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EFFECT OF DC VOLTAGE ON AC MAGNETISATION OF TRANSFORMER CORE STEEL

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Primary windings of transformers are fed with alternating sinusoidal voltage, but often this voltage contains small DC offset due to unsymmetrical voltage levels. To emulate such working conditions in a controlled environment (Epstein frame) the excitation waveforms were emulated as a DC voltage superimposed on an AC waveform. This resulted in non symmetrical excitation of the core steel. The harmful effects of this type of excitation on magnetising current, power loss and the B-H characteristics of the steel are shown.

Keywords: electrical steel, power loss, DC bias

1 INTRODUCTION

Power transformers are normally designed for operation with a sinusoidal input voltage. Today there is growing concern over the increasing number of cases where primary voltage distortion can cause deterioration of performance or even damage to transformer cores. The voltage distortion can be produced in many ways [1]. Much work has been carried out on measuring or predicting the increase in iron loss, which can easily double under Pulse Width Modulation excitation [2, 3].

The effect of small DC voltage components superimposed on a sinusoidal supply on transformer performance has been studied several years ago [4 - 6] and the core loss increase due to even a small voltage offset is well known. In recent years it is becoming more important because of the greater possibility of its occurrence in transformers and it appears in an IEC standard specifications [7].

The DC voltage can arise from unsymmetrical voltage levels due to AC-DC energy conversion and its magnitude depends on the DC current, network impedances and transformer design. Geomagnetically induced currents (GIC) caused by increased solar activity can also introduce DC biased magnetisation in transformers through their grounded neutral terminals. This can lead to unsymmetrical magnetisation of the core resulting in overheating, emission of harmonic voltages, corrosion of earthing fixtures and all the problems associated with core saturation [8].

Previous reports have tended to quantify DC offset conditions in various ways which can lead to some confusion and makes comparative measurements difficult or impossible. As far as material comparisons are concerned, the offset is best defined in terms of a known DC component of flux density on a known AC component. This is difficult to set up and control in practice.

This paper reports on the effect of DC voltage offset on the magnetisation of grain-oriented electrical steel of the type used in power transformers assembled in strips in an Epstein frame. A novel method of controlling the flux density is given. In this way the basic performance of the steel can be measured accurately under controlled magnetisation conditions from which the effect of the DC voltage in a full size transformer can be estimated.

2 EXPERIMENTAL PROCEDURE

Epstein strips of 27M4 grade, grain-oriented 3 % Si-Fe were assembled in an Epstein frame and magnetised at 50 Hz under pure sinusoidal flux density or in the presence of a controlled DC voltage offset applied to the primary winding. Magnetisation was carried out in a fully automated, computerised system, using LabVIEW in order to generate, measure and control the various waveforms. The iron loss of the steel under test was 0.8515 W/Kg (130.3 J/m^3) and 1.278 W/kg (195.5 J/m^3) at 1.5 T and 1.7 T respectively under sinusoidal 50 Hz magnetisation.

The magnetisation waveforms were designed in LabVIEW before applied to the steel inside the Epstein frame. An example of the way the target input voltage waveform was designed is shown in Fig. 1 to Fig. 3. The final waveform shown in Fig. 3 shows the target, ideal, DC biased sinusoidal flux density waveform that the steel was magnetised at in the Epstein frame. It is designed by combining the waveforms in Figures 1 and 2. The purely AC waveform, Fig. 1, determines the desired peak to peak amplitude of the flux density whereas the waveform in Fig. 2 determines the amount of DC offset applied.

A digital feedback control algorithm ensures that the measured flux density of the sample is as close as possible to the ideal flux density waveform we are trying to achieve. When the measured peak flux density value is within 0.1% of the ideal and the total harmonic distortion of the measured flux density waveform is within 0.3% of the ideal the measurement is taken.

