Design Improvements to a Three-Material Passive Magnetic Current Limiter

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Abstract—**This paper shows that flux nonuniformity in a passive magnetic fault current limiter softens the transition characteristics from the saturated to the unsaturated state. Soft transition characteristics lead to higher core losses and a derating in the maximum nominal operating current. Flux uniformity is improved by using a combination of extended magnets and an anisotropic saturable core. The use of distributed permanent magnets or an extended magnet leads to larger differential inductance ratios.**

Index Terms—**Fault current limiter, finite element analysis, permanent magnet, saturable core.**

I. Introduction

Increased reliability in power systems is achieved by interconnecting power systems. However, increased interconnectivity increases the short circuit current levels that leads to protection coordination problems. A fault current limiter (FCL) connected in series with the load can be used to alleviate this concern.

The authors have presented previous results on a novel passive magnetic current limiter consisting of a NdFeB permanent magnet, a high saturation flux density yoke, a low saturation density saturable core and a current winding. Two of these devices (FCLs) are required to provide bipolar current limiting capability. The windings of the two devices are connected in series with each other and the load [1], [2]. The magnetomotive force direction in the magnet of device 1 is opposite to that in device 2. The design of this current limiter has not been optimized.

The objective of this paper is to explore solutions for improving the performance characteristics of the FCL. A 2d finite element analysis software package is used to study the impact of material properties and geometry on the FCL performance characteristics.

Section II provides a brief summary of the FCL design issues. Section III describes the geometries that were considered for the simulation studies including the actions taken to achieve acceptable accuracies. Section IV describes a) the effect of saturable core anisotropy on the sharpness of the transition, b) the effect of a distributed magnet on the sharpness of the transition and the differential inductance ratio and c), the effectiveness of an extended magnet in contrast to a distributed magnet. Section V presents the conclusions.

