Factors Affecting Normal Flux and Iron Loss in Laminated Cores

Ahmad Ebrahimi
University of Shahid Rajaee

Keywords:
Building Factor: Actual loss/ Nominal loss
ZDKH: A high permeability material
Normal flux: Flux transfer between strips during the ac magnetization process

Abstract: This paper presents experimental evidence that four types of magnetic laminated core materials of grain oriented 3% silicon-iron cut and magnetized at 0^o to their rolling direction and one type of amorphous material (POWERCORE) affects the magnitude of the normal flux density distribution transfer between them. Stacks of laminations were magnetized at 50Hz between 1.0 and 1.8 T and the normal flux was found to vary from about 0.5 to 1.2 mT. The flux transfer in any group of samples could vary by as much as 100% according to the different types of materials used with possible consequential differences in the power loss due to associated in-plane eddy currents.

1. Introduction

Before discussing some aspects of normal flux and loss distribution in electrical machines and transformers, it is worth briefly considering some of today's important advances in stacked of electrical steels and renewed interest in iron losses. Modern electrical steels have developed with the main objectives of achieving high magnetic induction and low losses combined with low production costs. However, the need for higher efficiency not only in transformers but also in relatively small rotating machines calls for a review of the present philosophy. As soon as 1979, losses in 500 MVA generator transformers were being capitalized at up to 2.5 million pounds and since then it has been estimated that a 0.1 Wkg^{-1} reduction in iron losses could save about 150 million pounds per annum[1]. The scale of core losses is difficult to quantify, but Werner [2] has estimated that in the USA they account for about 4.5% of all energy generated and about one third of this is dissipated in distribution transformers.

There are possibilities that large capitalized iron losses might receive the trend of using higher flux densities in transformers. One comparison [2] shows that designing a large transformer to operate at a flux density of about 20% lower than presently accepted would reduce the core losses by 30 to 50 times the energy required to produce the necessary large core. Another analysis [3] shows that as capitalized costs increase above 2.5 \$ W^{-1} it becomes economically sound to operate at 1.5 T or below, compared with levels of 1.7 T and above used at present. More accurate predictions of life cycle costs of ownership are necessary but closer liaison between user and manufacturer is essential if the general low loss capitalization values are to be corrected [4].

The tendency to consider the use of lower flux densities casts doubt on the use of modern high permeability grain-oriented steels which have been purposely developed to have optimum properties at high flux densities. Table 1 illustrates the superiority of such material over other electrical steel, but significant improvements have been made recently in the properties of non-oriented steels to narrow the gap and even to make them possible economic replacements in some large devices [5].

Table 1 also shows some characteristics of rapidly quenched materials whose properties are superior to those of conventional steels. If current trends towards lower losses at the expense of lower normal flux densities continues, such materials, particularly the 6.5% silicon iron semi-crystallized alloy, will compete in several markets with conventional steels.

Material	**Thickness (mm)**	**Total loss (Wkg^{-1}) (1.5 T, 50 Hz)**	**Flux density at 800Am^{-1}, 50 Hz(B_{800})**
high permeability grain-oriented 3%laser scribed	0.30	0.72	2.01
high permeability grain-oriented 3% silicon iron	0.27	0.74	1.37
conventional grain oriented 3% silicon iron	0.30	0.95	1.82
best quality non-oriented 3% silicon iron	0.35	2.12	1.50
6.5% silicon iron semicrystalline	0.08-0.15	0.5-0.7	1.70
amorphous material (POWERCORE)	0.14	0.25	1.50

Table 1.Comparison of typical properties of a range of electrical steels

In order to use any of these materials to the best advantage in any particular device, it is necessary to have a good knowledge of the normal flux distribution from which the power loss may be estimated. In this connection the so-called building or destruction factor is an important parameter as it represents the increase in per-unit loss found in an assembled core over that of the same material measured in an Epstein test, i.e. the nominal loss. Building factors typically range from 1.0(i.e. no increase in loss) to over 2.0 and in general they are highest in cores with complex geometries. It is shown in this paper that the building factor is very dependent upon the normal flux distribution in a device.

2. Experimental Method

Pairs of 280-mm-long, 80-mm-wide, 027 and 0.30-mm-thick strips of grain oriented 3% silicon iron and amorphous material 0.14-mm-thick cut with their longitudinal direction parallel to the rolling direction were magnetized at sinusoidal flux densities from 1.0 to 1.8 T (peak) at frequency of 50 Hz. Search coils made from 0.05-mm-diam copper wire were glued in position at selected points on the surface of laminations in order to detect the interlaminar flux when the laminations were placed on top of each other. The average value of the emf, e_{Av}, induced in each 4-cm^2 coil was measured and used to calculate the normal flux density B_N from

$$B_N = \frac{e_{Av}}{4fNA} \qquad (1)$$

Where f is the magnetizing frequency, N is the number of turns (one in this case) and A is the area enclosed by the coil ($4 * 10^{-4}\ m^2$). The longitudinal flux density, B_L, was monitored in a similar way with a 20-turn search coil surrounding the pair strips under test.

