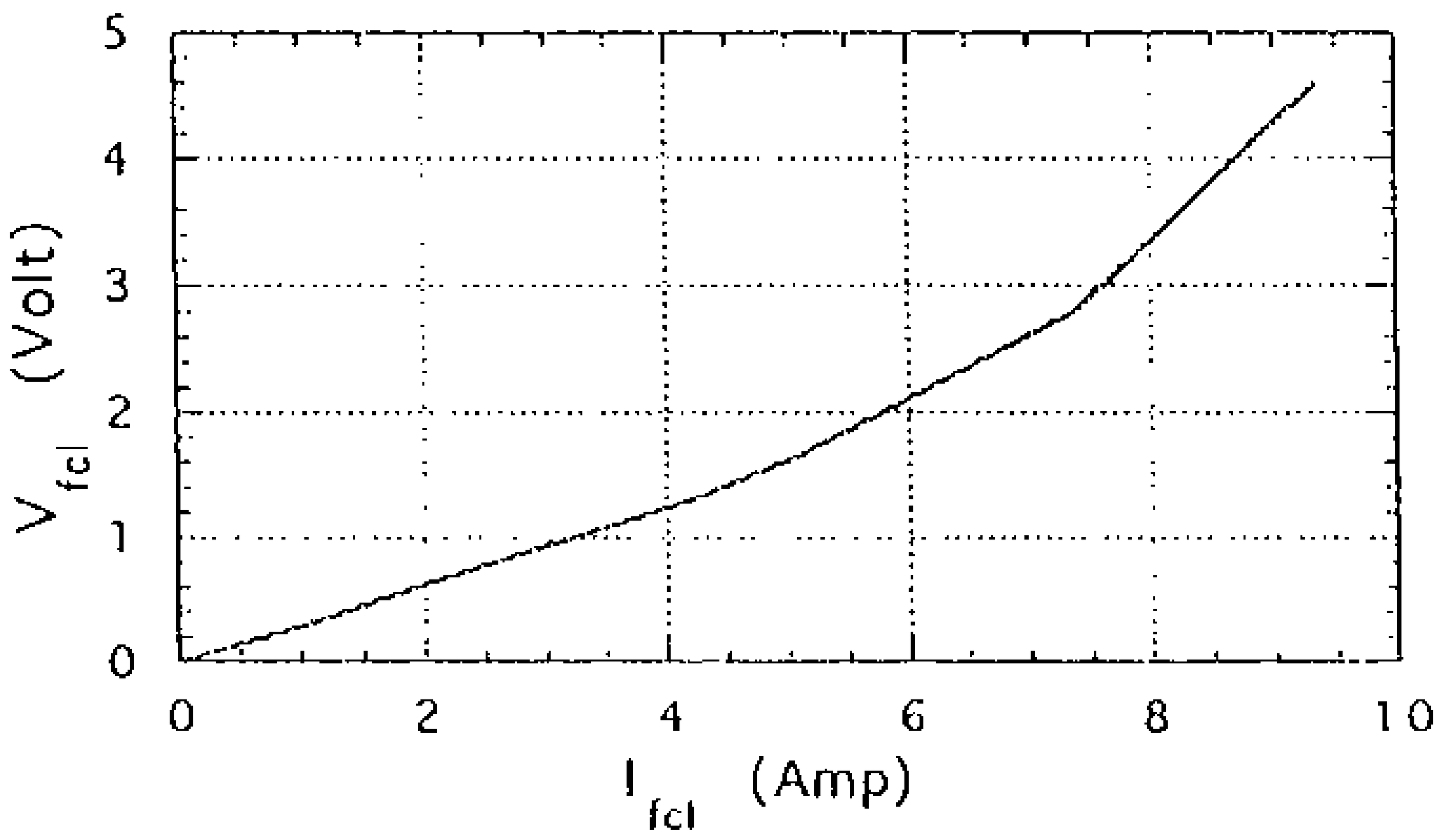


Fig. 4. RMS voltage vs RMS current of FCL.