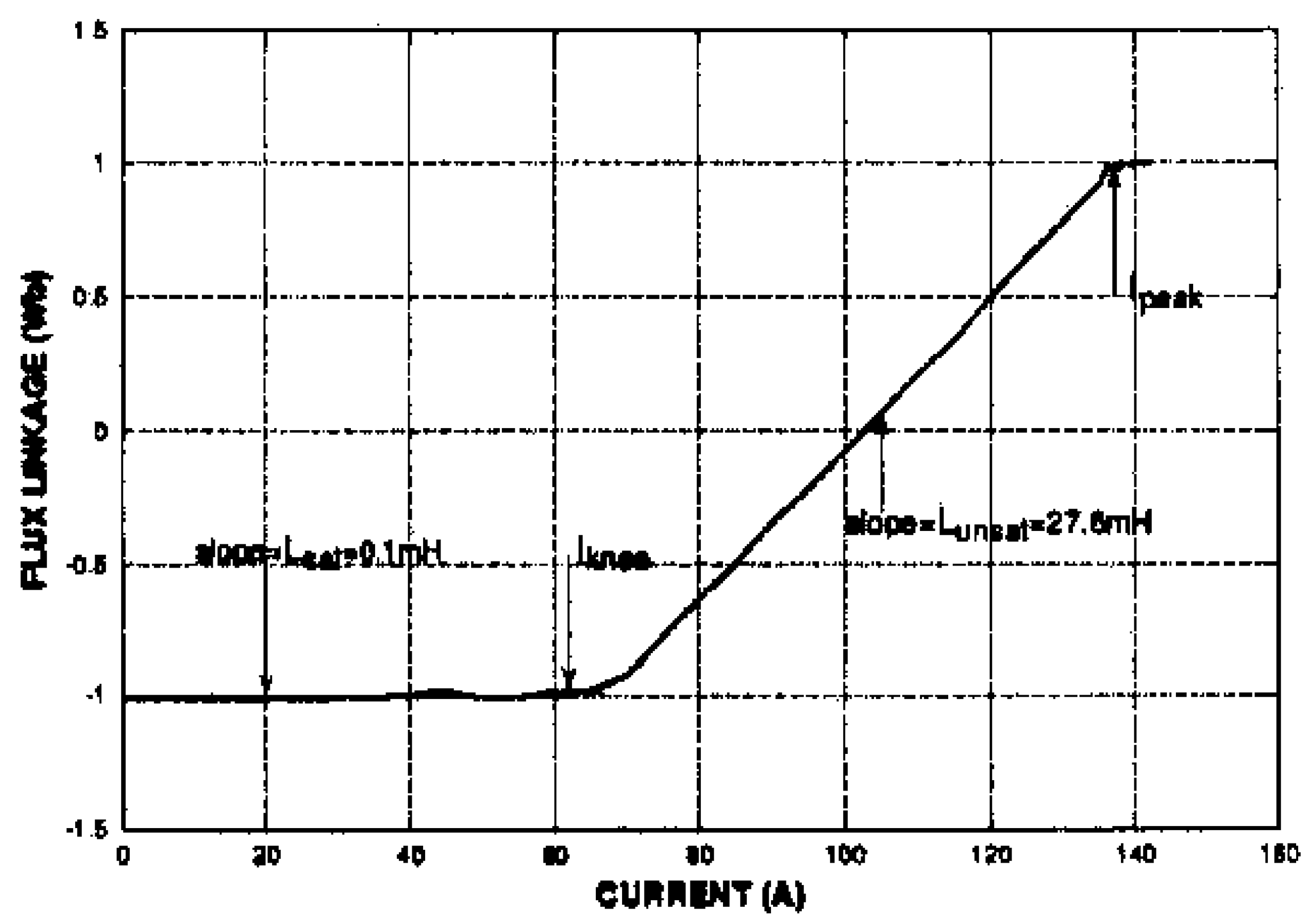

Fig. 1. Flux linkage versus current for an axisymmetric FCL geometry.

II. FCL Design Issues

A typical magnetic flux linkage versus current characteristic for a unipolar FCL is shown in Fig. 1. Under normal conditions, the core is in saturation. Above a specific threshold current level, (I_{knee}) and below a maximum current level (I_{peak}) the core operates in the linear regime. The device has a low differential inductance (L_{sat}) under normal conditions and a high differential inductance (L_{unsat}) above the threshold current.

The core geometry and material properties should be designed so as to achieve a sharp transition between the two different operating states and a large unsaturated to saturated differential inductance ratio. A sharp transition leads to a reduction in core losses and a reduction in the difference between the desired current threshold limit and the maximum nominal current. A large differential inductance ratio leads to an improvement in the current limiting effectiveness.

III. Geometry Studied and Simulation Issues

Fig. 2 shows one quarter of the geometry used for studying the effects of anisotropy. Anisotropy ratios (μ_{rz}/μ_{rr}) of 1, 10 and 100 were considered in this study. Fig. 3 shows one quarter of the geometry used for studying the effects of a distributed magnet and an extended magnet. The total magnet thickness for the distributed magnet example was maintained at 2 mm. 1 magnet, 2 magnets and 4 magnets were considered.

Table I provides the geometry and material details for the anisotropy tests. The material properties for the magnet and

