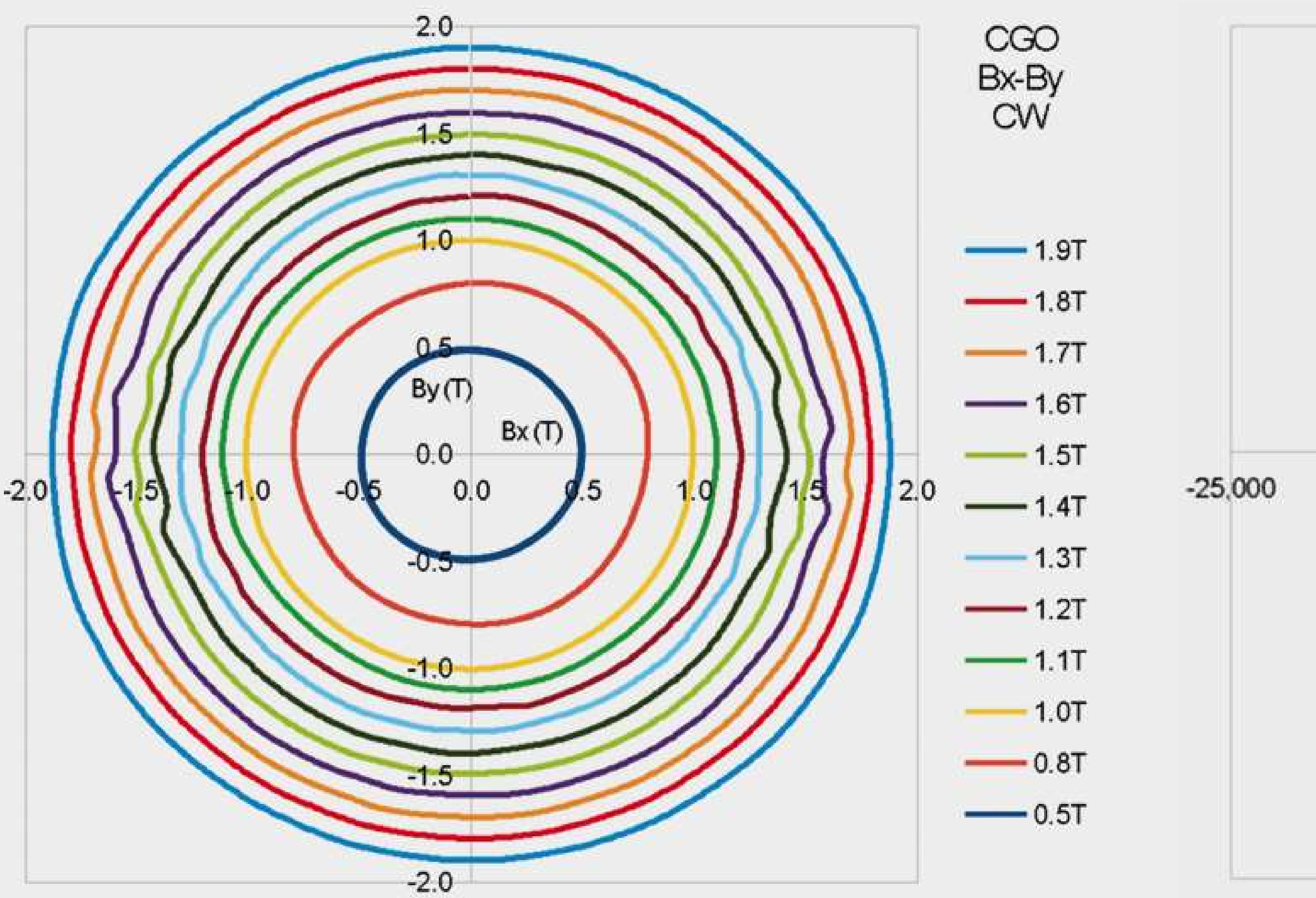


Rotational magnetisation

A phenomenon in three-phase three-limb transformer cores

ABSTRACT

Rotational magnetisation is a phenomenon that occurs locally in the magnetic cores of three-limb transformers. The power loss dissipated under rotational magnetisation can be several times higher than under usual magnetisation conditions as defined by manufacturers of the electrical steels. The phenomena were discovered over 100 years ago and have been studied since, but it is difficult to model it theoretically and apply the knowledge practically in transformer design. This article focuses on the definition and discussion of the phenomenon in order to introduce it to a wider audience of the transformer community.

