Finite Element Analysis of the Virtual Gap Technology: Controlling the Magnetizing Curve

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***Abstract*— Through nonlinear finite element simulations it is shown how the virtual gap technology can be used to control the characteristics of the magnetization curve of gapless iron-cores. A virtual gap is produced when passing current through holes in a core. This technique has been used in the past to control inrush currents and to obtain improved soldering with ac currents. In this paper we show that it is possible to control the magnetizing curve by varying the injected current in the holes. This feature opens the possibility of designing and building new devices for energy conversion equipment. In addition to the inrush current and soldering control, one could build gapless linear inductors, transformers with reduced acoustic noise, etc.**

***Index Terms* — Transformers, Inductors, Magnetizing Curve, Virtual Gap, Finite Elements.**

I. Introduction

AIR GAPS are introduced in magnetic devices to modify the saturation characteristics of the iron core. Iron-cores are used in inductors to obtain a large inductance value in a reduced package. However, because the ferromagnetic materials used in the iron-core are highly nonlinear a gapless inductor would have an inductance value that changes with the excitation (current or voltage) level. For most applications this behavior is unacceptable and design engineers resort to (small) gaps to control the inductance value. The mechanical control of a gap is a complicated and expensive manufacturing process. Not only the mechanical structure is weakened by the introduction of a gap, but the inductance changes substantially with small variations of the gap length.

Gaps are also used to modify the hysteresis cycle of a transformer core. When the voltage applied to, or the current drawn from, the transformer has a large DC component, a gapless core saturates easily therefore rendering the transformer useless. Also, some transformer applications are prone to draw large inrush currents. In both cases, even when gapping a core is expensive, the use of a gap is required in lieu of external electronic devices.

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A new technology called the "virtual gap" was proposed in [1]. The idea is to pass DC currents through holes made on a core to produce a localized saturation region. Because one can control the current, the size and degree of saturation can be controlled. Therefore, one could take all the advantages of a gapless core together with the advantages of a gapped core.

In [1] virtual gaps have been used to limit the inrush current that a transformer draws from the line. In [2] the virtual gap technology has been used to produce an enhanced soldering machine. The new machine allows the use of AC power to produce the high quality soldering results typical of DC soldering.

In this paper we have used toroidal iron-cores because by design they do not have air gaps. They are built from a continuous strip of grain-oriented silicon steel. Toroidal cores offer simultaneously the best magnetizing properties, the least tolerance to DC excitation offsets and the largest inrush currents.

II. Theoretical Background

A. Gapless Cores

Iron-cores are used in transformers, inductors, motors, etc. to magnify the magnetic flux and therefore minimize the size and cost of the devices. Designers have looked for techniques to reduce the air-gaps that naturally occur in transformer constructions because it is necessary to insert the windings in the core. By doing this the magnetizing current is minimized and the core can be operated at a higher flux density. Figure 1 compares the hysteresis loop for a gapless and gapped transformer core. Note that the gapless core hysteresis cycle tends to be rectangular with a large slope of the vertical sides.

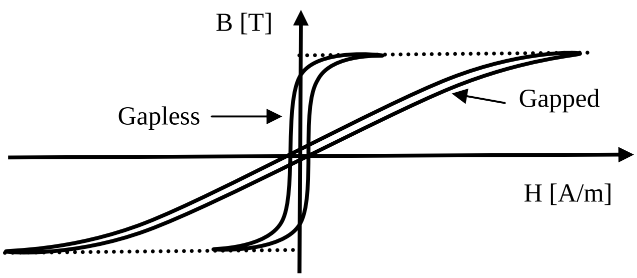

Figure 1. Hysteresis loop of a gapless versus a gapped core

B. Gapped Cores

When a gap, even a very small one, is introduced in a core, it determines the behavior of the entire magnetic system. The reason is because the relative permeability of the standard steels used for transformer/inductor cores is several orders of magnitude larger than that of the air. Figure 1 illustrates how the hysteresis loop is affected by a gap. Once can appreciate that the hysteresis loop is now thinner and linear for most of the operating range. Only when the core is operating close to saturation its intrinsic nonlinearity shows. Often inductor designers completely neglect the iron-core in inductance calculations. Figure 2 shows a toroidal core with a gap. The inductance for such arrangement is approximately computed from:

$$L = \mu_0 N^2 \frac{A}{l_g}$$

where:

μ_0 = Permeability of air (= 4 π 10^{-7})
N = Number of turns in the exciting winding
A = Cross sectional area of the core
l_g = Length of the gap

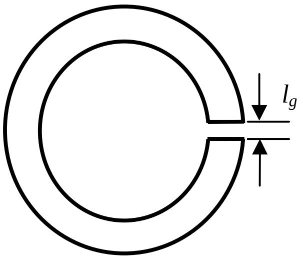

Figure 2. Gapped toroidal core

C. Virtual Gap

A virtual gap can be produced by saturating, in a controlled manner, a region of the core. This can be achieved by making holes on the core and passing currents through them. Figure 3 shows the basic idea of the virtual gap technology. Note that a saturation region is produced in the neighborhood of the holes. The size of the region can be controlled by the current intensity impressed on the holes.

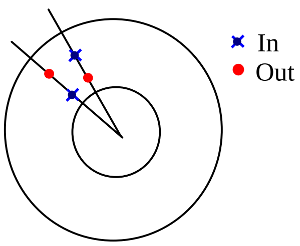

Figure 3. Producing a virtual gap

Although the same control can be achieved with only a pair of holes and currents, to avoid voltages induced in the virtual gap windings, it is preferred the use of two windings connected in contraposition as shown in Figure 3. This also cancels any circulating flux due to the current in the virtual gap windings.

III. Finite Element Simulations

Finite elements simulations were carried out with two purposes: first was the need to verify that a saturation region could be produced with the currents circulating in the holes; second we wanted to control the hysteresis curve of a core equipped with a virtual gap winding. Figures 4 and 5 illustrate how the virtual gap functions. Figure 4 shows a toroidal iron-core with no current circulating in the virtual gap windings (through the holes). Because the size of the holes is small the magnetic flux is not greatly disturbed by them. In Figure 5 a current is circulating in the virtual gap windings and a saturation region is clearly produced.

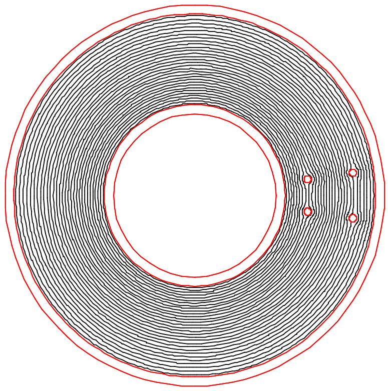

Figure 4. No current in the virtual gap windings

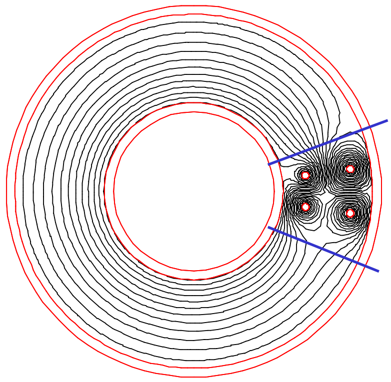

Figure 5. Virtual gap produced by DC currents

From Figures 4 and 5 one can make an additional important observation: The flux density in the case where the virtual gap is present is much smaller (Figure 5) than the flux density when the virtual gap is inactive (Figure 4). While the current in the main winding is the same, one can see many more flux lines in Figure 4 than in Figure 5. This indicates that for the same magnetic field strength (***H***) we have a smaller flux density (***B***). Therefore the hysteresis curve has been shifted down by the current circulating in the virtual gap winding, which is exactly what a physical gap does to the hysteresis loop. In the next section we will illustrate that by varying the current through the holes we can control the saturation curve.

IV. CONTROLLING THE MAGNETIZING CURVE

Extensive finite elements simulations were carried out varying the current injected in the virtual gap windings for a complete set of different excitation levels. The core was excited with the main winding to impress a flux densities form 0.1 to 1.8 Tesla in 0.1 intervals. Then a DC current was forced through the virtual gap windings and the new flux density was measured. Figure 6 summarizes the results. The numbers over the lines are the amperes that are injected in the virtual gap holes. Thus the upper line, labeled with "0" is the original magnetizing curve of the core.