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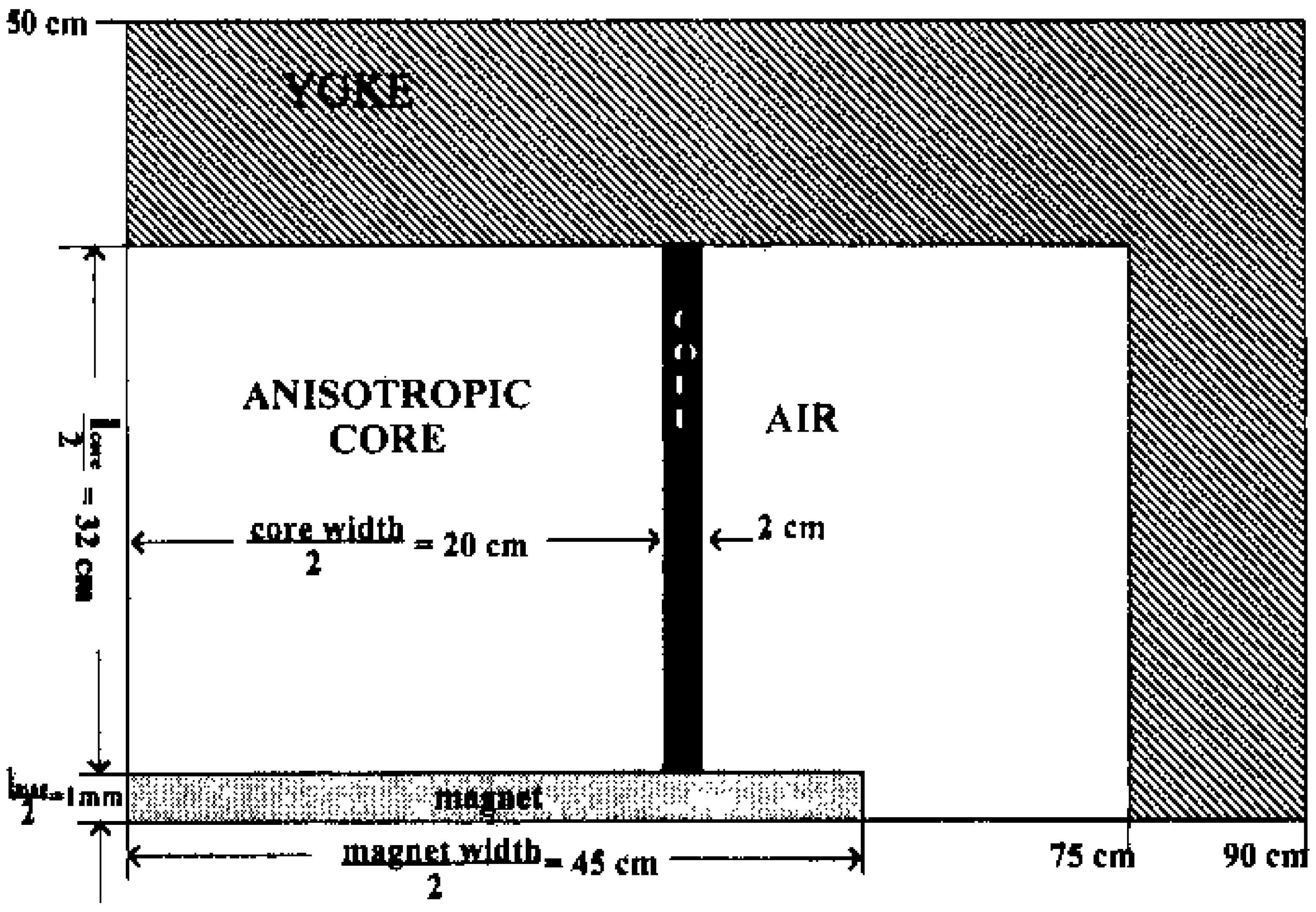

Fig. 2. Geometry of FCL used for anisotropy studies.

