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Possible Future Trends and Research Challenges related to 1 & 2 D Magnetic Properties of Soft Magnetic Materials

***Abstract**. One and two dimensional magnetisation studies of bulk soft magnetic materials have been researched and characterised over the past 100 years. Initially, focus was on dc rotational hysteresis and this has evolved to studies of losses permeability, and magnetostriction, mainly of electrical steels, under controlled complex magnetisation of the type known to locally occur in rotating machine and transformer cores. This paper briefly summarises present knowledge and then some new and unsolved problems of interest or potential industrial importance are reviewed.*

***Streszczenie.** Jedno- i dwuosiowe problem magnesowania materiałów magnetycznych miękkich były badane od niemal stu lat. Początkowo koncentrowano się na rotacyjnej histerezie dc i stąd określano takie parametry jak przenikalność, straty czy magnetostrykcję przy magnesowaniu rotacyjnym. Artykuł prezentuje obecny stan wiedzy oraz prognozuje przyszłe kierunki badań w tej dziedzinie. (**Trendy i wyzwania w badaniu jedno- i dwuosiowych parametrów materiałów magnetycznie miękkich**)*

Keywords: rotational losses, Epstein square, magnetic measurements, magnetostriction, electrical steel.
Słowa kluczowe: straty rotacyjne, aparat Epsteina, pomiary magnetyczne, blacha elektrotechniczna..

Introduction

This paper covers the keynote presentation given by the author at the 1 & 2 DM conference held in Oita in 2010. The predictions which are implied from the title of the paper are very subjective and the extent to which they might be realised depends on many intangibles. Research in this field is very much driven by emergence of new materials and industrial trends both of which are difficult to predict. However the global demand for more efficient energy usage and conservation is certain to continue and it is this that will drive the future need for 1 and 2 DM research. It is probable that demand will increase for measurement of magnetic properties more directly relevant to operating conditions in electrical machines and other devices where soft magnetic materials are crucial components. How these will relate to IEC standards remains to be seen, but is not discussed in this paper.

The industry is demanding quicker, cheaper measurements which can be carried out by inexperienced operators but is this compatible for the need for more wide ranging measurements directly relevant to operating conditions where temperature, cut edge stresses and mechanical stress are key parameters? These issues also are not discussed in this paper.

Electrical steel will dominate the soft magnetic materials sector for years to come so we will see gradual evolution of measurement techniques to cater for special characteristics of new products as they emerge. It is impossible to predict how competing materials for niche applications might come to the market but new measurement techniques may be necessary for products such as soft magnetic composites, layered materials, ultrathin materials (steels, wires, amorphous and nanocrystalline) and high strength magnetic components. Composite components comprising soft and hard magnetic materials may require in situ measurements of their overall magnetic properties as well as basic characteristics of the individual materials.

There have been substantial developments in 1 & 2 dimensional measurements much stimulated by the Conference series. This will be reviewed in Oita [1]. The predictions forwarded in this paper partly look at gaps and anomalies in research findings reported at the previous 1 & 2 DM meetings. There is not space to cover the whole field or to do full justice to individual researcher's work. A few topics are included either because of their potential growing industrial importance or simply from a scientific curiosity standpoint. The reader can judge which category each topic falls into.

The paper should remind readers of the basic electromagnetic theory on which many soft magnetic material measurements on electrical steel are based since new developments can be flawed without full appreciation of the basic concepts. In the later sections some aspects of Epstein testing, ac measurements under distorted flux, rotational loss, magnetostriction and sample shape are highlighted.

A fundamental expression

First reports of studies of magnetic properties of steels under rotational magnetisation were reported more than 100 years ago. Torque magnetometers were used to calculate rotational hysteresis loss simply by rotating steel discs slowly through 360^{O} between the poles of an electromagnet then reversing rotation and subtracting the curves to obtain the static hysteresis loss. The important spatial angular displacement between magnetic field H and flux density B was appreciated at the time [2] but not referred to as *vector hysteresis* as it is today. The energy loss, P, associated with changes in B and H can be expressed by the well know equation:

$$P = \frac{V}{T}\int_0^T H\frac{dB}{dt}dt \qquad (1)$$

For 1 or 2 D magnetisation, H is the instantaneous tangential component of surface field and B is the spatial instantaneous average flux density. This equation has been widely developed and applied for loss measurement, modelling and prediction under a wide range of 1 and 2 DM magnetising conditions. Versatile modern magnetisation control systems together with the evolution of field and flux sensors enable magnetic measurements to be made extremely reproducibly and accurately. Manipulation of time varying B(t) and H(t) signal data enables the user to provide a wealth of information to characterise magnetic properties of soft magnetic materials very effectively over a wide range of magnetisation conditions found in more demanding applications, particularly in power generation, conditioning and distribution.

