Invited paper

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Measurement techniques for the assessment of materials under complex magnetising conditions

***Abstract**. Magnetisation waveforms in many electromagnetic applications exhibit flux density waveforms which are far removed from the sinusoidal ideal. A test system is described which enables complex flux density waveforms to be controlled. The precautions and additional sources of error for characterisation under complex magnetisation conditions are outlined. Example results including the effect of introducing high order harmonics and a simulation of PWM exciting are presented along with examples of the use of a modified superposition of loss technique.*

***Streszczenie.** Kształt krzywej indukcji często odbiega od sinusoidalnego. Przedstawiono system umożliwiający kontrolowanie kształtu przebiegu indukcji. Przedstawiono przykłady badań materiału magnesowanego przy indukcji zwierającej wyższe harmoniczne oraz PWM. (**System do badania materiałów magnetycznych przy złożonych warunkach magnesowania**)*

Keywords: AC measurements, complex waveforms, PWM, waveform control
Słowa kluczowe: indukcja, badanie materiałów magnetycznych.

Introduction

The designers and users of electrical machines are placing increasing demands on the magnetic cores. Traditionally the electrical steels used in these devices are characterised under standard conditions with power frequency sinusoidal magnetisation requiring designers to over-engineer the magnetic components based on previous experience.

It is common knowledge that many applications of electrical steels exhibit flux density waveforms which are far removed from the sinusoidal ideal.

Power conditioning is of growing importance in electrical applications ranging from high power and voltage distribution systems to domestic, commercial and industrial motor drives. Power electronic converters with strategies such as pulse width modulation (PWM) techniques are a flexible means of affecting this control but this is usually achieved at the expense of waveform quality. There are substantial uncertainties when motors, transformers or inductors are subjected to voltage supplies with poor waveform quality. The key concern is the increase in magnetic core loss which can cause both a damaging temperature rise and extremely low efficiency.

Even for conventional sinusoidally excited devices such as induction motors the flux density waveforms vary from close to sinusoidal to highly distorted and, behind the teeth, rotational flux conditions.

Test systems have been developed at Cardiff University over several years to enable these complex magnetising conditions to be simulated in the laboratory. These enable designers to get real information about the performance of the core under conditions predicted by the design software as well as being able to compare the performance of different materials under these conditions.

Measurement System

The digital ac characterisation system replaces all of the components of traditional discrete ac measurement systems, except for the power amplifier, with a commercial data acquisition card. This card enables an analogue output to be generated with a sampling rate of 4 Msamples/s and will simultaneously sample up to 4 input channels with a maximum voltage of 42V and a maximum sampling rate of 1 Msamples/s.

Three channels are simultaneously sampled: magnetising current (voltage across a non inductive resistor in the ground return of the primary winding), secondary voltage and the input to the power amplifier.

Processing of the measured values is performed in software using the graphical programming language Labview. RMS and average voltages are calculated in the conventional manner, the secondary voltage is integrated and scaled to give the flux density waveform, power loss is calculated through a numerical integration of the product of H and dB/dt, a Fourier transform is used for harmonic analysis and THD calculation and values for coercivity and remanence are calculated by linear interpolation of the BH loop.

A user friendly graphical user interface allows input of the test and material parameters and presentation of results, figure 1.

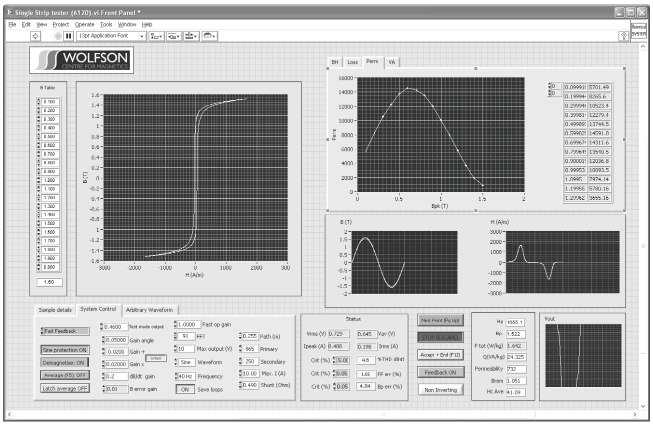

Figure 1: User interface

The main advantage of the digital system is the ability to employ digital control techniques to the flux density waveform as this enables the wave shape to be very closely controlled, at high speed and for highly complex waveforms.