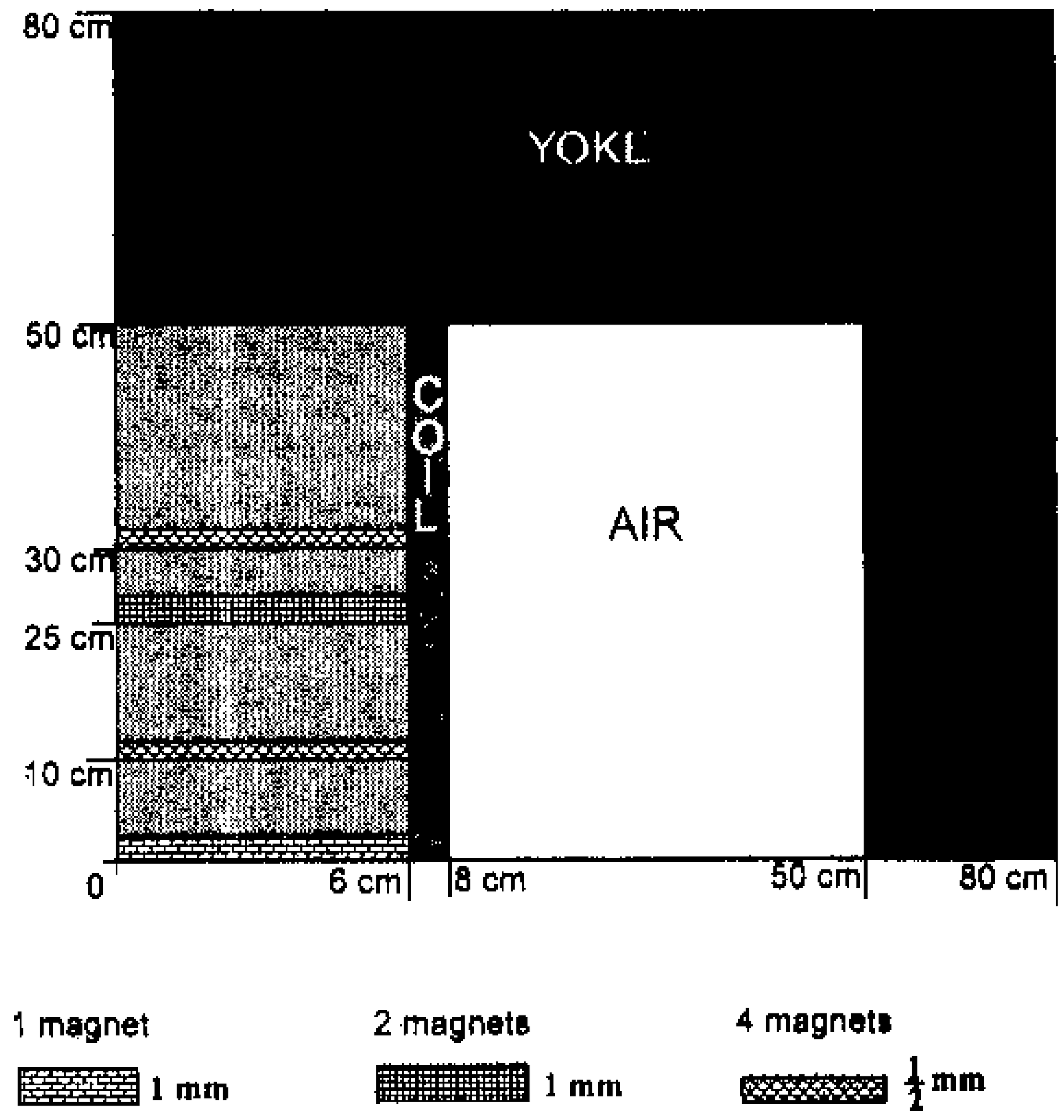

Fig. 3. Geometry of FCL used for distributed and extended magnet studies.

TABLE I
PARAMETERS FOR ANISTROPY STUDIES

$B_r = 1.12$ T	$H_c = 750$kA/m	$B_{is\_yoke} = 1.77$ T	$B_{is\_core} = 0.5$ T
$w_m = 90$ cm	$w_{core} = 40$ cm	$l_m = 2$ mm	$l_{core} = 64$ cm
$\mu_{r\_yoke} = 8000$	$\mu_{rz} = 5000$	$N = 32$	

TABLE II
PARAMETERS FOR DISTURBED AND EXTENDED MAGNET STUDIES

$B_r = 1.12$ T	$H_c = 750$kA/m	$B_{is\_yoke} = 1.77$ T	$B_{is\_core} = 0.5$ T
w_m = 12cm/46cm extended magnet	$w_{core} = 12$ cm	$l_m = 2$ mm	$l_{core} = 1$ m
$\mu_{r\_yoke} = 8000$	$\mu_{rz} = 5000$	$N = 16$	$\mu_{rz}/\mu_{rr} = 1$

yoke are representative of normal silicon steel and NeFeB magnet respectively. Table II presents the geometry and material details for the distributed and extended magnet tests. All simulation studies were performed using a commercial 2d finite element analysis software package [3].

Analytical design equations for determining the knee current (I_{knee}), differential inductance ratio (L_{unsat}/L_{sat}), differential saturated inductance (L_{sat}) and maximum current (I_{peak}) can be obtained by rederiving the equations in a cylindrical coordinate system (asymmetric geometry) using the procedure outlined in [2]. The analysis assumes a uniform flux density throughout the core and thus the flux versus current characteristic exhibits an ideal behavior, namely, an abrupt transition between the saturated and unsaturated state. The current limiter was designed to have a current knee point of 60 A.