The Epstein square and single sheet testing

The Epstein square is fully established for routine grading of electrical steel and the correlations with the standard single sheet tester (SST) are well documented [3]. However more research is necessary to extend the frequency and flux density range of Epstein-type testing or replace it with a suitable alternative if this cannot be done in a satisfactory way. For example, frames have been designed for high frequency, high induction measurements and indications are conversion matrices might be necessary to relate to the low frequency square [4]. This needs further investigation to determine how this can be overcome and indeed if the new methods give acceptable results and if so can it be extended to the more difficult problem of applying equation (1) to distorted flux measurement in a *traceable* way.

Computation work [5] shows that field, flux density and eddy currents are quite different in the Epstein square to that in the SST. This is bound to be more significant under extremes of testing and deserves deeper investigation which might include further analysis of the correlation between the two methods.

A factor which is becoming more critical and deserves revisiting is proper quantification of the *magnetic path length* of the Epstein square. Although it has long been known that the magnetic path length is dependent on material properties and magnetization conditions [6] a fixed value of 0.94 m is used in practice. This is becoming less acceptable as steel users need more *absolute* loss and permeability data. The double Epstein method has recently been proposed to determine the true magnetic path length over a wide range of conditions and to demonstrate the importance of taking it into account [7]. Figure 1 shows an example of how much the path length can vary under complex magnetization conditions and acts a warning in basing comparative measurements on a fixed path length. The double Epstein method is time consuming so other approaches to the problem need to be investigated.

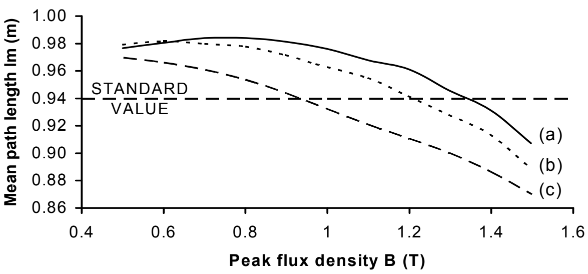


Fig. 1. Variation of true magnetic mean path length when testing NO steel under controlled PWM magnetisation conditions (a) f=50 Hz, f_s= 250 Hz (b) f=100 Hz, f_s= 500 Hz (c) f=200 Hz, f_s= 1000 Hz [8]

Compensated Rowgoski Chattock Potentiometer (RCP)

The principle of the RCP was established almost 100 years ago [9] and its more specific application in single strip testing was reported more than 30 years ago [10]. The magnetisation compensation applied ensures that the field H in equation (1) is directly proportional to the magnetising current in the main winding so the problem of determining the magnetic path length is avoided. It can be claimed as an *absolute* method of measuring losses which does not suffer from the inherent problems of the standard Epstein square and SST. In the early days of its development, electronic control and feedback systems were difficult to apply and the method was considered to be too problematical for practical implementation.

The RCP system has been demonstrated to be applicable to SST and on-line testing [11] [12]. More research is necessary not only to answer the question posed earlier [12] as to why the method has not been standardised but will it be equally or more superior to conventional SST and Epstein testing at high flux density, frequency or under high flux distortion?

Another potential application of the RCP principle is in the measurement of overall and local surface field properties of strips using an array of magnetoresistive sensors [13] The advantage of this approach is that the sensitivity and output signal is high and an error-introducing integrating circuit is not necessary. It appears that the RCP could be the subject of a range of fruitful research areas.

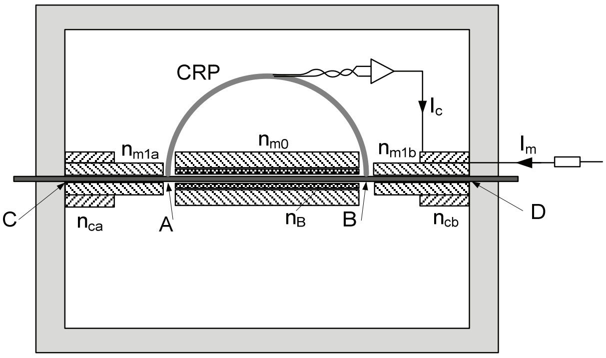


Fig. 2 Layout of typical compensated RCP measurement system

There has been pressure to completely eliminate the IEC Epstein and SST testing and all their associated issues and simply grade electrical steel as is it produced directly on the production line. Such on-line testers are well developed [14] and their outputs correlate well with measurements made on Epstein strips cut from the ends of the same coils. The use of the RCP in this context could provide *absolute* power loss and permeability measurements anywhere along the length and across the width of a coil giving the end user far more detailed and real properties of the material. Further research in this area could lead to this being achieved but it depends on the willingness of industrial producers and users in the IEC community to want it to happen. However, it should be pointed out that should on-line testing be fully accepted there would still be a need for SSTs in the research environment.