The digital waveform control algorithms used previously [1] relied on complex phase adaption code to overcome the non-linearity of the card and amplifier. The use of the latest generation of simultaneous sample and hold data acquisition card enabled an additional input to be added monitoring the voltage output from the previous generation of the control algorithm. This removed the requirement for the adaption code and greatly simplified the control algorithm. A simplified schematic of the algorithm is shown in figure 2. This simplified algorithm enabled the processing time to be halved and also reduced the number of iterations required to achieve control so that the overall test time was reduced by approximately 75%.

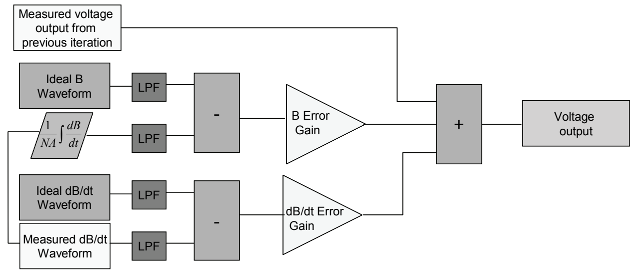

Figure 2: Waveform control algorithm

Arbitrary waveforms can be designed by the user in one of two ways:
1. By building an array of frequencies, amplitudes and phase shifts for each harmonic present.
2. loading waveforms created from simulation packages or measured from real machines to be directly into the software

This system has several advantages over traditional systems.
1. It allows real time recording of B and H waveforms which can give a greater insight into the mechanisms of magnetisation.
2. It is low cost
3. Digital waveform control may be employed allowing highly complex waveforms (including PWM) to be controlled
4. It allows automation of a series of complex measurements. For instance, a range of 20 flux densities at 5 frequencies and 2 different waveforms may be programmed into the software and run without user intervention
5. Performs measurements of other parameters such as remanence and coercivity.
6. Compensation for flux contained within the air gap between the sample and the secondary windings may be performed numerically. However, care must be taken since errors in assumed path length will lead to errors in measured H and hence over or under compensation.

The disadvantages of this approach are:
1. Lower bandwidth limits the number of harmonic components which can be measured/controlled
2. Calibration not as easily available as for separate instruments
3. Version control for the software is extremely difficult and bugs can remain hidden for long periods – hence the requirement for regular checks against the reference system.

Testing under complex magnetising conditions

A variety of sample geometries may be used with both test systems discussed above. These include:
- Rings or toroids
- Single Epstein samples
- Epstein frame

The preferred geometry is usually rings or toroids. These are best suited to measurement under complex magnetisation conditions since the number of magnetising windings may be used to tailor the impedance of the circuit and achieve a good match with the power amplifier being used to maximise power transfer and minimise additional non-linearity.

After the toroid or ring has been weighed and dimensionally measured a thermocouple is fastened to the surface and it is tight wound with appropriate secondary and primary windings spread evenly around the core.

The core and winding details are entered into the user interface together with the frequency, range of flux densities, waveform and feedback gains (determined during preliminary measurements). The software then runs through the range of tests. Every test point was recorded when all of the control criteria are met, these are:
- THD error (nominal value < 0.5%)
- Form factor error (nominal value < 0.02%)
- B peak error (nominal value < 0.01%)

Apart from the requirement to define the magnetisation waveform, operating the system for magnetisation with complex waveforms is identical to operation for sinusoidal magnetisation. However, there are several additional sources of errors and precautions which should be taken.