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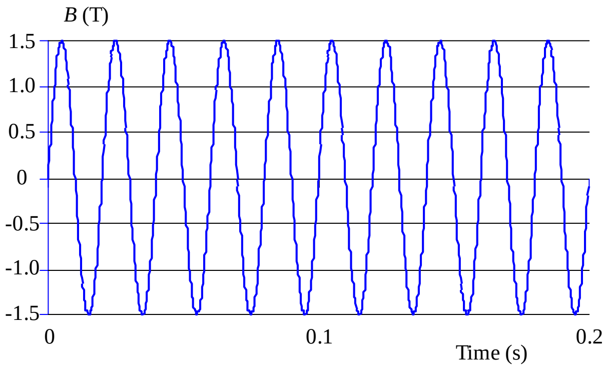

Fig. 1. The basic AC waveform (without DC offset) with *B* pk-pk set to 3T

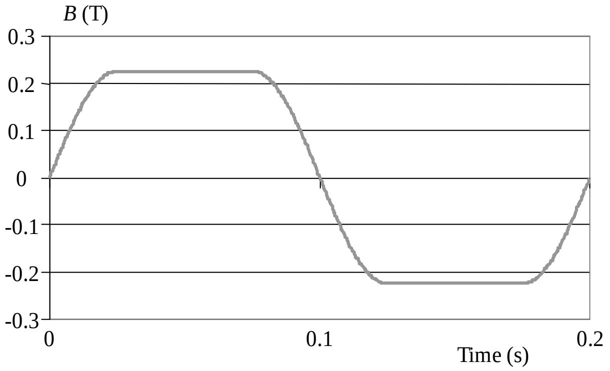

Fig. 2. The “DC” waveform applied to shift the AC flux density by 0.23 T

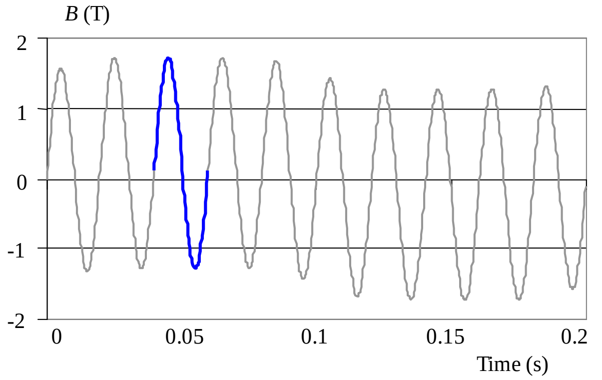

Fig. 3. The resulting waveform is a combination of both “DC” and AC waveforms. The third period is isolated and used for the measurements.

3 RESULTS AND DISCUSSION

The DC voltage was varied from 1% to 3 % of the input voltage when the sinusoidal flux density was pre-set to values between 1.0 T and 1.7 T. Table 1 shows the effect of DC offset from 0 % (pure sine) to 3 % on the magnetising current and power loss when the flux density was set at 1.5 T (*ie* 3 T AC peak to peak).

The main observations from table 1 are that although the RMS magnetising current increases by almost two and a half times in the case of 3 % DC bias compared to pure sinusoidal, the power loss only changes by 12 %.

In practice the magnetising current of a power transformer is less than 5 % of full load current, in which case this increase and change in wave shape is relatively insignificant. However, it is significant that the peak value of the magnetising current increases 5 times compared to that of the pure sine excitation.

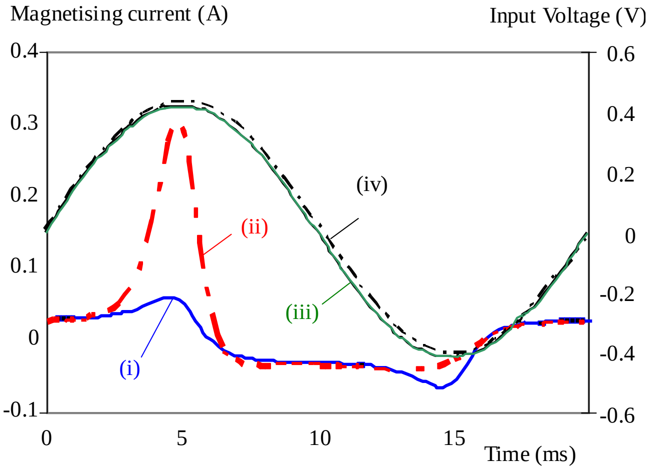

Fig. 4. Effect of 3% DC offset in the input voltage on the magnetizing current waveform (B_p=1.5 T): (i) – current under sine excitation, (ii) –current under excitation containing 3% DC offset (iii) – V_{in} sine, and (iv) – V_{in} with 3% DC offset.

Figure 4 shows how the shape of the magnetising current changes as the DC bias field is applied. We can clearly see the increase in peak magnetising current during the first half cycle of the magnetisation process.