KEYWORDS

magnetic loss, iron loss, rotational loss, electrical steels, power transformers

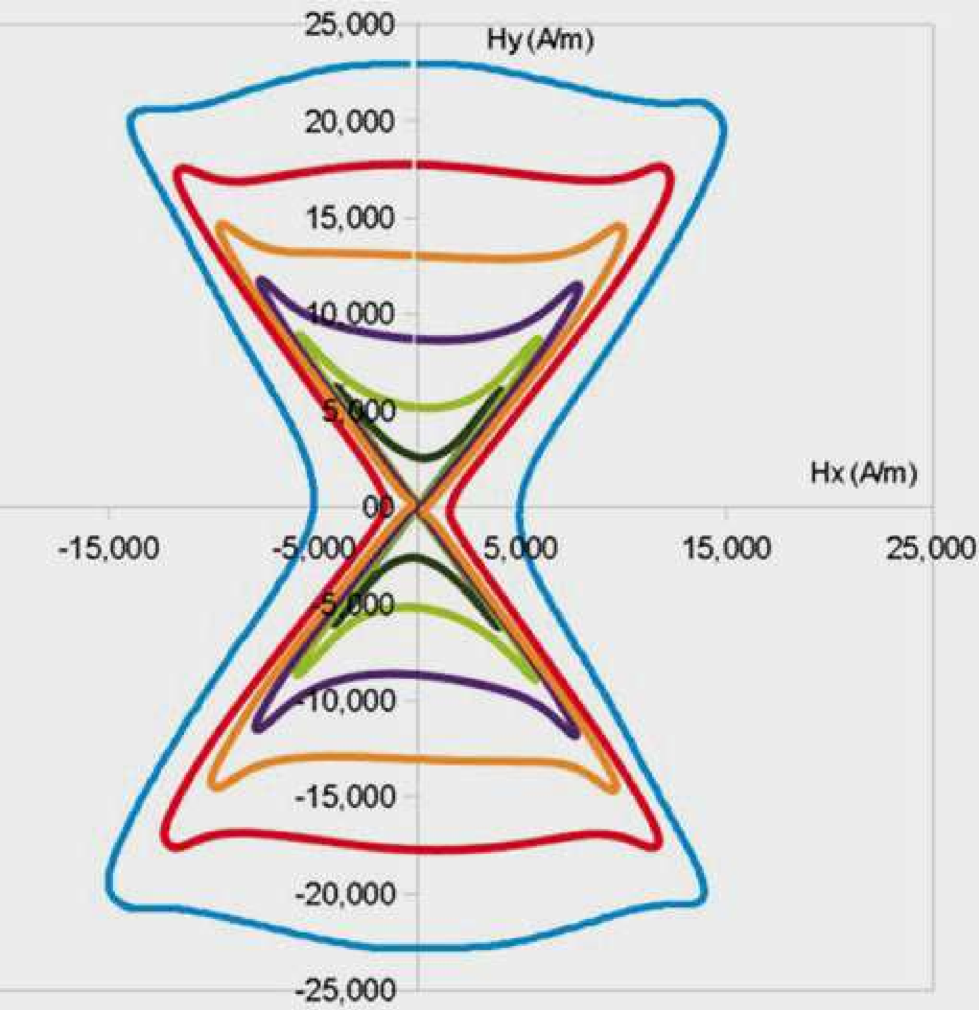
1. Introduction

Transformer magnetic cores are built from strips of Grain-Oriented electrical steel (GO). The cores are designed so that the excitation is applied along the "easy magnetisation" direction, synonymous with manufacturing rolling direction of each of the electrical steel strips (Fig. 1a) in order to optimise the performance and minimise the magnetic losses.

The cyclical magnetisation results from alternating currents in the windings – therefore, such excitation is also referred to as alternating magnetisation.

Magnetisation of electrical steel can be illustrated and explained with the help of a *B*-*H* loop (Fig. 1b). Such loop also illustrates the idea of magnetic saturation, where a further increase in excitation (magnetic field strength *H*) yields a diminishing increase of the response (flux density *B*).

Measurements of magnetic properties should be carried out under well-con-



" A commonly used method to measure the magnetic properties of materials is the Epstein frame, with which the measurements should be made under *controlled sinusoidal B*

trolled conditions, so that the results are reproducible in different laboratories [1]. A commonly used method is the so-called Epstein frame [2] on core samples, with which the measurements should be made under *controlled sinusoidal B*. The measurement apparatus must be capable of controlling such conditions and capturing accurately the *B* and *H* waveforms used to compose *B-H* loops.

It should be noted here that for electrical steels only the *controlled sinusoidal B* condition is used, because it is more akin to the real application where pure sinusoidal voltage leads to sinusoidal *B*. Of course, it is also possible to apply *controlled sinusoidal H*, but this condition is far less important in practice because it would require pure sinusoidal currents. *B-H* loops resulting from such two conditions are different and *controlled sinusoidal H* condition usually generates higher power loss for the same material.

Several magnetic quantities can be derived from a measured *B-H* loop: coercivity, permeability, and core loss (directly proportional to the area of the loop), to name but a few. The core loss, also mostly called the no-load loss, is a very important parameter for transformer design because any heat dissipated in the transformer must be taken into account in the design of the cooling system for the given transformer.

The magnetic losses are also used as the basis of classification and grading of electrical steels from which the magnetic cores are built. For example, electrical steel defined as M150-30S means electrical steel