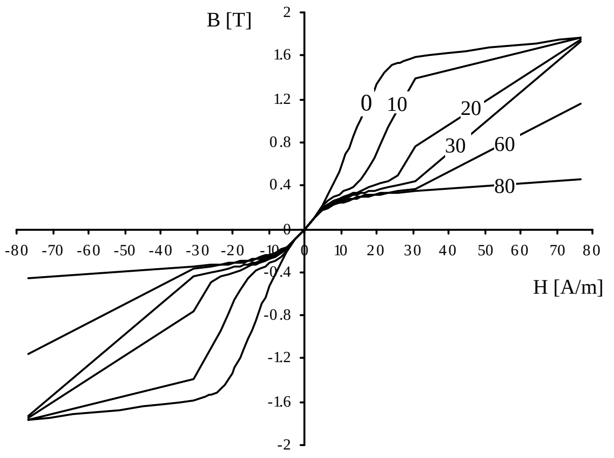

Figure 6. Controlling the saturation curve

We can appreciate how as the current through the holes increases the magnetic flux density reduces for a given excitation. This is equivalent to have a core with a reduced permeability or a real air gap. Note that the initial permeability is the same for all cases. The curve labeled with "10" resembles the original magnetizing curve, but it is moved slightly down. As we increase the current in the holes the effect of the gap is more pronounced. For "80" amperes circulating in the holes we have a linear magnetizing curve.

Note that the curves exhibit sharp corners because in the finite elements program used for the simulations, ANSYS, nonlinear materials were represented by piecewise linear models.

Figure 7 illustrates the sequence of the behavior of the magnetic field for different main winding excitation levels for the case when the current in the holes is 20 A. As we can see from the figure, the saturation region is a function of the current in the holes and the instantaneous magnetic field strength applied to the core.

Figure 7(a) corresponds to the case where the current in the main winding is zero. Once can appreciate that the current in the holes produces a local field in the neighborhood of the holes. There is no net flux circulating around the core, however when the current in the main winding is large enough the saturation region around the holes disappears, see Figure 7(d).

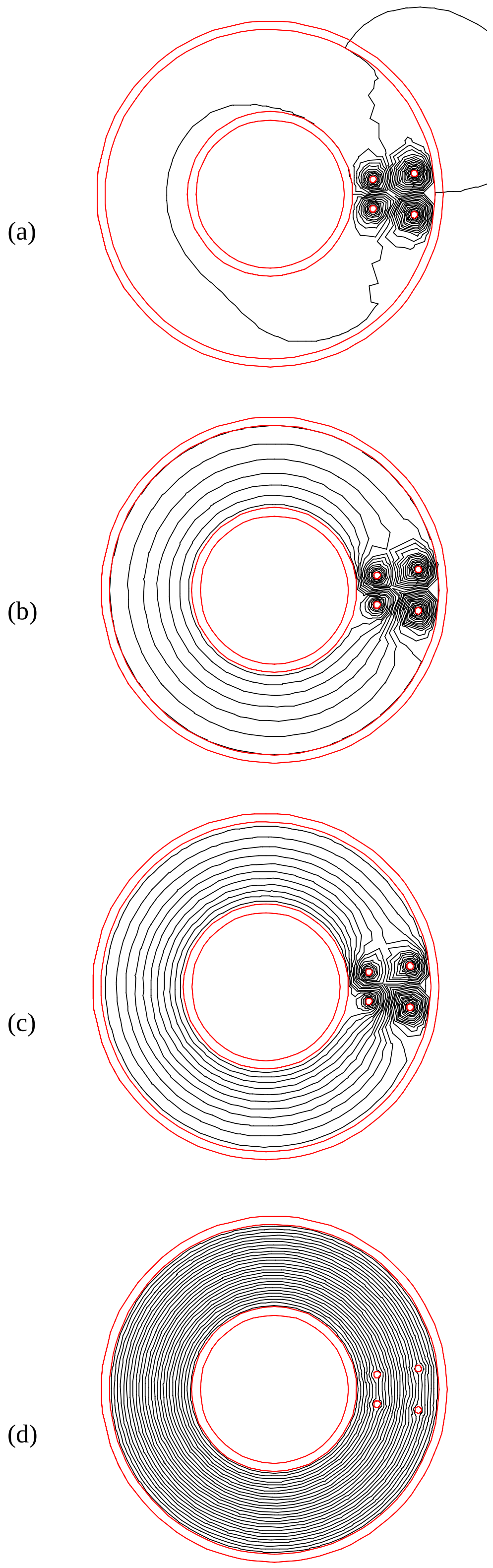

Figure 7. Magnetic flux density for 20 A applied to the virtual gap windings and different excitation levels in the main winding:

(a) $I_{winding} = 0A$
(b) $I_{winding} = 5 A$

(c) $I_{winding}$ = 15 A
(d) $I_{winding}$ = 75 A

V. Virtual Gap Size

Figures 8 illustrates how the size of the virtual gap (the saturated zone around the holes) can be controlled by the current intensity applied to them. Figure 8(a) shows the magnetic flux density when the current in the holes is one ampere and Figure 8(b) shows the magnetic flux density for a current in the holes of one hundred amperes. Not only the saturated zone is larger when a larger current is applied to the holes, but also the saturation is higher. In Figure 8(a) the magnetic flux density varies from 0.4 in the region far from the holes to 1.8 T right at the holes. In Figure 8(b) the magnetic flux density goes from 0.77 T in the shaded region to 2.04 T for the darker internal region. The magnetic flux density of 2.04 T corresponds to the complete saturation of the region. Therefore a gap has truly formed since the permeability of that region has reduced to the same of the air.

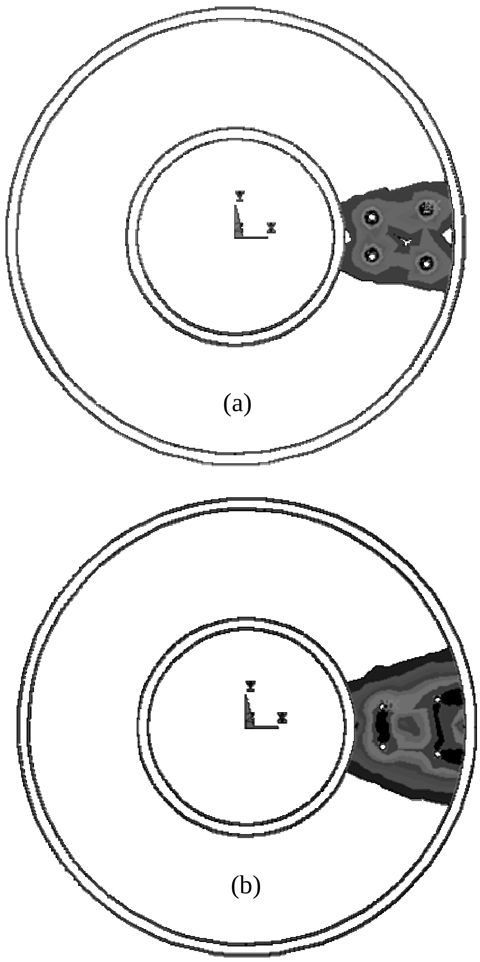

Figure 8. Magnetic flux density due to the current in the holes. (a) I_{holes} = 1 A, (b) I_{holes} = 100 A

We can conclude from this experiment that effective control of the size of the gap can be gained by varying the current in the holes.

VI. Applications

As it was mentioned in the introduction the virtual gap technology has been already used to limit transformer inrush currents and to build soldering machines [1], [2]. In these applications a DC current was passed through the holes.

We have experimented with AC currents though the holes and have obtained interesting results. A quasi-virtual linear inductor has been built on a gapless core. This has allowed substantial savings in materials, since very large inductance values can be obtained from small cores when there is no gap. Inductances in the order of henries can be built in 10 cm diameter toroidal cores. The results of those developments are to be presented in a sequel to this paper.

We also intend to use the knowledge gained in this work to build transformers with reduced acoustical noise emissions.

VII. Conclusions

With finite element simulations we have demonstrated that the virtual gap technology can be used for controlling the saturation characteristics of an iron-core. The size of the virtual gap is directly proportional to the current circulating in the virtual gap winding. The virtual gap technology opens many possibilities to the designer of electromagnetic devices.

VIII. References

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IX. Biographies

Francisco de León (S’86, M’92, SM’02) was born in Mexico City in 1959. He received his B.Sc. and M.Sc. from Instituto Politécnico Nacional in 1983 and 1986 respectively. He obtained his Ph.D. from the University of Toronto in 1992. He has held several academic positions in Mexico and has worked for the Canadian industry. Currently he is with CYME International developing commercial grade software for power and distribution systems. His research interests include the electromagnetic modeling and design of electrical machines.

Salvador Magdaleno was born in La Piedad, Michoacán, Mexico in 1983. He is an undergraduate student of electrical engineering at Universidad Michoacana de San Nicolás de Hidalgo (UMSNH). His research areas of interest include the numerical calculation of electromag-netic fields using the finite element method.