3. Discussion and Results

In order to clarify the relation between the building factor and the magnetic properties of the steel sheets, used in this investigation as core materials, four types of grain-oriented 3% silicon-iron and one type of amorphous materials were employed. These included three high permeability materials, Hi-B, which include two non-scribed and a laser-scribed materials with thicknesses of 0.30 mm, 0.27 mm and 0.30 mm respectively. Conventional grain-oriented materials, C.G.O., with a thickness of 0.30 mm, were also used in this investigation.

Normal flux in stacked sheets increased with increasing number of laminations of each stacking unit in the experimental material as presented in Figure 1.

The building factor in the C.G.O. materials is known [6] to increase as the number of laminations per stacking in the unit increase, as shown in Figure2. This is because the normal component of magnetic flux increased while the longitudinal flux deviated from the rolling direction especially at the T-joints and corners of the transformer cores.

It can be deduced, from Figures 2, 3, and 4 that an increase in the magnitude of normal flux density of about 1.0 mT increased the nominal loss by around 4% and consequently destroyed the building factor ratio by about 0.1 in the C.G.O. material.

The magnitude of the normal flux density in stacked sheets of grain-oriented silicon-iron material increases with decreasing μ_c/μ_L of the sheets. The μ_c/μ_L is the ratio of the permeability in transverse direction, μ_c, to the permeability in longitudinal (rolling) direction, μ_L, of the strips. This could be interpreted as follows. At any instant during the period of magnetization when the magnetic flux in the middle limb of a 3-phase transformer core is zero, shown in Figure 5, the longitudinal flux at the T-joints flows in the transverse direction of the sheets as the magnetic reluctance in this direction is very high.

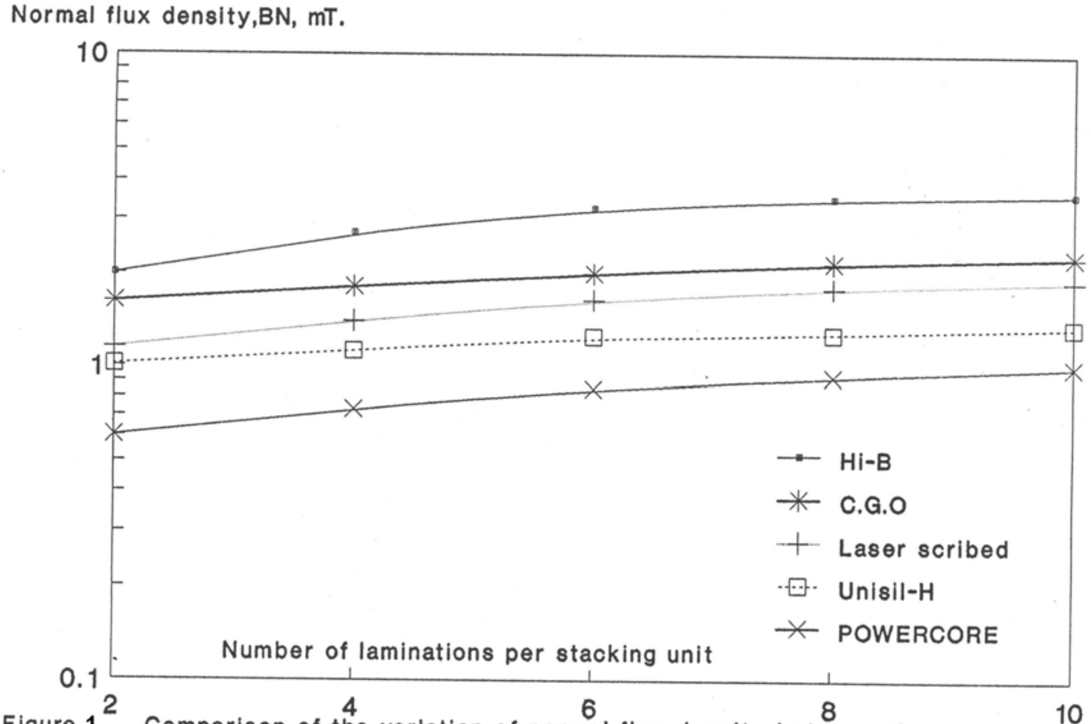

Figure 1 Comparison of the variation of normal flux density between the same pair of strips of various materials when placed in stacks of the same materials (amorphous material is 1.4T,50Hz, grain oriented steels is 1.7T,50Hz,magnetised).