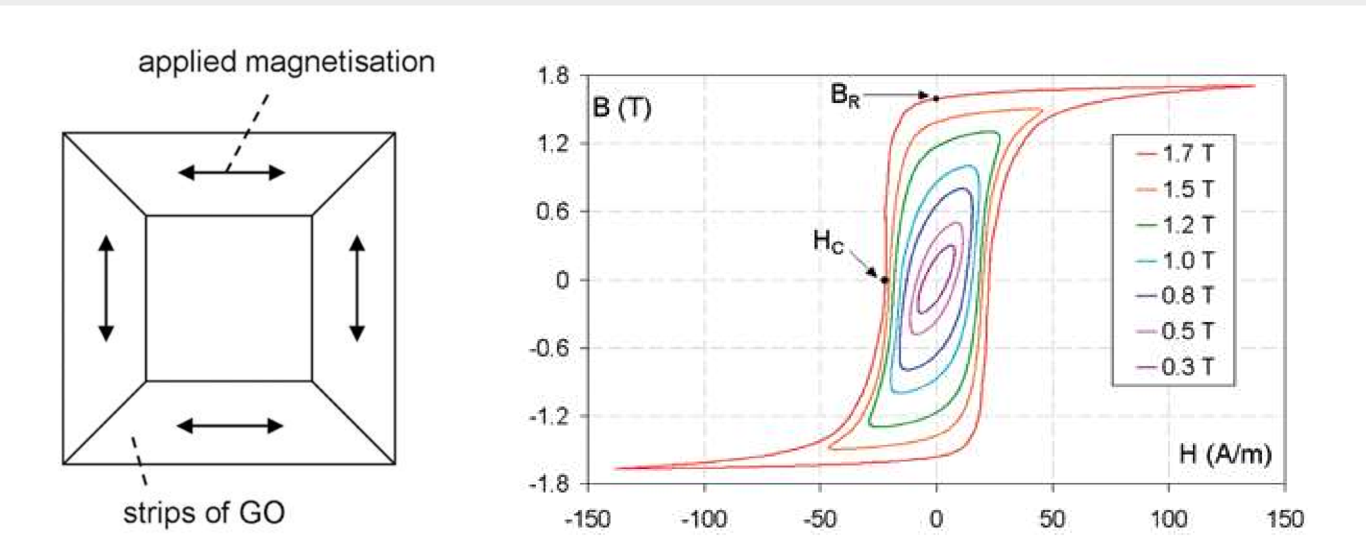


Figure 1. Grain-Oriented electrical steel (GO) is usually magnetised along one direction (a); and a typical family of *B-H* loops (b)

> **It was experimentally verified that rotational magnetisation takes place in the so-called T-joint, a point of connection between the limbs and the yokes of the transformer core**

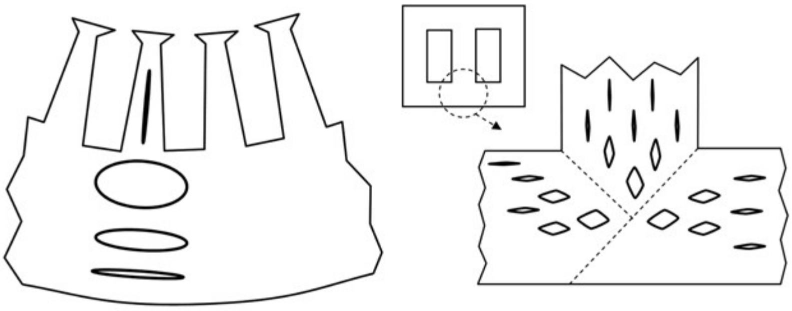


Figure 2. Rotational magnetisation in three-phase machines: a) in an electric motor core; b) at the T-joint of a three-limb power transformer

(M), whose specific loss at 1.7 T does not exceed 1.50 W/kg (150), with thickness 0.3 mm (30) of conventional grade (S) [3]. Armed with such information the designer can estimate how much loss should be dissipated in the magnetic core and adjust the design accordingly.

The specification provided by electrical steel manufacturers only gives information for magnetisation under ideal conditions where the excitation is uniform and the material is free from mechanical stress. Such conditions cannot be met in a transformer core and transformer manufacturers employ such methods as "building factors" [4] (commonly named "k" or "BF") which are empirical coefficients defining the differences between the specified *material* values and those actually found in the magnetic cores subjected to all required stages of assembly. Depending on transformer construction such correction values could exceed 1.25 [4].

2. Rotational magnetisation

However, building factors are not the best tool for describing phenomena occurring very locally in a given core. One such local phenomena is the so-called rotational magnetisation.

Three-phase electricity became widely used because of its intrinsic ability to create a rotating magnetic field, which is the basis of all three-phase motors and generators. Such a rotating field produces torque in the rotor and thus converts electricity into mechanical force and vice versa.

But rotating fields can also occur in regions which do not contribute directly to useful energy transformation, for instance at the back of the core teeth in motors and generators as shown in Fig. 2a [5, 6]. Such rotating magnetisation is an unwanted side effect of the fact that the magnetic flux in the core is generated by three phases. Most of the magnetic flux is utilised for "useful" work of interacting with the rotor, but unfortunately some small percentage circulates just in the stator itself, magnetising it in a rotational manner.

Three-limb, and more, power transformers also combine three phases to create magnetic fluxes. Each individual limb is effectively excited by alternating magnetisation, but at the point of connection of different partial fluxes a very local rotation of the magnetic field can occur [7]. This is in the so-called T-joint, which is the connection between the limbs and the yokes of the core, and it was experimentally verified that indeed such rotational magnetisation does take place (Fig. 2b).

Under alternating magnetisation the direction of applied excitation is constant and only the magnitude and sense of the alternating B_{ALT} vector changes (Fig. 3). Therefore at the instances of "zero crossing" of the field the length of the vector is zero and the magnetic material is continuously magnetised, demagnetised, magnetised in the opposite way, and so on.