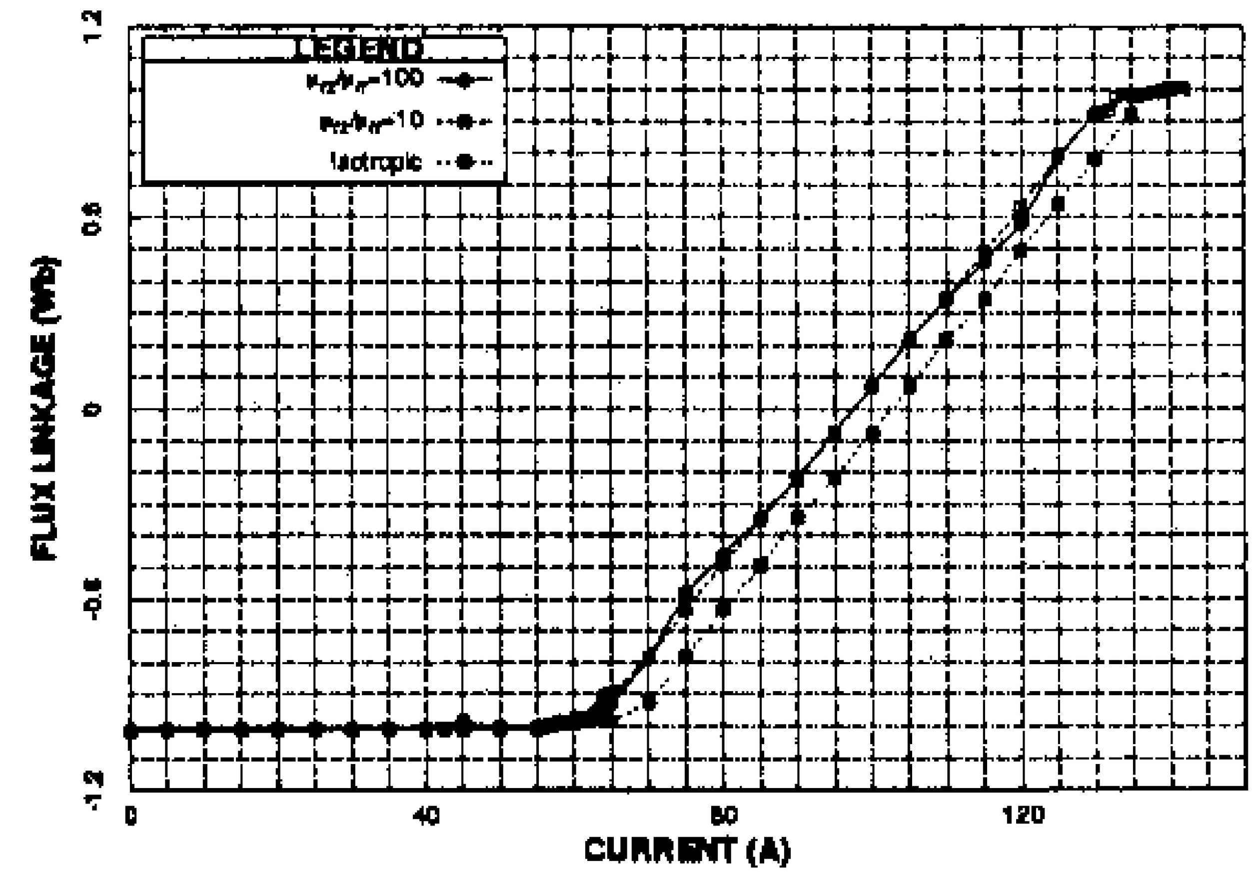

Fig. 4. Flux linkage as a function of current for three different saturable core anisotropies.