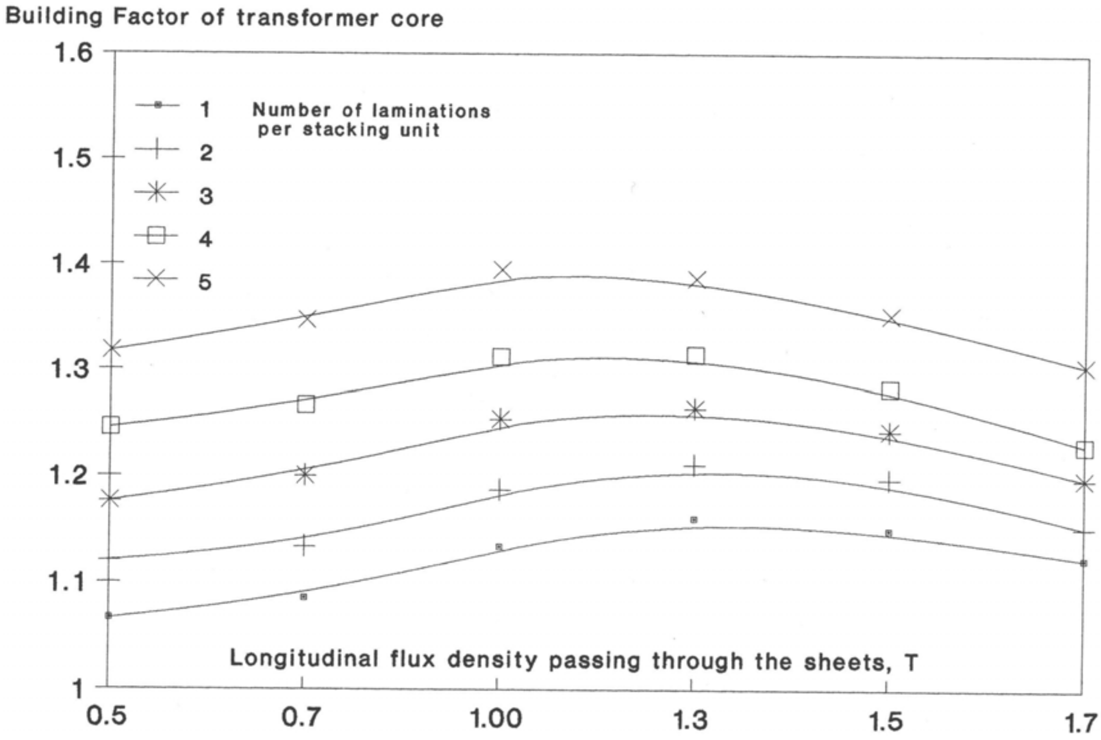

Figure 2 Variation of Building Factor with induction levels in different stacking units in C.G.O. strips at 50Hz.[1]