Rotational magnetisation occurs if the length of the vector does not decrease to zero but the direction continuously changes, for instance within the plane of the magnetic laminations. So, the magnitude can be constant, but the vector rotates [5-11]. The rotation can be created with an arbitrary shape if the length of the vector does not decrease to zero (Fig. 3).

As stated above, measurements of magnetic properties must be carried out under controlled conditions in order to ensure reproducibility. For alternating magnetisation this was *controlled sinus-*

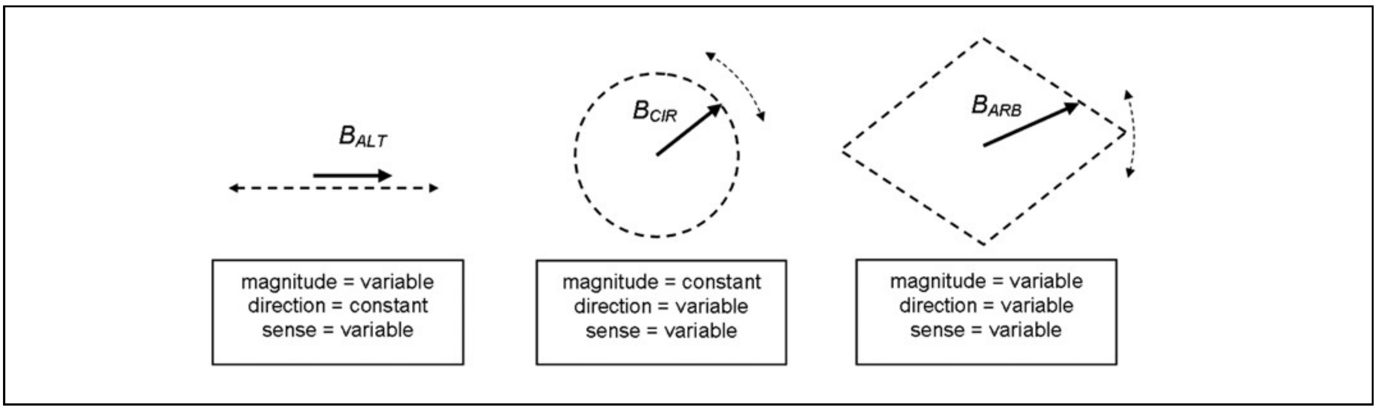
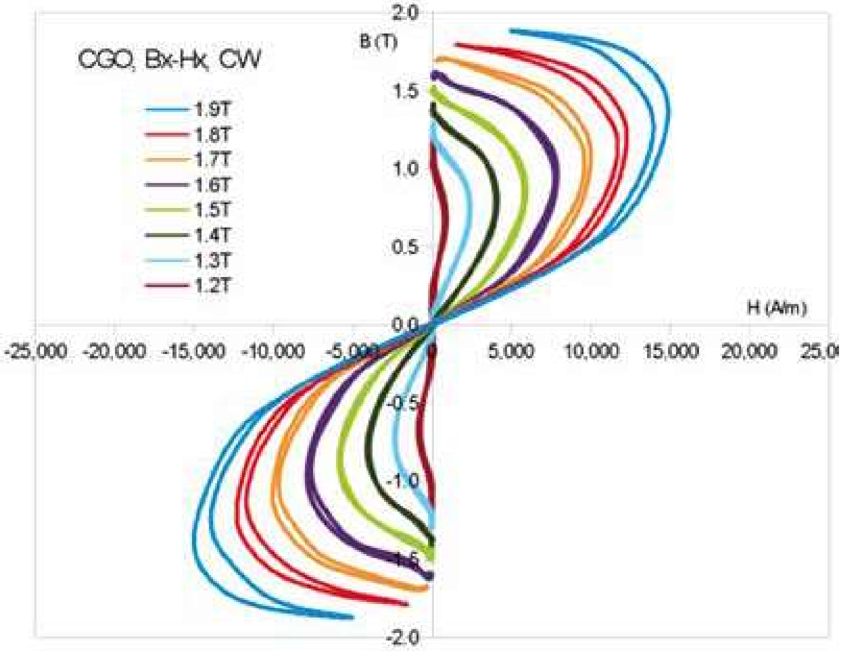


Figure 3. Definition of alternating B_{ALT}, circular B_{CIR} and arbitrary B_{ARB} magnetisation