These include:
1. Path length
2. Bpk setting
3. Capacitance and dielectric effects
4. Temperature
5. Sampling Frequency
6. Skin effect

Of these the first two are the most often neglected and offer the largest potential sources of error.

When making measurements at higher frequency, under complex waveforms or at high or low flux density, it is important to be aware of the, often very significant, additional errors in the measurement due to changes in the mean magnetic path length. Research on the Epstein frame [2] has shown that the mean magnetic path length depends on many factors including: material properties, peak flux density, frequency and magnetisation waveform. This is demonstrated in figure 3 where it can be seen that the Epstein path length (nominally 0.94m) can vary by greater than 6% for the waveforms considered. All sample geometries will suffer from similar variations although the magnitude and characteristic will be dependent on the geometry.

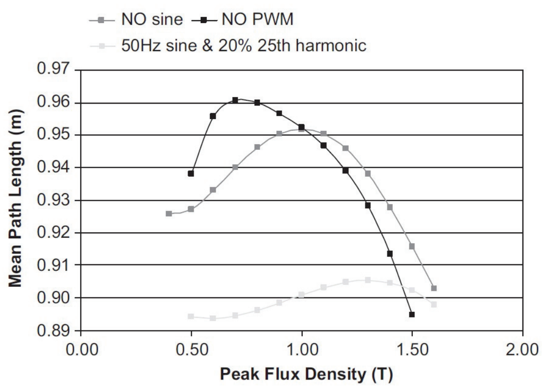

Figure 3: Variation of mean magnetic path length in an Epstein frame for sin, PWM and arbitrary waveform magnetisation.

Many systems utilise the relationship between peak magnetic flux density and the average secondary voltage for setting the peak flux density in the sample (equation 1)

(1) $$V_{ave} = 4\hat{B}ANf$$

This is based on a derivation from:

(2) $$B(t) = \sum_{r=1} a_r \sin(r\omega t + \phi_r)$$

With the assumptions that r is only odd and dB/dt will have zeroes when B=Bpk separated by half a wavelength. Therefore the equation cannot be used when the B waveform contains even harmonics or when minor loops are present in the BH loop.

It is best when dealing with non-sinusoidal waveforms to base the setting of peak flux density on an integrated secondary voltage which has been correctly scaled for the number of turns and area.

Results

Several examples of characterisation performed by the digital system utilising complex waveforms are given below.

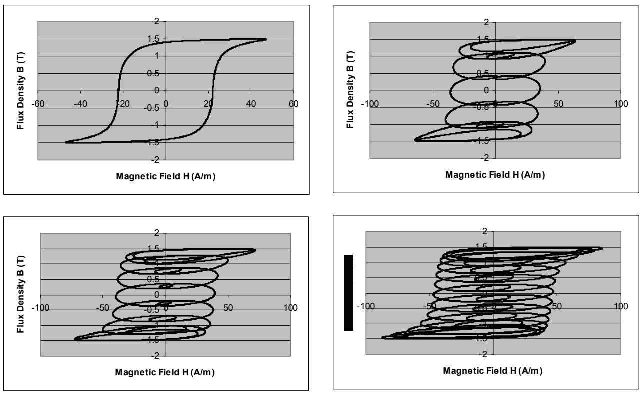

Figure 4: BH loops measured using the digital AC measurement system for GOSS at 1.5T, 50Hz

Figure 4 shows the measured BH loops for a grain oriented silicon steel sample magnetised at a peak flux density of 1.5 T and a fundamental frequency of 50 Hz. The measurements were made using an Epstein frame deigned with regard to the precautions outlined previously. The first loop shows a pure sinusoidal waveform. The remaining loops contain in-phase harmonics at 10% of the amplitude of the fundamental at 11, 15 and 25 times the fundamental frequency. Table 1 gives the measured values of peak magnetic field strength and specific total loss under the same conditions as figure 4. As can be seen the effect of these harmonics is extremely significant on the specific total loss which increases with the order of the harmonic. The peak magnetic field strength also increases signifying a decrease in the permeability of the sample.