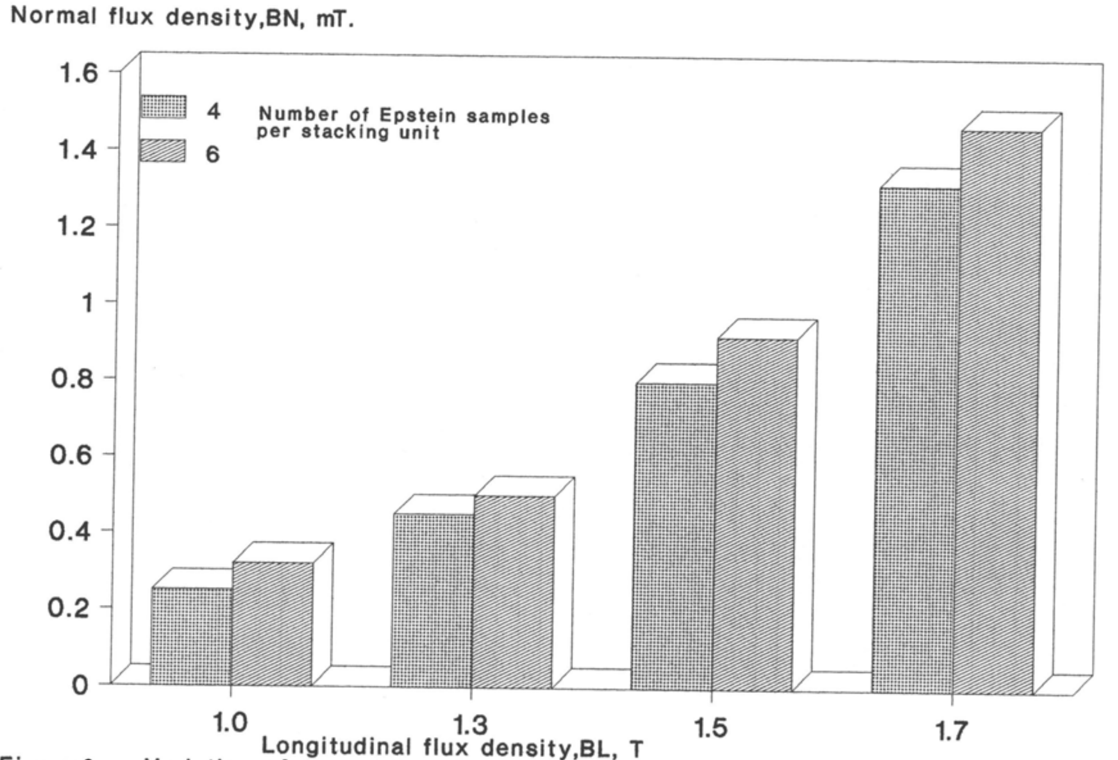

Figure 3 Variation of normal flux density with longitudinal flux density in C.G.O strips magnetised along the rolling direction

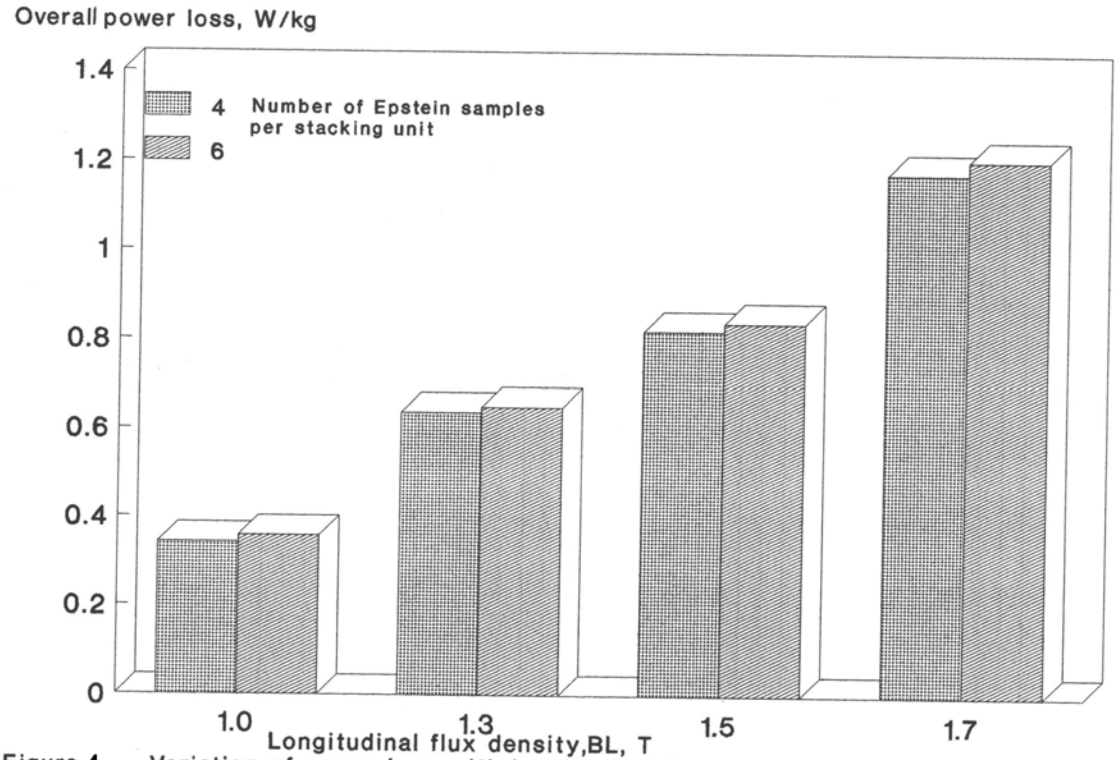

Figure 4 Variation of power loss with longitudinal flux density in C.G.O strips magnetised along the rolling direction

Normal flux transfer from lamination to lamination increases because of this high magnetic reluctance. The flux at the T-joints easily tends to deviate from the transverse direction and flows into the middle limb. The amount of the deviated flux would therefore increase with decreasing μ_c/μ_L. It has been found [6] that the building factor diminishes with increasing peak flux density. This is no interpreted by the concept of the lfux penetration because the relative permeability in the transverse direction, μ_c/μ_L, decreases with increasing flux density. This decrease in building factor is considered to be due to the decrease in normal flux being generated in the vicinity of the lap joints.