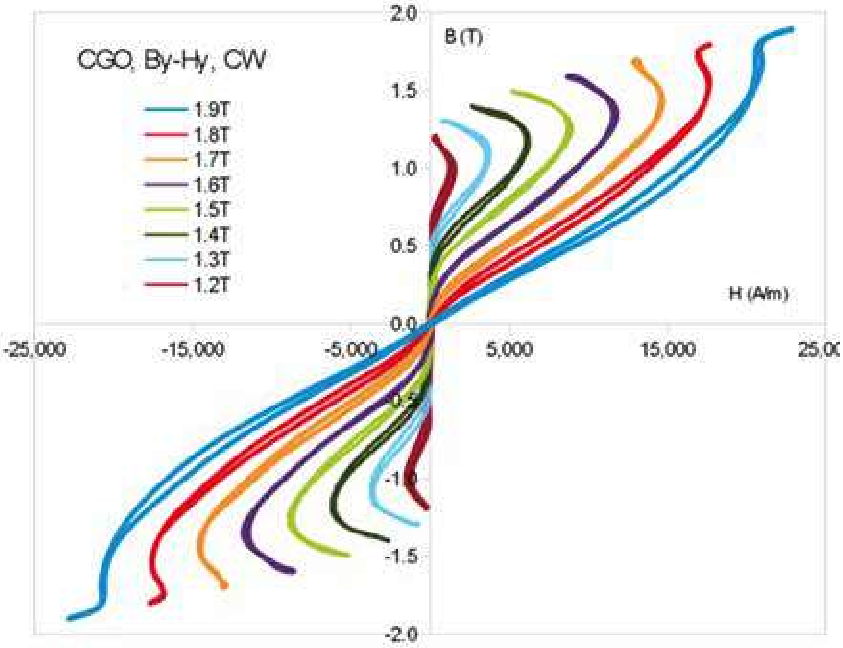


Figure 4. Experimental data for rotational magnetisation for Conventional Grain-Oriented electrical steel (CGO) magnetised under *controlled circular B*: B_X-H_X (left) and B_Y-H_Y (right)

oidal B. A similar approach can be taken for rotational measurements where the rotation can be created in a two-phase system with one phase applied to a sample at 0° as sine and the other phase at 90° as cosine. If both components are appropriately shaped, then a condition of *controlled circular B* can be attained. In an analogous way, *controlled circular H* can be achieved for the same core sample.

The intriguing aspect of rotational magnetisation is that the total loss dissipated in magnetic material exhibits a peak, after which it decreases towards zero

The phenomenon is so interesting that there is even an international scientific conference devoted to rotational measurements

Rotational magnetisation does not have to follow a purely circular shape. For instance, as shown in Fig. 2b, the shape can resemble a rhomboid caused by the anisotropy of the Grain-Oriented electrical steel as used in transformers core. This can have an interesting consequences and it is discussed in more details below.

The "*B-H* loops" as detected under rotational magnetisation experiments can take quite peculiar shapes (Fig. 4), for which notions such as "coercivity" or "remanence" become almost meaningless. Firstly, the *B* and *H* can be decomposed into two components for the orthogonal X and Y directions so that the full set of data becomes: B_X-H_X and B_Y-H_Y and two families of *B-H* loops are produced simultaneously.

Under such magnetisation conditions the power loss exhibits a somewhat counterintuitive behaviour. Namely, the intriguing aspect of rotational magnetisation is that the total loss dissipated in magnetic material exhibits a peak, after which it decreases towards zero, as shown in Fig. 5. For alternating magnetisation the power loss always increases roughly with the square of *B*.

This was initially shown by Baily as early as 1896 [10]. At the time, the results were so controversial that they were ridiculed and criticised by his peers. However, further theoretical analysis by Ewing (1900) [11] as well as measurements with improved accuracy and other techniques proved that the effect is indeed real and that the rotational power loss vanishes when approaching saturation.

The phenomenon is so interesting from theoretical viewpoint that there is even an international scientific conference devoted to rotational measurements [12].

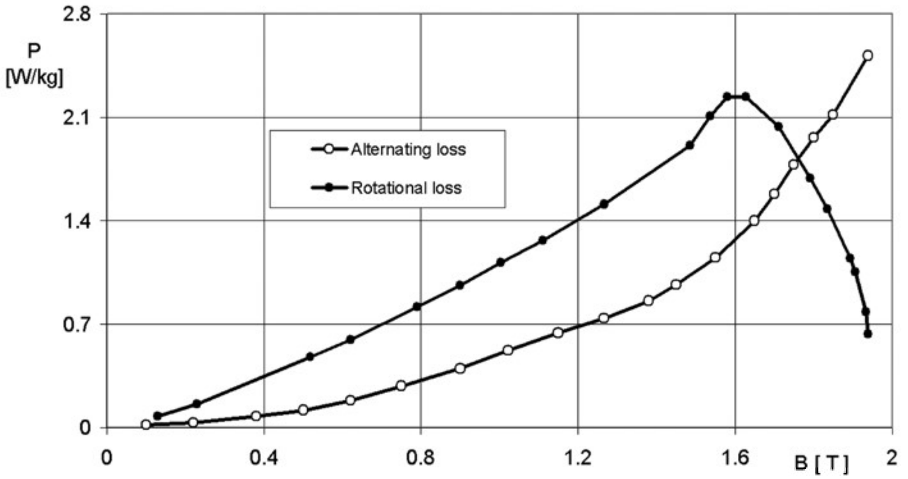


Figure 5. Comparison of power loss characteristics for Conventional Grain-Oriented silicon-iron electrical steel sheet for alternating and circular magnetisation [9]

3. Rotational loss

Magnetic loss can be conceptually split into three components: *eddy current, hysteresis,* and the so-called *additional* or *excess* loss.

Eddy current loss occurs in any *conducting* material, magnetic or not. Exposure to a varying magnetic field induces eddy currents in the whole volume of such material, as dictated by Faraday's law of induction. This loss depends on cross-sectional area (hence the thickness) of lamination and it is therefore the primary reason why all electrical steels must be used as laminations, otherwise those losses become too excessive for practical use. Alloying iron with silicon increases resistivity and lowers the eddy currents, but the silicon content cannot exceed 3 % for mechanical and commercial reasons (the steel becomes too brittle and hence too expensive to process).