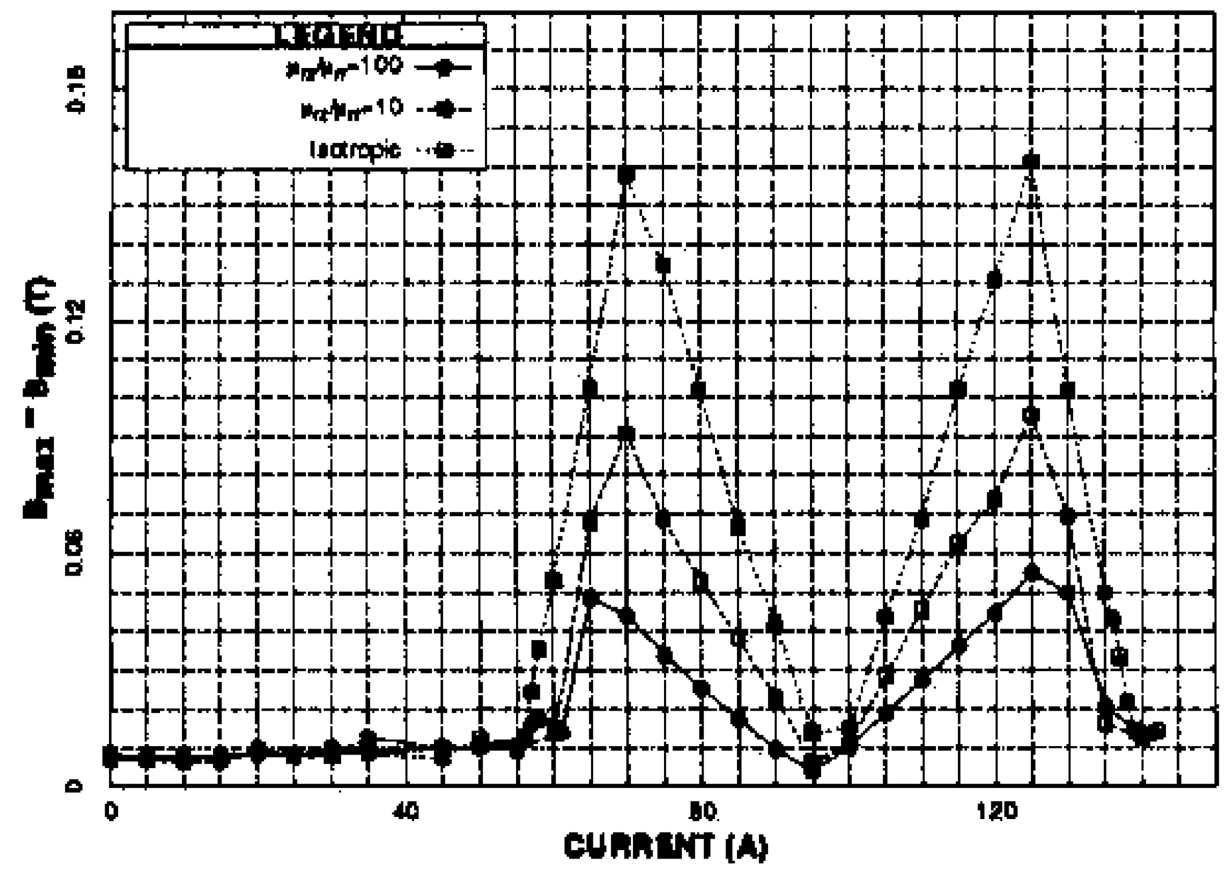

Fig. 5. Flux density uniformity ($B_{max}-B_{min}$) as a function of current for three different saturable core anisotropies.

Unfortunately, flux uniformity cannot be achieved in practice and therefore geometry or material modifications that can improve the flux density uniformity are of interest to the designer. Field uniformity was determined by considering the difference between the maximum and minimum flux density at all nodal points within the meshed area. The calculated values of flux density near material discontinuities is known to be inaccurate and therefore these values were not considered in the studies. Also, points at which the residual calculated errors were higher than 10 were ignored.

IV. RESULTS AND DISCUSSION

Fig. 4 shows the flux linkage versus current characteristics for three different anisotropies. The transition from the saturated to unsaturated state becomes more abrupt as the anisotropy ratio is increased. The improvement in the abruptness when the anisotropy is changed from 10 to 100 is not as great as when the anisotropy is changed from 1 to 10.