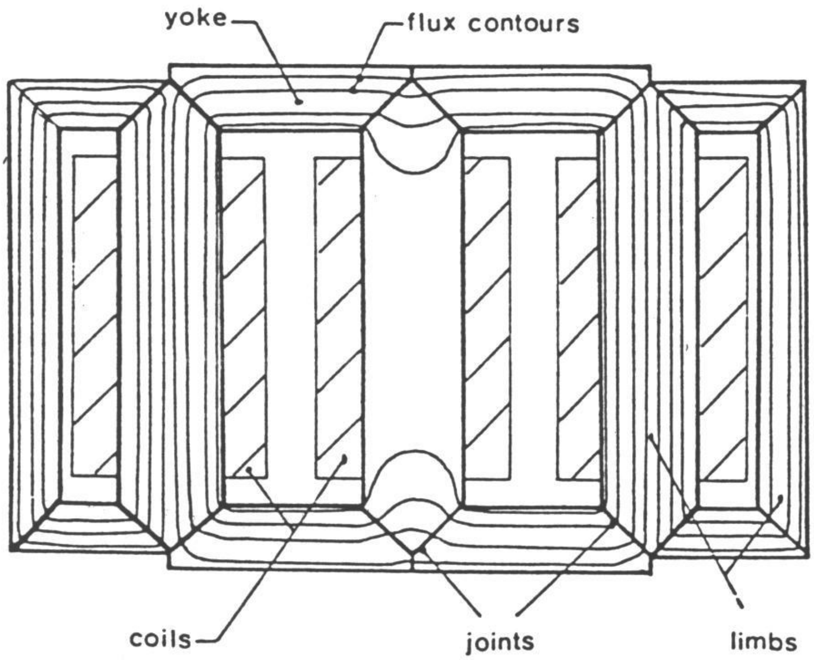

Fig. 5 Theoretical vector potential distribution in a 5 limb, 3 phase transformer core at an instant in the cycle when the centre limb coil voltage is zero ($B_{peak} = 1.5$ T, 50 Hz).

The magnitude of normal flux density of conventional grain oriented material with respect to the high permeability one, is low as presented in Figure 1. It was found that the power loss and magnitude of normal flux density in the stacked amorphous material, POWERCORE, were lowest among the present experimental materials. This is shown in Figures 6, and 1 respectively. In identical conditions the building factor of conventional grain-oriented material, would be less than that of high permeability grain-oriented ones as shown in Figure 7. In the ingle phase model with amorphous and high grade non-oriented materials, the building factor is close to unity.

The normal flux density transfer from lamination to lamination during the magnetization process in magnetic core materials increased in the order of POWERCORE, Unisil-H, Laser scribed, C.G.O. and Hi-B materials as presented in Figure 1.