Hysteretic component of loss is generated in all *magnetic* materials. During magnetisation and re-magnetisation the size of magnetic domains changes, so that the domain walls move accordingly (Fig. 6 and Fig. 7). In CGO the domain walls can be several mm long but only hundreds of atoms thick. Therefore, their movements can be impeded (e.g. by chemical impurities or crystallographic defects) and the lost energy manifest itself as hysteresis. In a first approximation the hysteresis component does not depend on frequency of magnetisation but is a function of the amplitude of magnetisation.

Additional loss component is generated from very localised micro eddy currents generated around the fast moving domain walls. The "normal" eddy currents flow in the whole width of the magnetised steel strip, but the micro eddy currents are generated only in the immediate vicinity of the domain walls, due to the local change in magnetisation (Fig. 7). In Grain-Oriented electrical steels the size of magnetic domain walls is comparable to the thickness of lamination (around 0.3 mm) and the so-called additional loss becomes significant [13, 15].

Under alternating magnetisation, a sum of all three components (eddy current, hysteresis and additional loss) creates a *B-H* loop, as shown in Fig. 1.

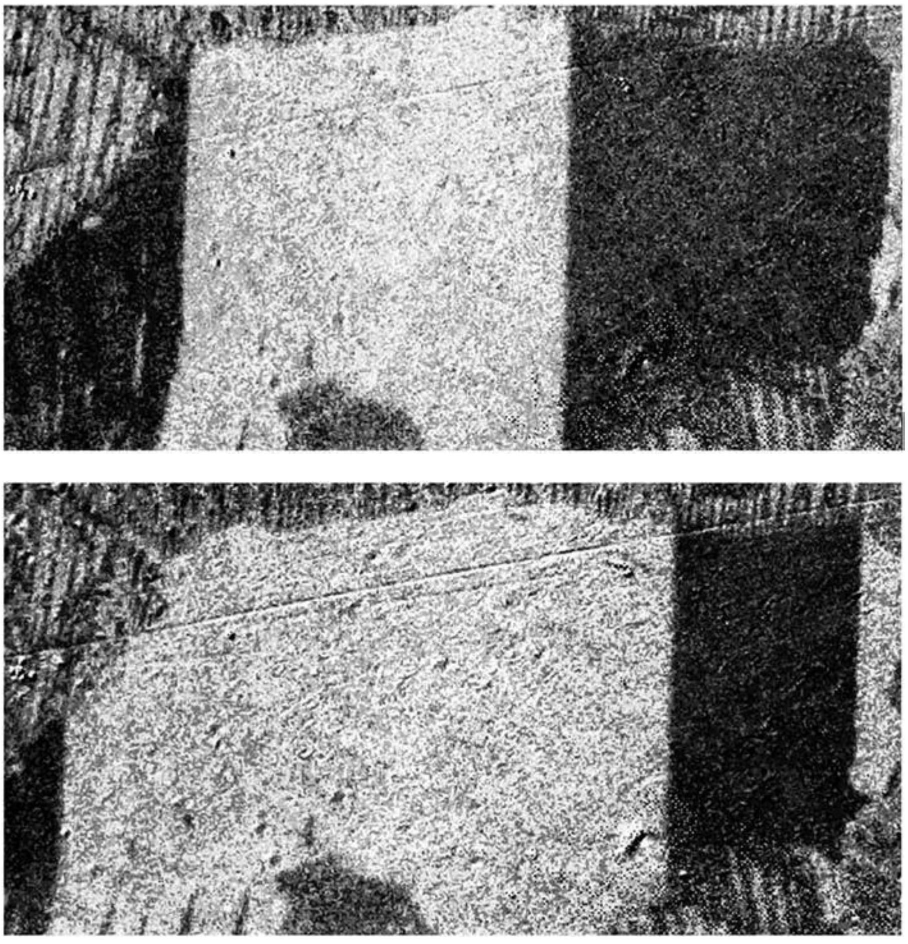


Figure 6. Magnetisation occurs because the magnetic domains (dark and light regions) change their size and in a demagnetised state the "up" and "down" domains occupy roughly the same volume (left), but during magnetisation the domains grow and shrink (right)

Under alternating magnetisation, a sum of all three components of magnetic losses – eddy current, hysteresis and additional loss – creates a *B-H* loop

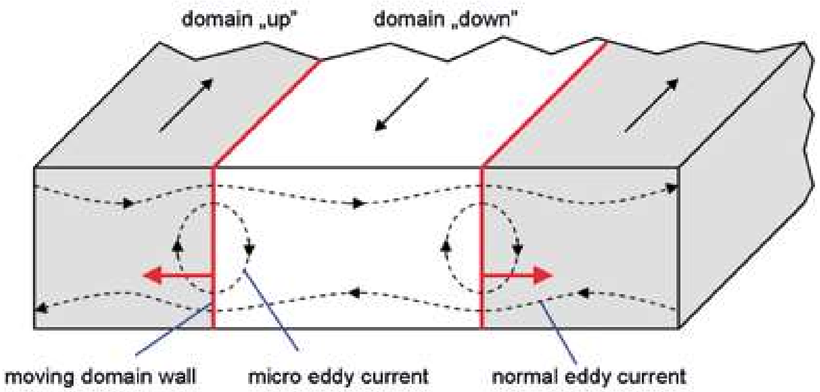


Figure 7. Conceptual illustration of domain walls extending through the whole thickness of laminations (see also Fig. 6) [15]

However, under rotational magnetisation, with approaching saturation the domain walls vanish because one large domain is rotated in the plane of the lamination. As shown in Fig. 7 and explained above, the presence of domain walls is responsible for two loss components: *hysteresis* and *additional*. With the absence of the domain walls both of these loss components also disappear and the total loss decreases, as shown in Fig. 5.