Rotational magnetisation

The first rotational magnetisation workshop in Braunschweig (1991) was held because the topic, although not new of course, was of growing interest, particularly its relevance to transformer and rotating machine performance, and it was not covered in a focussed manner at any other conferences. The importance of establishing its relevance to machine performance was well appreciated [15]. The international research community took excellence opportunity from the following workshops to network and collaborate to make major strides in the measurement and understanding of rotational magnetisation processes.

Today, rotational magnetisation studies form a smaller proportion of the 1 & 2 DM conference programme because many of the identified research objectives have been realised. Results from an extensive European *Round Robin*, comparing magnetisation and measurement techniques [16], highlighted common targets such as defining the best magnetisation system, overcoming anomalies in clockwise and anti-clockwise rotational measurements, establishing consensus on best test sample size and B and H sensor methodologies.

Many of the above issues have been clarified [17], so is any further basic research needed related to rotational magnetisation in electrical steels? It seems that sufficient work has been carried out to form the basis of a recommendation for an IEC standard, but is such a standard necessary?

However, one issue that is still not resolved is whether it is more appropriate to focus on measurements and analysis under controlled rotational field conditions rather than rotating B, as is commonly the case [18], [19]. This should be fully resolved before any new drive for an IEC measurement standard. Also it is necessary to obtain clarification and consensus on which are the most relevant magnetisation conditions to standardise upon to ensure they are relevant to machine design and performance prediction [18].

It is well known that equation (1) can be expanded such as below to conveniently represent B and H as orthogonal components from which the loss can be obtained as the sum of two components

$$(2) \qquad P_r = \frac{1}{T\gamma}\int_0^T \left(H_x \frac{dB_x}{dt} + H_y \frac{dB_y}{dt} \right) dt$$

where γ is the density. It should be appreciated that the two components are not *real losses* but simply is a mathematical result of the analysis (and measurement). It is certainly not the sum of losses occurring during 1_D magnetisation in the two directions (although for a limited range of magnetisation conditions it gives similar numerical result).

It is common to split losses measured under 1-D magnetization into hysteresis, classical eddy current and excess loss components. The same can be attempted for 2-D magnetization [20]. This is carried out to try to relate magnetisation processes and losses to physical properties and microstructures, but even for 1-D magnetisation, there is increasing concern over the accuracy or meaning of these components under non-standard magnetisation conditions in particular. There is clearly scope for measurements to help obtain more confidence in the meaning of such loss separation methods.

Sources of errors in common approaches to loss measurement under rotational conditions are well quantified [21], but continued research and development is anticipated to try to reduce them further. Other on-going research into measurements at high flux density, under mechanical stress, on improved magnetisation conditions and on other smaller issues, which have not been fully concluded, must not be undervalued, but it seems as if the core issues relating to traditional 2-D measurements are mainly solved.

An alternative technique, which is frequently used for localised loss measurement in machine core, is based on the fact that the initial rise of temperature at a point on a lamination is proportional to the local loss at that point [22]. B and H sensors are more often preferred for 2-D loss evaluation, but the thermal method does avoid the uncertainties and limitations of the sensor method. A drawback of the thermal method is that measurements normally must be made over a few seconds time period and, before a further measurement, the specimen must be allowed to cool to a stable temperature which might take a few minutes. Also, normally the temperature rise is only a few millidegrees centigrade so sensitive fast acting sensors and processing systems are essential.

With care, the thermal method can produce accurate results and in *absolute* terms. It has been shown to agree well with B and H sensor loss evaluation under 2-D conditions [23]. Furthermore the thermal technique is potentially the most suitable method at high induction or under high flux harmonic distortion, so continued research in this area should prove fruitful.