Fig. 5 shows the flux uniformity as a function of current for the same three anisotropies. The nonuniformity becomes more sharply defined at the transition point (I_{knee} =60 and

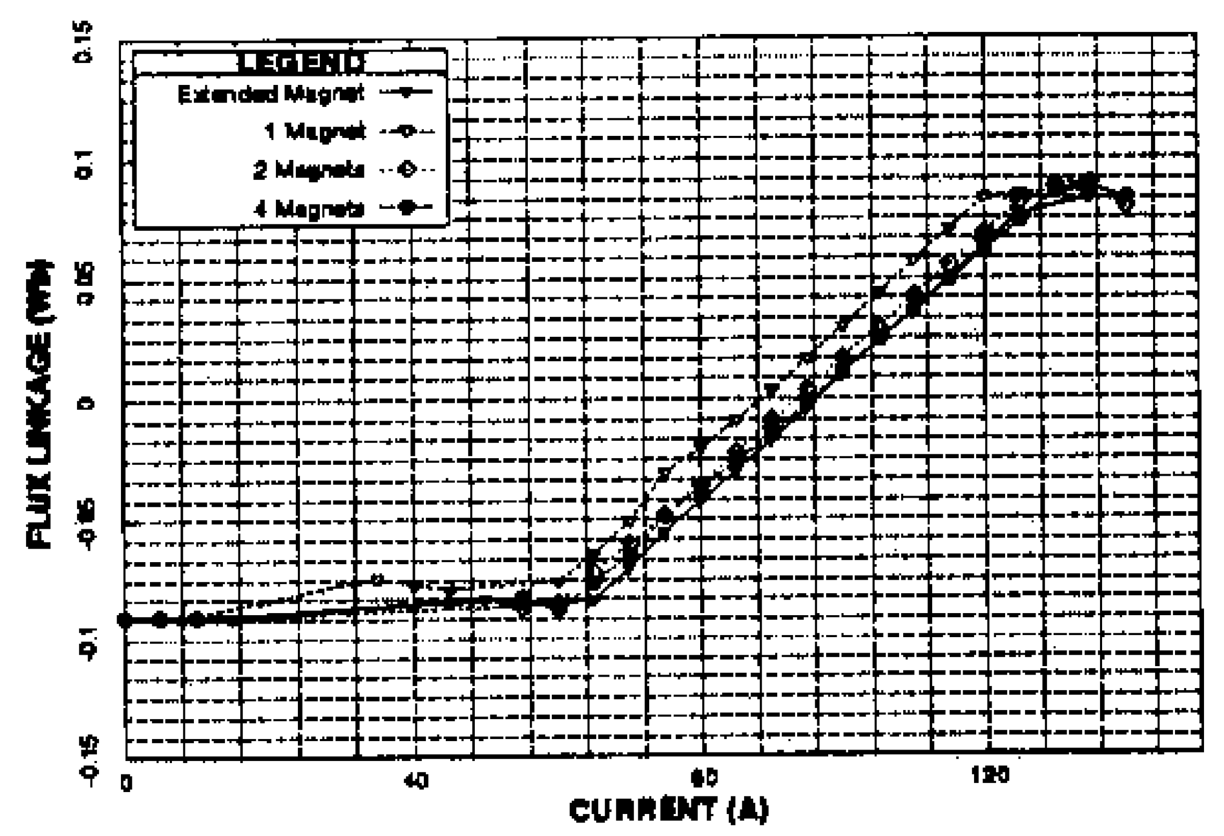

Fig. 6. Flux linkage as a function of current for distributed and extended magnets.