Table 1: Measured specific total loss and peak magnetic field strength for waveforms containing increasing orders of harmonics and a peak flux density of 1.5T.

Waveform (Bpk = 1.5T)	Peak H (A/m)	Specific Total Loss (W/kg)
Sin 50Hz	46.9	0.840
Sin + 10% 11th	63.9	1.698
Sin + 10% 15th	71.5	2.327
Sin + 10% 25th	85.6	4.079
Sin + 10% 27th	89.8	4.611

Figure 5 shows BH waveforms for simulated PWM magnetisation in a non-oriented electrical steel at 1.5 T, with a fundamental frequency of 50 Hz. The resulting BH loop is shown in figure 6.

2 level PWM is characterised by a fundamental frequency at the modulating frequency and significant harmonics at the harmonic equal in frequency to the carrier plus the odd harmonics either side of this. Thus PWM can be more simply represented in terms of a fundamental plus single carrier frequency harmonic. An example of this is shown in figure 7 with 2 level PWM demonstrated along with 50Hz sin with a superimposed 19th harmonic (corresponding to the 950 Hz carrier).

Whilst there are clear differences in the measured BH loops the measured losses of 7.41 W/kg and 7.10 W/kg (compared to that under sin magnetisation of 4.72 W/kg) are reasonably close and a simplified approach such as this may be applicable when the full spectrum of the PWM waveform cannot be repeatably produced.

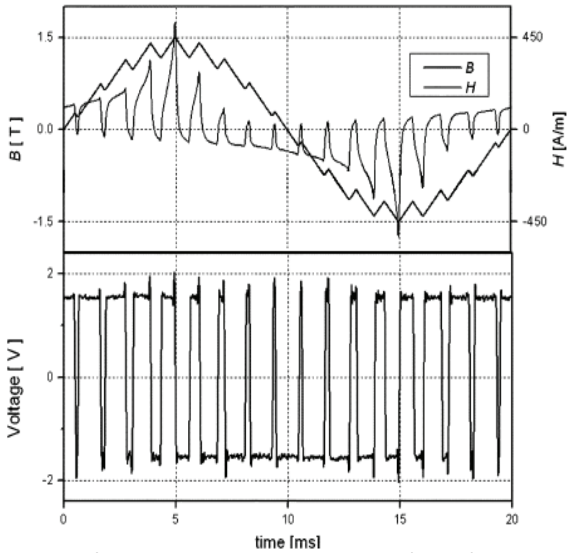

Figure 5: Simulated B, H and voltage waveforms for a non-oriented electrical steel at 1.5 T, 50 Hz

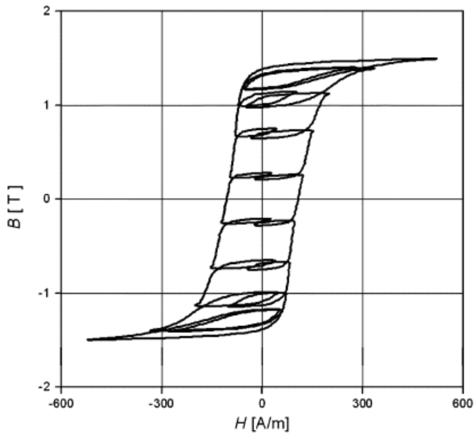

Figure 6: BH loop under simulated PWM excitation for a non-oriented electrical steel at 1.5 T, 50 Hz