3-D magnetisation

There is growing interest in soft magnetic composite (SMC) materials and the use of laminated strip in complex topologies where magnetisation can be changing in all three directions. Here controlled magnetisation and B/H detection are more difficult issues than for 1 or 2 DM testing and they are still at early stages of development. Measurements have been reported on cube shaped specimens of SMCs magnetised in a 3-D yoke assembly [24]. Arrays of B and H coils were used to determine the loss for various forms of 2-D magnetisation. Measurements under full 3-D excitation do not appear to have been reported. The extension of equation (2) to 3-D magnetisation needs to be carefully considered. The theory behind the equation is developed on the basis that magnetisation does not occur out of the plane of a sheet. (*As a side, this type of magnetisation occurs within magnetic domains even under overall 1-D magnetisation, so is this a source of error even in what is assumed to be the most basic loss measurements using B and H sensors?*). It does appear that there is scope for comparative measurements to verify initial findings such as in [24], then more research is necessary to determine what forms of 3-D magnetisation are prominent in machine cores before attempting to optimise measurement systems, to accurately reproduce such magnetisation conditions, and sensors which are confirmed to provide data from which loss can be confidently calculated.

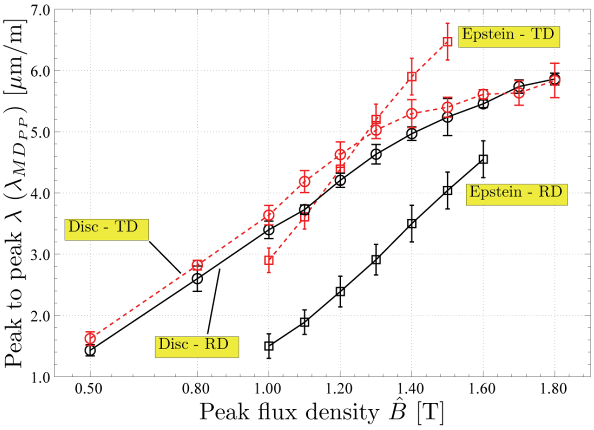
Magnetostriction under 1 and 2 dimensional excitation

Magnetostriction is an important parameter because it is a major source of transformer noise which is becoming of greater concern in power transformer operation. The most appropriate methodology for measuring magnetostriction of electrical steel under unidirectional magnetisation is still being debated and it is likely that recent research will lead to a drive towards an IEC standard approach [25]. However, it is not known if any particular magnetostriction characteristic is dominant in terms of transformer noise. Furthermore, in three phase transformers, rotational magnetostriction could be of more significance than under unidirectional ac conditions since its magnitude is higher although more localised. At present, knowhow, measurement experience and comparisons of results, to gather material for possible development of a standard characterisation method for electrical steel, is focused on unidirectional magnetisation. In the mean time, if it is found that some other magnetostriction characterisation is more relevant when assessing materials for low noise applications, it will require refocused studies of other approaches to measurement and characterisation.

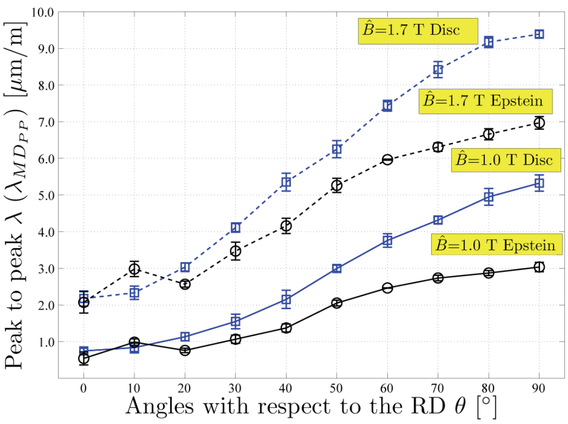
Early work [26] [27] on rotational magnetostriction established its complexity. More recently [28] magnetostriction measured in disc samples magnetised in a two-dimensional magnetisation system revealed that the highest magnetostriction in the sheet plane may not occur along the magnetisation direction if the material is anisotropic. Also differences of the magnitude of magnetostriction measured in Epstein and disc samples have been found to be due to the *form effect*, so even magnetostriction measured in Epstein strip form should be used with caution for calculation of core deformation and vibration of large electrical machines. Figure 3 illustrates the form effect related to magnetostriction measurements [28]. In this case the effect of sample shape can be seen to depend on texture and magnetic anisotropy of non-oriented electrical steel. From these results, it seems that more research is necessary to quantify the shape effect, so if a sheet size of 100 mm by 500 mm is selected as an IEC standard, (as many researchers suggest), then results can be related to other size strips used in actual transformer cores.