Unfortunately, the peak in the power loss curve in electrical steels tends to appear between 1.4 - 1.8 T, which is near the operating point for power transformers, typically around 1.7 T. So the effect of vanishing loss cannot be employed in most practical applications.

Measurements in research laboratories can be carried out for any grade of GO under *controlled circular B*, so that the *H* vector loci resemble a "butterfly" shape, caused by the crystallographic anisotropy of the material (Fig. 8). Along the "easy" direction, the required *H* is smallest to produce a given *B* – this direction is along the X axes in Fig. 8. On the other hand, in order to set up the same *B* in the "hard" direction, the required *H* is much greater (Y axes in Fig. 8).

Another measurement can be taken under *controlled circular H*, and for the same material the *B* loci become "rhomboidal" (Fig. 9) [8, 14, 16], again as dictated by the anisotropy of the Conventional Grain-Oriented electrical steel (CGO).

These two magnetising conditions (controlled *B* or *H*) differ only by the way the excitation is applied. Namely, just the magnetising currents have different shapes controlled in such a way as to produce required shape of *B* or *H*.

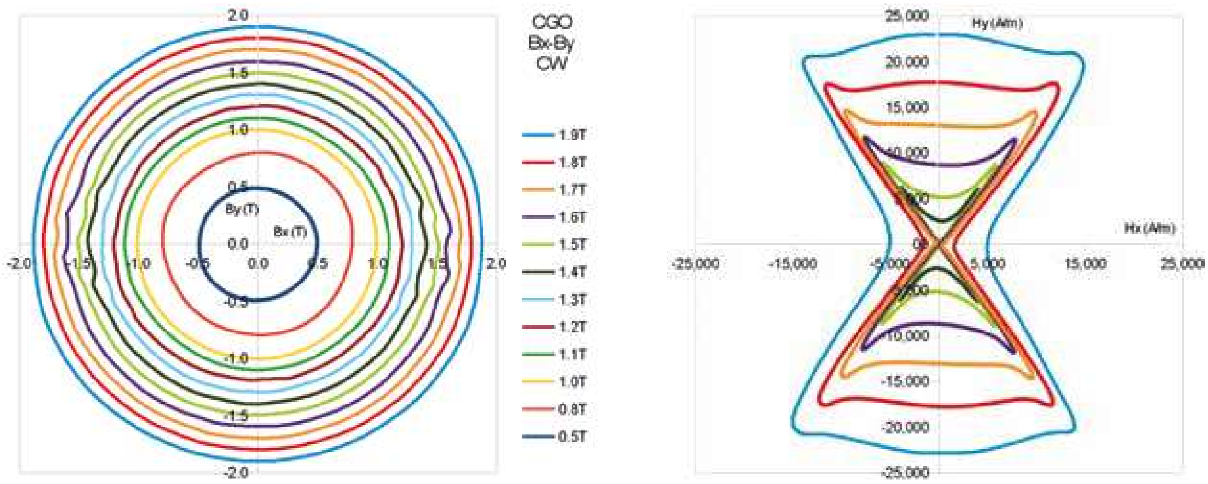


Figure 8. Magnetisation of CGO under *controlled circular B* (left) leads to "butterfly" shape of *H* (right)

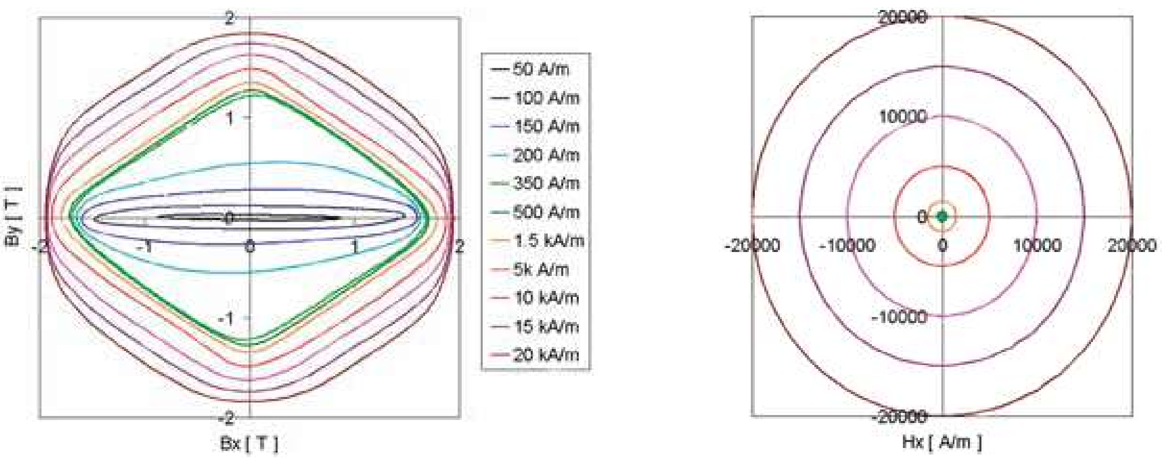


Figure 9. Magnetisation of CGO under *controlled circular H* (right) leads to "rhomboidal" shape of *B* (left)