This will cause the core to approach saturation when the DC offset is applied resulting in a five fold increase of the peak applied magnetic field. Figure 5 shows a typical result, at 1.5 T, for pure sine compared to sine with a 3 % DC offset.

In the real transformer this would give rise to harmful harmonics in the secondary voltage. This effect is of course more pronounced at higher flux densities or with higher DC voltage components.

Figure 6 shows the magnetising current as the DC offset is increased from 1% to 3%.

As the amount of DC offset increases the magnetising current increases exponentially. It is worth noting that when just 3 % DC offset is present an increase in magnetising current of 135 % occurs leading to the flux density in the steel under test to approach saturation, causing high distortion to the secondary voltage.

Although the DC bias field itself cannot cause eddy currents the increased magnetising current due to the DC bias excitation can cause high leakage flux in the transformer clamps and tank leading to high planar eddy currents and localised hot spots in the tank wall as previously suggested in [9]. These in turn can cause deterioration to the properties of the transformer oil creating a cascading effect with potentially devastating consequences.

Table 1. Effect of offsets from 0-3 % on the magetising current and loss when the flux density is set at 1.5 T

Magnetisation at B_{peak}=1.5 T	$V_{input,\ max}$ (V)	$V_{input,\ min}$ (V)	$I_{mag,rms}$ (A)	$I_{mag,\ rms}$ (%)	P_{loss} (J/m^3)	P_{loss} (%)
Sine (no DC in input voltage)	0.4169	-0.4169	0.0362	**100**	130.3	**100**
Sine + 1% DC in input voltage	0.4238	-0.4138	0.0397	**110**	131.3	**101**
Sine + 2 % DC in input voltage	0.4284	-0.4121	0.0470	**130**	135.3	**104**
Sine + 3 % DC in input voltage	0.4334	-0.4084	0.0852	**235**	146.3	**112**

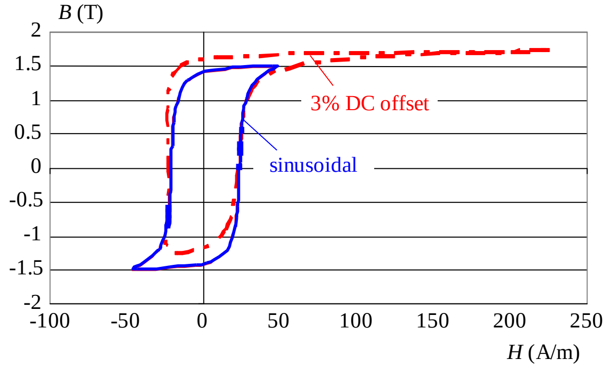

Fig. 5. Effect of 3% DC offset in the input voltage on the *B*-*H* loop ($B_{\text{pk-pk}}$=3.0 T)

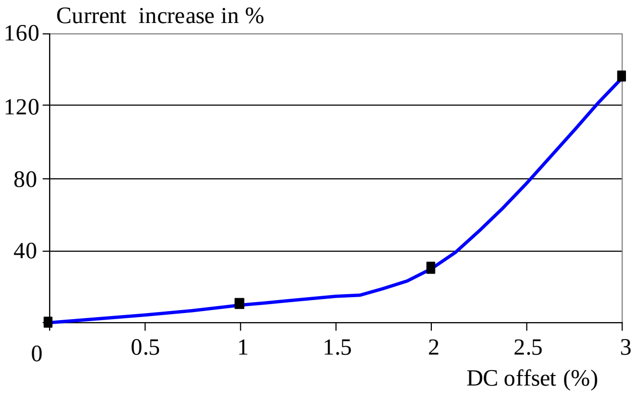

Fig. 6. Effect of different levels of DC offset on the magnetising current when $B_{pk\text{-pk}}$ is constant, magnetizing current increase is compared to sinusoidal excitation (%)

4 CONCLUSIONS

Designers and users need to carefully consider what level of DC voltage might be present in distribution or power transformers and be prepared to de-rate operating flux density where appropriate. A small DC offset can cause a very large increase in magnetising current but this, or the increase in iron loss, is usually of little importance. However, core saturation, resulting leakage flux and flux distortion and associated secondary voltage harmonics might be of concern.

Acknowledgement

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