The measurement of power loss using the Epstein square has many weaknesses as pointed out earlier for determining *absolute* losses which should be the baseline for core designers. It would be of long term benefit if any proposed IEC standard magnetostriction system could be used, not only as a method of comparing an arbitrary magnetostriction characteristic of one particular sheet shape, but also, more importantly, as a reference from which the component of transformer noise due to magnetostriction could be directly quantified. This is a formidable long term challenge.

The shape, or form, effect is prominent particularly when testing strips magnetised at angles to the easy direction [29]. Misleading measurement of permeability and loss as well as magnetostriction may arise if the phenomenon is not properly accounted for.



(a)



(b)

Fig. 3 Effect of sample shape on magnetostriction measured along various directions in two samples of NO electrical steel: (a) 0.35 mm thick fairly isotropic, (b) 0.50 mm thick anisotropic [28]

Measurements under DC offset conditions

Loss increase of electrical steel magnetised under ac conditions in the presence of a dc field offset is a well known phenomena [30]. Sources of dc offset fields are increasing in modern electrical distribution systems and present a possibility of transformer failure [31]. The phase errors of current measuring instrument transformers also are seriously affected by dc biasing [32]. Although it is not difficult to magnetise a sample with ac and dc flux components, setting up the asymmetrical flux density in a controlled way is not so straightforward [33].

Figure 4 shows an example of an approach to synthesising a required percentage of dc component of flux density on a residual known, set value of ac flux. Here the peak to peak flux density is set at 2.0 T and the waveform is shifted by 0.2 T by combining the two waveforms shown. The third period of the target flux density shown on the right is isolated and used for the magnetisation. It would be valuable to compare this approach with others and try to arrive at a preferred methodology. There are of course many ways of defining dc voltage, field or flux density offsets. More discussion with machine designers seems necessary to ensure that most relevant measurement parameters are focussed upon.

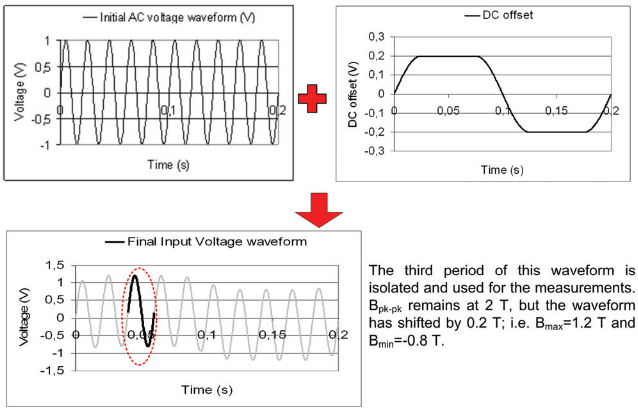


Fig. 4 Synthesis of a dc offset of 0.2 T on a 50 Hz, sinusoidal flux density waveform of 1.0 T peak [33]

Measurements under distorted flux density

There is a growing need to measure magnetic properties such as permeability, losses and magnetostriction under controlled distorted flux densities similar to those locally occurring in machine cores. For example, transformers and inductors in the power conversions systems connecting wind farms to conventional electricity distribution systems are subjected to severely distorted voltages. Systems for measurements under controlled conditions of this kind are common in research laboratories but their performances in general have not been verified and little work has been done to integrate with IEC standards.

In principle it is straight forward to determine losses under distorted flux density. Application of equation (1) to a magnetisation waveform containing harmonics in B and H reveal that, under unidirectional magnetization, the instantaneous energy loss, *P*, can be written as

(3) $$P = \sum 0.5 \cdot \omega_n \cdot B_n \cdot H_n \cdot \sin(\varphi_{bh})$$

where *n* is the harmonic number, $\omega = 2\cdot\pi\cdot f$, is the fundamental frequency, B_n and H_n are the peak values of the *n*-th harmonic components of flux density and field and φ_{bh} is the phase angle between them. When material is to be magnetised under flux density waveforms characteristic of PWM voltages, it is necessary to have an accurate and reliable means of controlling the *b* waveform. The waveform can be expressed as

(4) $$b = \sum_{1}^{n} n \cdot B_n \cdot \sin\left(n \cdot \omega \cdot t + \varphi_n\right)$$

where φ_n is the phase angle of the *n*-th harmonic. All the terms in equations (3) and (4) are experimentally accessible. In practical PWM waveforms, values of *n* higher than 500 need to be considered for either accurate measurements or loss prediction. Each hardware and software component of the loss measurement system must be confirmed to be accurate at the highest harmonic level. Also great care is necessary when determining specific values of B and H harmonics by harmonic loss superposition methods to ensure that second order harmonics are taken into account. No convenient approach to this appears to have been reported so loss measurement under high harmonic distortion is still open to debate.