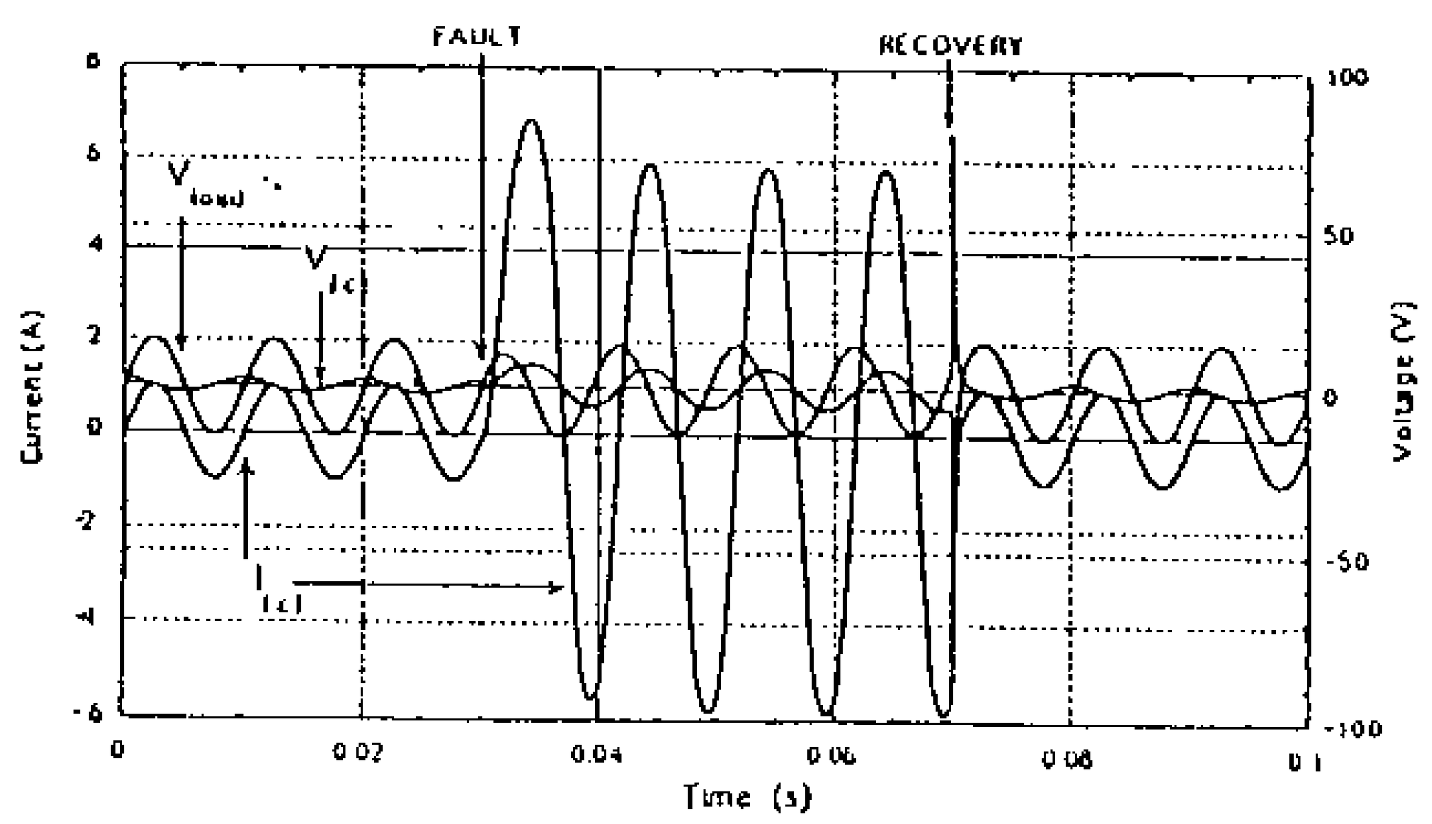


Fig. 5. Simulated waveforms for a typical fault condition.

V. Experimental Results

We have constructed an experimental current limiting device according to the material and geometrical specifications given in Table 1 and have tested it in the laboratory. Fig.6 show the rms voltage as a function of line current. Fig.7 shows the time domain waveforms of the load voltage, load current and FCL voltage prior to, during and subsequent to a fault. These results are in qualitative agreement with the simulation results shown in Fig.5.