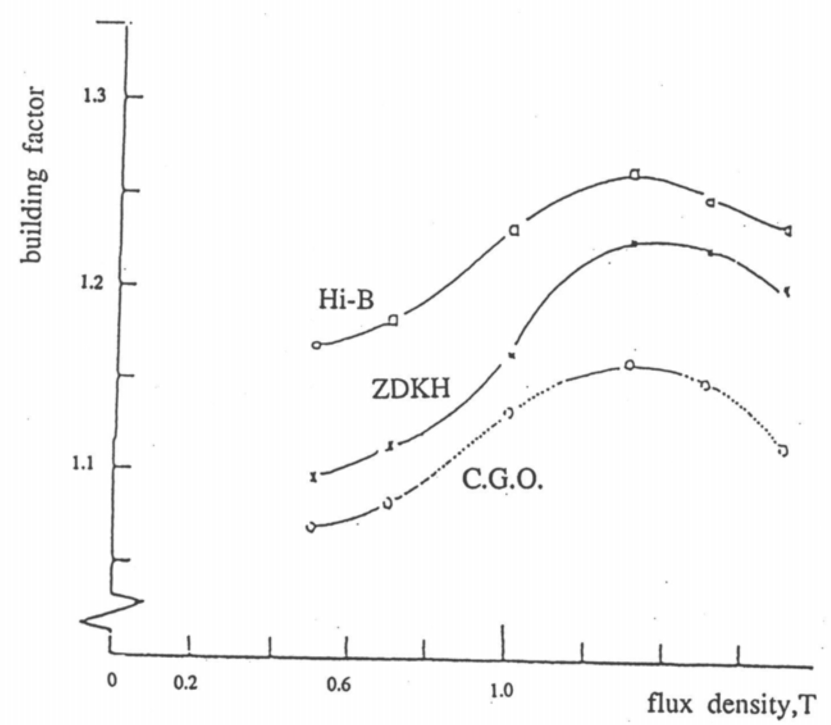

Figure 7 Effect of core material on building factor

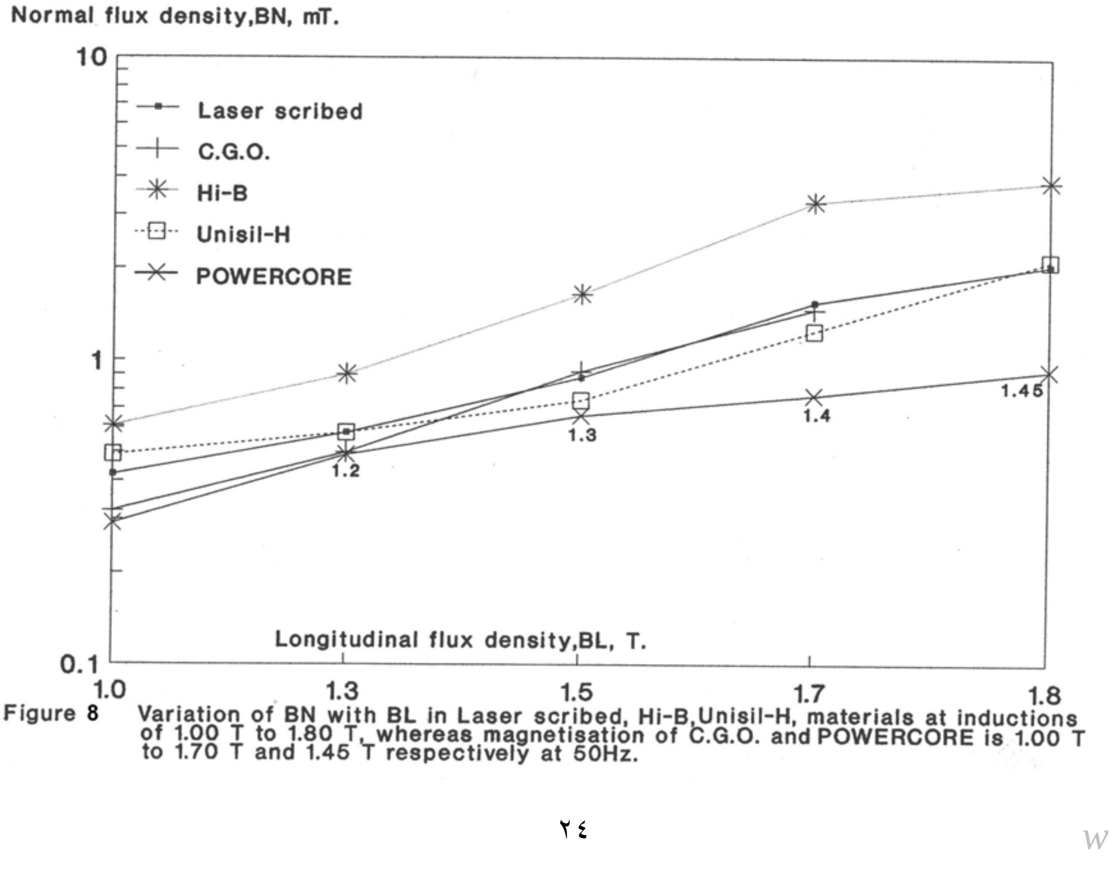

Figure 8 Variation of BN with BL in Laser scribed, Hi-B,Unisil-H, materials at inductions of 1.00 T to 1.80 T, whereas magnetisation of C.G.O. and POWERCORE is 1.00 T to 1.70 T and 1.45 T respectively at 50Hz.

also makes the flux distribution less uniform in the normal direction, and causes flux concentration in adjacent layers of each unit. That in turn gives rise to localized saturation at the lower flux density level, especially while the sheets were magnetized at large angles to their rolling directions in the corners and T-joint of 3-phase transformers. The normal flux density can cause an increase of about 10% in the localized power loss in areas around the butt joints [7].