Loss and machine core performance prediction

Loss prediction is often required under mechanical stress, at elevated temperatures or under rotational conditions all of which add to the measurement challenge. Such predictions need the back up of several types of measurements. We will see incremental advances in such associated measurements but what might be more challenging is how losses under such conditions can be predicted outside the normal measurement and characterisation regimes. There are several approaches to loss prediction [8] many of many of which need reference measurements to build models or to base predictions upon. At one extreme, artificial neural network methods need a large database of measurements from many specimens under a range of conditions whereas other approaches need sets of second order B-H loops measured over a wide range of flux densities. Although basic approaches to such measurements are widely reported, continued research will be needed to ensure they fit best with loss models.

An associated area of interest is embedding magnetic measurement data into computational electromagnetic modelling software for machine design and performance analysis. This does not need new approaches to measurements but research is necessary to provide measurement data in the most suitable format for manipulation in numerical routines. Of course the greater challenge is not only to incorporate provision for prediction at high flux density, under severe harmonic distortion, with dc offsets, etc, but also to fully take into account 2-D magnetisation and the non-absolute nature of Epstein and SST testing.

Texture and anisotropy effects

An IEC standard defines the anisotropy of loss in the case of non-oriented steel taking into account power loss P_0 in the rolling direction and P_{90} in direction perpendicular to rolling direction. This loss anisotropy factor is given by

$$\delta P = \frac{P_{90} - P_0}{P_{90} + P_0} \tag{5}$$

There is a growing interest in measurements of effects of texture on losses and other magnetic properties and the above relationship is no longer a sufficient measure of the anisotropy or effect of texture. Magnetization at intermediate angle to the RD can also be an important factor. They are either needed by steel producers to help understand texture parameters and controlling mechanism or by machine designers who need data to represent localised B-H characteristics in machine cores more accurately. Strips can be cut at angles to the RD and either measured singly or in an Epstein frame. Single sheets can be magnetised at selected angles to the RD in a 2-D tester. Both approaches have merits and weaknesses. Recent work shows how the choice of method depends on the magnitude of flux density [34]. It will not be surprising in the future to find that the choice of measurement technique depends also on other factors such as magnetising frequency, harmonics and, above all, sample size.

Magnetic shielding measurement

Safety regulations for low frequency magnetic shielding are a topic of hot debate. However shielding effectiveness can be a complex combination of the effect of geometry and magnetic material. The present IEC standards [35] mainly assess shielding geometry so comparison of magnetic properties is either completely neglected or not based on the magnetising conditions shielding materials are subjected to in practice [36]. Sheet material such as grain-oriented electrical steel is used for shielding up to 100 kHz but its effectiveness is not well quantified. Methods such as described in [36] have been proposed for measurement of shielding effectiveness of electrical steel subjected to fields perpendicular to its plane but more research is necessary to establish the most appropriate test conditions and how results can be related to effectiveness of large scale shielding applications. Ultimately computational magnetic modelling might be the answer but even then appropriate material characteristics will be necessary input data.

Conclusions

This paper highlights some areas of research which might be of industrial or scientific interest over the next few years. There will be scope for more comparisons of measurement systems from different groups but it is impossible to gauge to what extent this will be encouraged by the IEC standards community. If it is accepted that the Epstein test is outdated there is scope for new approaches to 1 and 2 DM routine measurements of ac properties of electrical steels.

Interest will certainly increase in measurements under distorted flux density. It would be desirable to move towards standardisation at a much quicker rate than it has since suggestions were first made [35]. Relationships between specimen size and magnetic properties need to be established more firmly to make sure laboratory test data can be confidently used to make predictions of practical performance of electrical machine cores.

Some researchers argue that with more reliable computational models being developed it will become less necessary to develop and use complex 1 and 2 DM measurement systems, but we are probably very far from that stage.

Great strides in 1 and 2 DM measurements have been made over the last 20 years and this is certain to continue as core designers use magnetic materials in new applications under more extreme magnetisation conditions. As new materials are developed, they themselves will stimulate new applications. It will continue to be important for researchers to keep close watch on trends in the development and use of bulk soft magnetic materials so that they can foresee and tackle measurement and characterisation challenges.

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