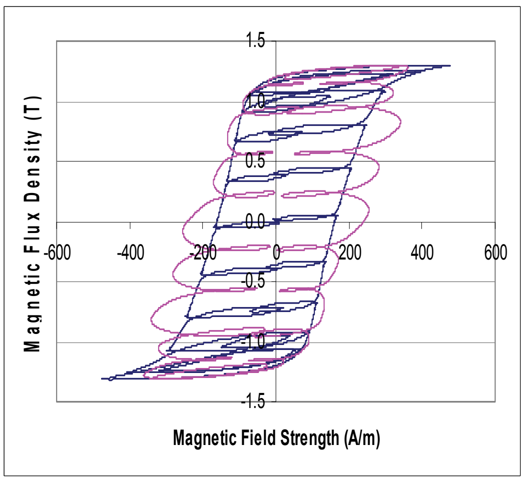

Figure 7: Simulated PWM and sin plus 19th harmonics at 1.3 T, 50 Hz

Superposition of losses

Superposition is quite commonly used by machine designers to determine the loss under operational waveforms. The loss of each of the components of the B waveform is summed to give the total loss under distorted conditions as shown in equation 3.

$$(3)\quad P_{Total} = \sum_{n=1}^{f\max} H_n . \frac{dB_n}{dt} dt$$

By taking measurements under sinusoidal conditions across whole B range for each of the components should be able to estimate the loss for any harmonic amplitude.

An example of superposition is shown below for an M290-50 non oriented electrical steel magnetised with at 1.0T 50Hz for a sin wave with 10% 19^{th} harmonic.

Example 1: Superposition of loss

Complex waveform, total loss:	**2.190 W/kg**
Sin waveform (0.918T, 50 Hz):	0.940 W/kg
Sin waveform (0.0918T, 950Hz):	1.160 W/kg
Total loss by superposition:	**2.100 W/kg**

This appears a reasonable estimate for the loss under the complex waveform. However, for a second waveform: 1.5T, 50Hz, sin plus 10% 3^{rd} harmonic (shown below) there is a large error.

Example 2: Superposition of loss

Complex waveform, total loss:	**2.970 W/kg**
Sin waveform (1.667T, 50 Hz):	3.322 W/kg
Sin waveform (0.1667T, 150Hz):	0.206 W/kg
Total loss by superposition:	**3.528 W/kg**

The reasons for the large error are likely to be due to assumption that the BH characteristic is linear. This can cause errors for the following reasons. Firstly, the approach above uses loss measurements made for independent harmonics centered about zero B. In reality the minor loop generated by the harmonic will be offset by some DC value and may be pushed into the non linear portion of the BH characteristic giving significant differences to the loss. Although losses could be measured with a DC offset, the more measurements which need to be made limit the usefulness of the method.

Secondly, the scalar sum of the loss of the independently measured harmonics ignores the range of H harmonics present for sinusoidal B measurement. These H harmonics have no influence on the loss as there is no corresponding B harmonic (hence the vector sum is zero). However when considering the summation of harmonics we must take these H harmonics into account. Thus when adding in the loss of a third harmonic component (as in example 2 above), the loss due to the vector sum of the third harmonic H in the 50 Hz component and the fundamental dB/dt in the 150Hz component must be added - shown as Sin (150Hz, extra 3rd harmonic loss). This approach is demonstrated below.

Example 2: Modified superposition of loss

Complex waveform, total loss:	**2.970 W/kg**
Sin waveform (1.667T, 50 Hz):	3.322 W/kg
Sin waveform (0.1667T, 150Hz):	0.206 W/kg
Sin (150Hz, extra 3rd harmonic loss):	-0.430 W/kg
Total loss by superposition:	**3.098 W/kg**

As can be seen this technique results in a closer estimate of the loss with a negative loss being attributed to the large out of phase H harmonic required to generate sinusoidal B.

These techniques will be investigated further to ascertain their accuracy under a range of conditions including out of phase harmonics.

Conclusion

Magnetic cores are being subjected to ever more demanding magnetisation conditions including highly complex magnetisation waveforms.

As data acquisition hardware improves, and becomes lower in cost, laboratory equipment is able to simulate these waveforms in a repeatable and accurate fashion.

With further development modified superposition techniques may be able to give a reasonable estimate of loss under complex waveform conditions.

REFERENCES

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