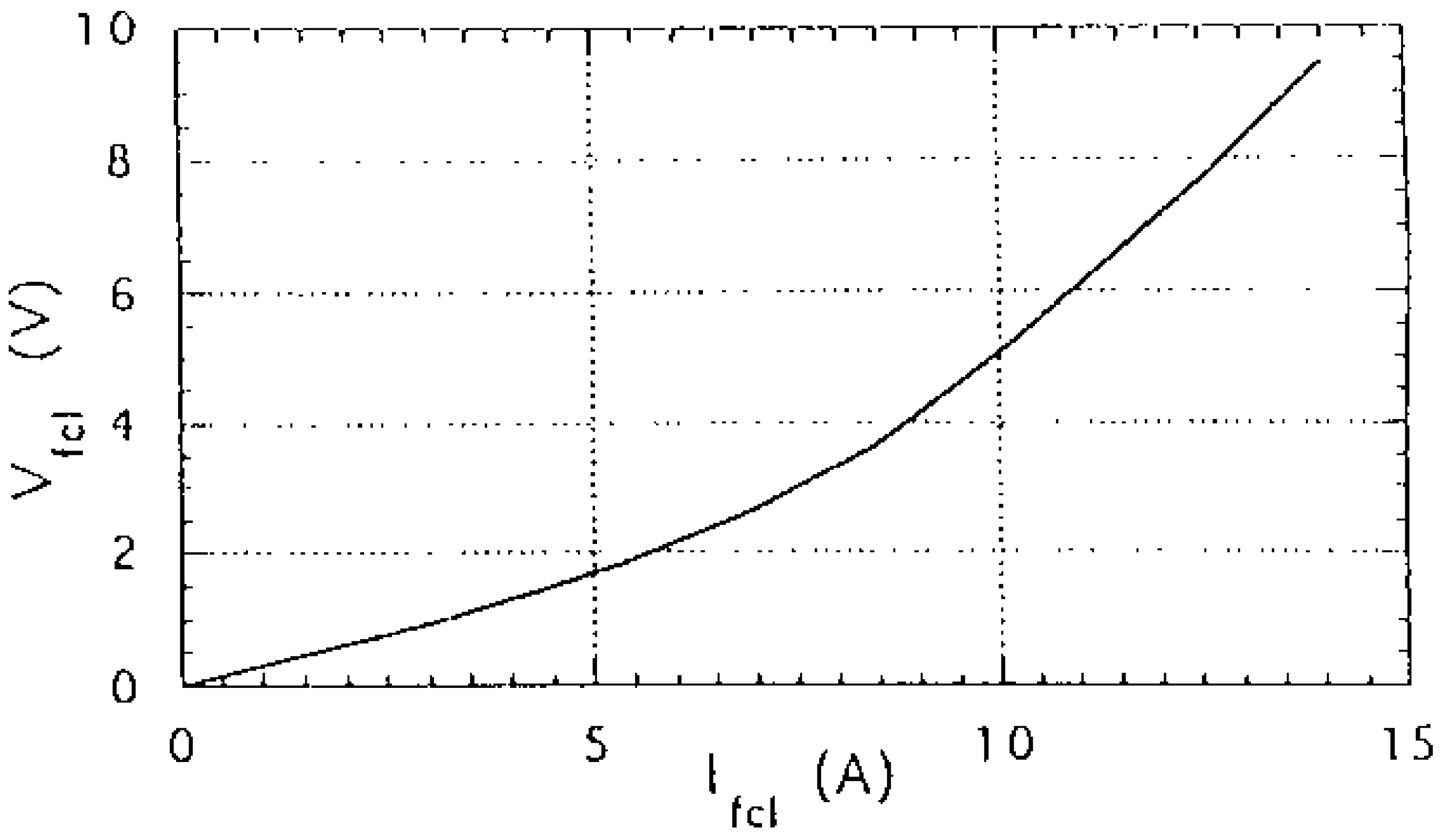
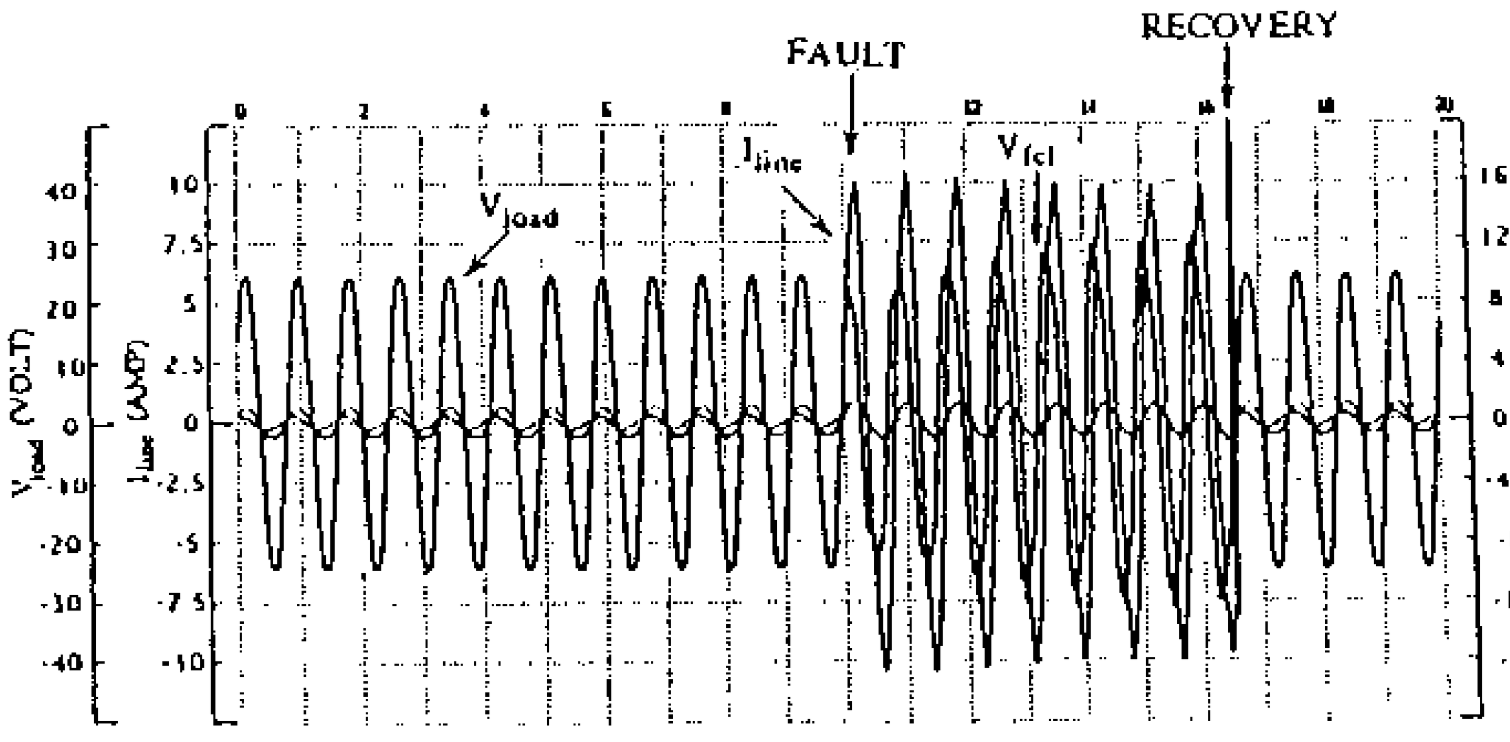


Fig. 6. RMS voltage vs RMS current .



Time (20ms/div.)

Fig. 7. Experimental waveforms for a typical fault condition.

VI. Conclusions

We have investigated the performance of a passive current limiter consisting of a permanent magnet and a steel core Design equations for this structure have been presented in this paper. The transient behavior of the device accounted for eddy current effects was analyzed using the Tableau approach. The experimental results are in qualitative agreement with the simulation results. Thus a full field output model which requires significant constraint resources can be avoided.

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