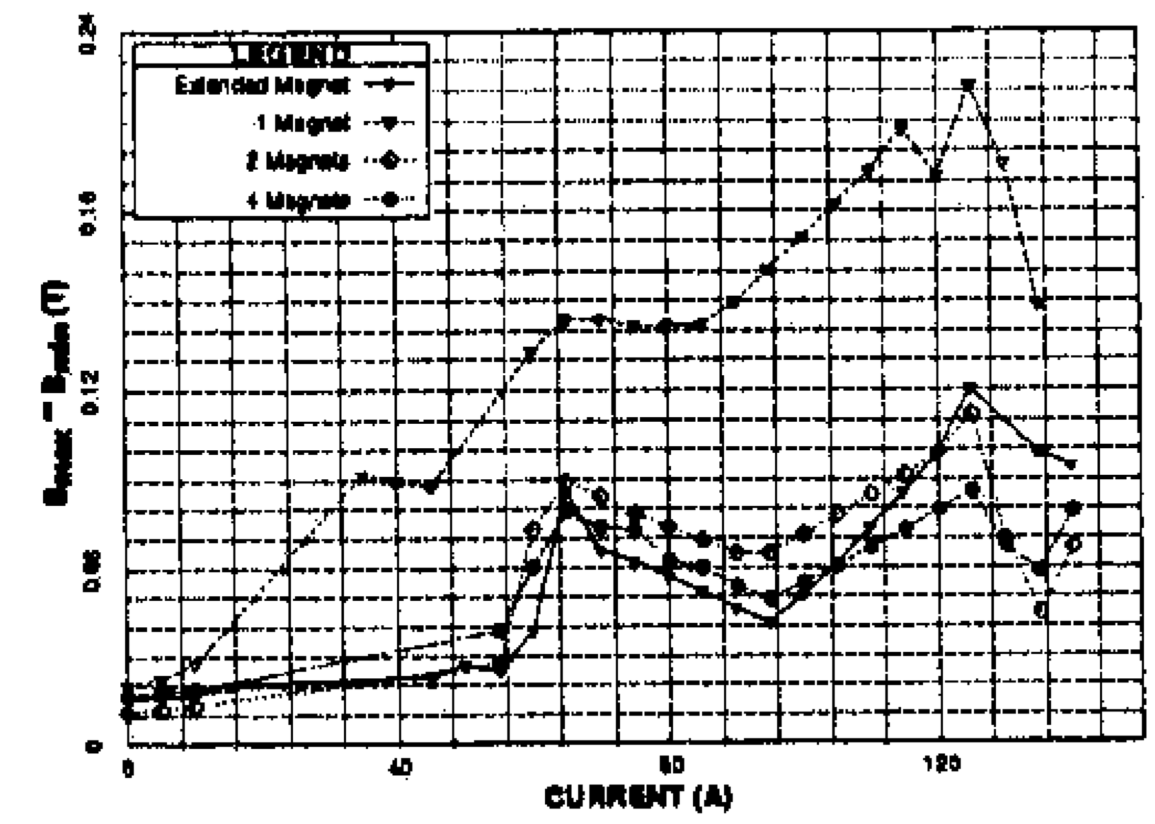

Fig. 7. Flux density uniformity ($B_{max}-B_{min}$) as a function of current for distributed and extended magnets.

I_{peak} =140 A) as the anisotropy ratio is increased. The relative peak nonuniformity is approximately halved for each order of magnitude change in the anisotropy ratio. Notice also that the abrupt change in uniformity occurs precisely at the I_{peak} and I_{knee} points if larger anisotropy ratios are used.

Fig. 6 shows the flux linkage versus current for distributed magnets and an extended magnet. The slight bump in the curve at 40 A for the 1 magnet example is a numerical artifact. The existence of a distributed magnet provides for a sharper transition. However, an extended magnet has the same effect, as long as the ratio [(intermagnet or saturable core length)/magnet width], A_r, for a distributed magnet is of the same order as the ratio [core length/(magnet width − core width)], A_m, using a single magnet.

Fig. 7 shows the flux density uniformity as a function of current for distributed magnets and an extended magnet. The nonuniformity is restricted to a small zone either side of the I_{knee} and I_{peak} transition points on the flux linkage versus current curve. Notice however that the single magnet example has a nonuniform flux density at all currents due to the significant amount of magnet flux that does not link with the yoke.

V. Conclusions

Fault current limiter losses can be reduced by increasing the sharpness of the transition between the saturated and unsaturated state. Sharp transition characteristics can be achieved using an extended magnet and an anisotropic saturable core material. Anisotropy ratios over 100 provide only marginal improvements. Distributing or extending the magnet leads to a larger differential inductance ratio. A combination of distributed magnets and extended magnets should be used for applications that require a high differential inductance ratio. The ratio A_r should be less than 1. The relative change in the differential inductance ratio as a function of the ratio A_r becomes insignificant if the ratio A_r is much less than 1.

The ratio A_m has the greatest impact on flux density uniformity. Its value should be less than 1. The improvement in flux density uniformity appears to scale linearly as the ratio A_m is decreased.

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