The magnitude of normal flux density for stacking at 45^o magnetization direction was found to be around 22 mT. It is predictable that the eddy current loss due to the normal flux will increase by around 30% of the nominal loss [8]. Where the longitudinal flux should be deviated from the rolling direction, the localized normal flux density will increase sharply in the T-joint and corners of 3-phase grain-oriented transformer core.

The building factor of conventional grain-oriented core material compared with the Hi-B stacked sheets, is lower over the complete flux density range as shown in Figure 2. The distribution of longitudinal flux density is more uniform in C.G.O. stacked sheets compared to that in the Hi-B stacked sheets due to low permeability, small magnitude of normal flux density, small permeability and readiness to be magnetized in the transverse direction.

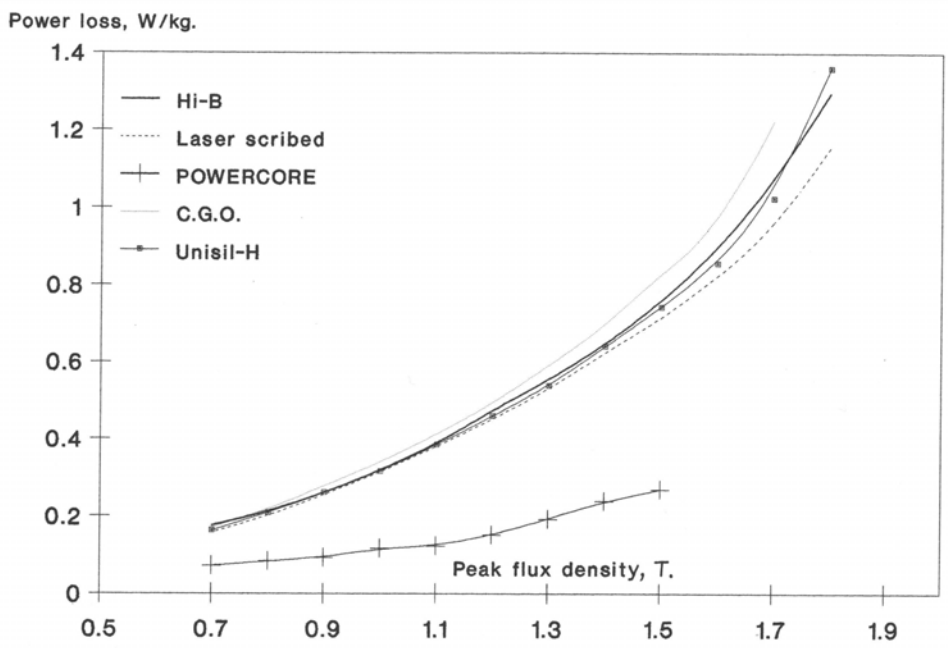

Figure 6 Variation of power loss with flux density in grain-oriented 3% silicon-iron & amorphous material.

The magnitude of longitudinal flux at the corner joint is large in the C.G.O. laminated core and small in the Hi-B core. This seems to indicate that much more flux is transferred in the normal direction in the corner joint of Hi-B stacked laminated core than in the C.G.O. core [6]. The present experiments have shown that there is a considerable difference between the magnitudes of normal flux density when the stacks of laminations are magnetized at different angles to the rolling direction (corner joints of transformer core). Also the magnitude of normal flux density should increase in 3-phase transformer core with respect to single phase due to increased number of T-joints and corners, consequently eddy-current loss and building factors in 3-phase core will be increased. Hence the building factor depends on both the core type and properties of the material.

In this sense, from experimental results of the materials used, if the magnitude of the normal flux density is low the power loss and building factor decrease and the opposite is also correct for high magnitude of normal flux density. It is expected from the results, and discussions mentioned above, that the building factor of stacked core material is roughly proportional to the magnitude of the normal flux density transfer from lamination to lamination during the magnetization process in magnetic core materials. The rate of increase in normal flux density after 1.3 T induction level would be low and the building factor was found to decrease slightly.