Typical values of power loss under alternating magnetisation vary between 0.7 - 1.0 W/kg at 1.5 T for CGO electrical steel, but the maximum value of rotational loss can reach 4.5 W/kg for circular *B* or 6.5 W/kg for circular *H*, which is probably more applicable to the T-joints of transformers

Typical values of power loss under alternating magnetisation vary between 0.7 - 1.0 W/kg at 1.5 T for CGO electrical steel (e.g. grade M4 or M130-27S).

But the maximum value of rotational loss can reach 4.5 W/kg for circular *B* (as shown in Fig. 10a) or 6.5 W/kg for circular *H* (Fig. 10b), which is probably more applicable to the T-joints of transformers – as evident from Fig. 2b (rhomboidal *B*). Depending on the grade of the electrical steel these values can be even higher.

Therefore, under worst case scenario the peak of the rotational loss can occur locally only in the T-joints of the cores (see also Fig. 2b), which could lead to hot spots in the T-joints of the cores. This is because locally the loss could be around five times higher than for the rest of the core exposed only to alternating magnetisation. Interestingly, this factor gets worse for *better grades* of electrical steels and high-permeability Grain-Oriented steel (HiB) exhibits even greater rotational losses with factors up to nine times reported in the literature [16].

The rotational loss phenomenon is very difficult to model from a theoretical viewpoint [17]. Also, the measurements are not performed with accuracy comparable to the standardised and widely applied alternating measurements. So far, there is no standardised method for measuring such losses because previous attempts at standardisation failed due to large discrepancies (up to 50 %) in measured values between the participating laboratories [18].

The phenomenon is real and continues to be studied in laboratories. However, due to its nature it is very difficult to include it into the design procedure of transformer cores.

Within scientific community there are rumours that in the past rotational loss contributed to catastrophic failures in transformers, but because of confidentiality and commercial sensitivity understandably the manufacturers are not forthcoming with details. As a result, the *practical* problem is not discussed in any technical or scientific publication. Mostly just the material behaviour or laboratory version of transformer cores are studied in isolation and further articles are published at each edition of the 1&2DM conference.

As a transformer designer or manufacturer, have you experienced any such or similar unexplained problems with T-joints of three-phase transformers? Perhaps you witnessed elevated temperatures or some unexplained behaviour around a T-joint? Would you be able to give any information about the problems with rotational magnetisation encountered in practice?

There could be hot spots in the T-joints of the cores, because locally the loss could be around five times higher than for the rest of the core

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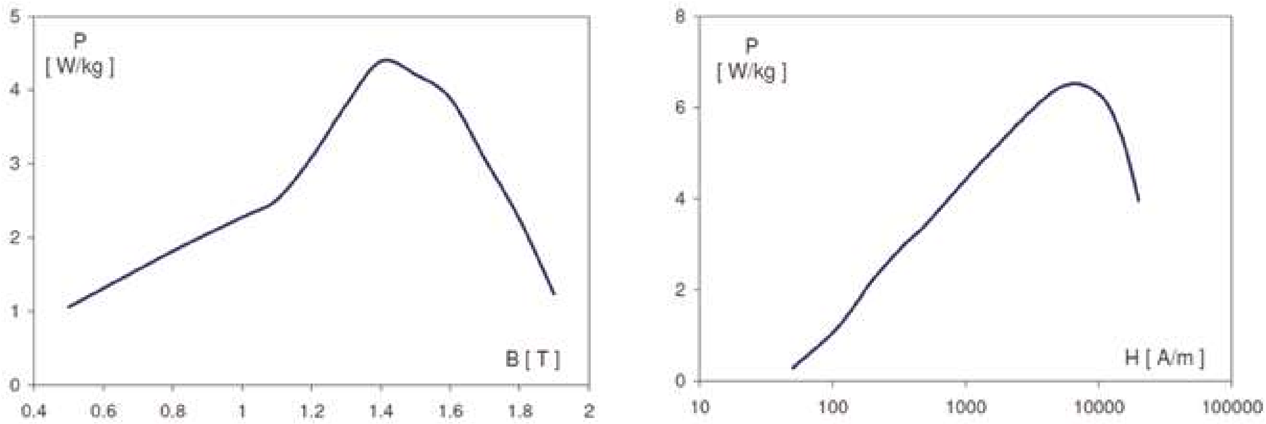

a) b)

Figure 10. Rotational power loss for CGO at 50 Hz for: a) *circular B*; b) *circular H*

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Author

Stan Zurek completed a PhD in electrical engineering in 2005 and continued research in magnetic materials at Wolfson Centre for Magnetics, Cardiff University, UK. He joined Megger in 2008 and is Manager of Magnetic Development. He is the author and co-author of over 60 scientific publications related to magnetics and magnetic materials. Dr. Stan Zurek is a Senior Member of IEEE Magnetics Society.