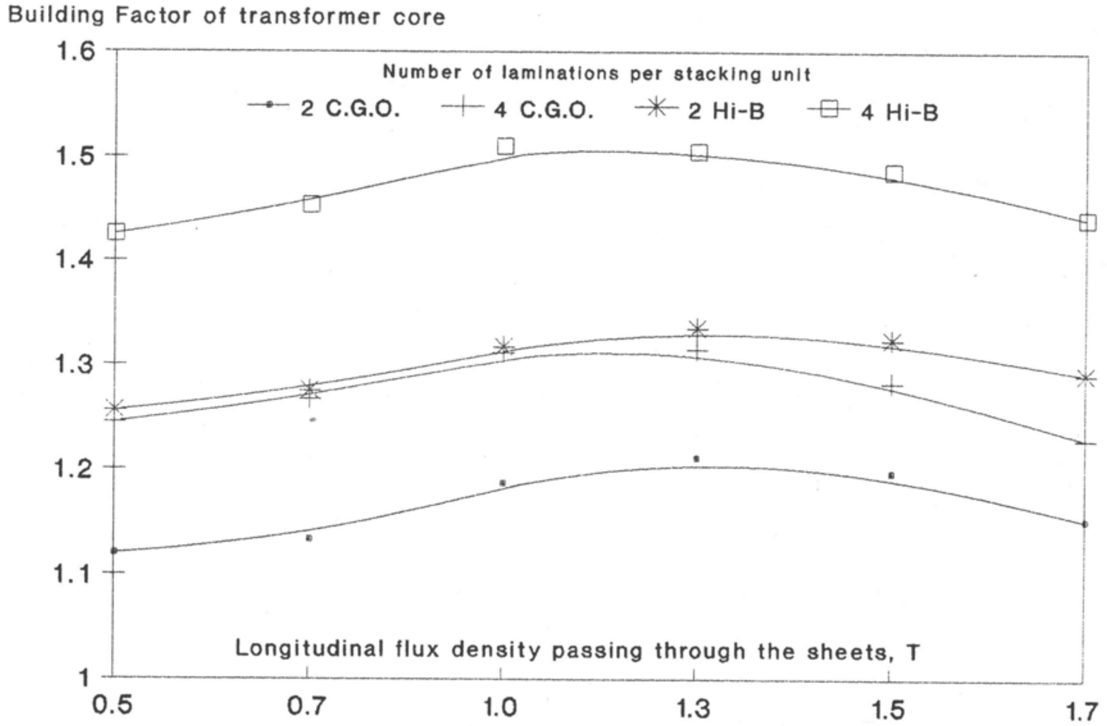

Figure **10** Variation of Building Factor with induction levels in different stacking units in C.G.O. and Hi-B strips at 50Hz.[1]

3. Conclusions

The high magnitude of the normal flux density indicates that it has a major effect on the design and performance of transformer joints, particularly at the T-joint and corners in 3-phase laminated cores where longitudinal flux is known to flow at angles to the rolling direction. The variation of normal flux density magnitude in amorphous material is independent of the magnetization at angles to the rolling direction due to lack of grains and orientation in this material.

The low loss conventional grain-oriented materials are suited for stacked cores because of the low magnitude of normal flux transfer between laminations as a result of a low eddy-current loss caused by low permeability with respect to high permeability in Hi-B material, although this also depends on the thickness of the material. Consequently, the building factor in C.G.O. stacked laminated cores would be low compared with identical design in the Hi-B material.

Normal flux distributions in machines can be used to obtain a better understanding of the effects of using various geometries, materials, or core designs on the power loss. As core losses have become far more important, the required optimum selection of material-geometry combination should be possible. Already some important effects of flux distribution on the building factor of high permeability steel cores has been established and further work will help core builders to optimize their designs for minimum cost of ownership.

Early assessment of high permeability 3.25% grain-oriented steel showed that it more than paid for its increased cost in its lower power loss and higher permeability at high flux density when used in transformer cores. Over 10% reductions in iron loss and 40% reductions in magnetizing volts-amps were reported in large transformers and comparable improvements were observed in several single and three phase model cores.

The variation of normal flux density magnitude in amorphous material due to isotropic texture, with good uniformity and low magnitude of normal flux density, a low building factor should be obtained. Due to above reasons, the POWERCORE has the lowest building factor among the experimental materials in identical conditions.

References:

[1] Y. Ito, Japanese Exposition of Machinery and Technology, Mexico City (1980)

[2] F.E. Werner, TMS/AIME Symposium of Energy Efficient Machines Pittsburgh (1980)

[3] M.F. Littma, J. Appl. Phys. 53 (1982) 2416.
[4] H. Braunstein, Electrical World (July 1982) 123.
[5] H. Shimanaka. Y. Ito. T Irio. K. Matsummura. H. Nakamura and Y. Shono TMS/AiME Symp. On Energy Efficient Electrical Stools Pittsburgh (Oct. 1980).
[6] Sakida, A.,Ph.D. Thesis, University of Wales 1986.
[7] Fukuda, B., Satoh, K., Shimizu, Y. and Ito, Y., Research Laboratories, Kawasaki Steel Corp., Chiba 260, Japan, 1985.
[8] Ebrahimi, A., and Moses, A.J., Mag. Mat., Vol 112, P.129, 1992.