Characterization of Grain-Oriented Electrical Steels Under High DC Biased Conditions

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Power transformers are designed to operate under pure ac excitation; however, they may be subjected to superimposed dc voltages and consequential offset currents, for example, from geomagnetically induced currents, geomagnetically induced quasi-dc currents, arising from solar activity. To determine the effects of dc offsets, a single-sheet tester was used with a digital excitation signal created with an ac waveform summed with a dc voltage addition and measured with a digital feedback control algorithm to ensure an ideal flux density waveform. Using this method, results with 300% additional dc contribution were able to be measured for results up to $B_{ac} + B_{dc} = 1.9$ T. The measurements of grain-oriented 3% Si–Fe show increasing power losses and peak applied magnetic field for peak-to-peak flux densities above 3 T, with a 33% increase in power loss and 500% increase in applied magnetic field for an offset of 25%.

***Index Terms*—DC bias, electrical steels, power losses.**

I. INTRODUCTION

POWER transformers are normally designed to operate with a sinusoidal input voltage. Increasing studies are being performed when the primary voltage becomes distorted; an example of this is due to the addition of a dc bias. A dc bias may arise in a transformer from many sources, such as unsymmetrical voltage levels due to ac–dc energy conversion and monopolar operation of HVdc [1], and solar activity may lead to geomagnetically induced quasi-dc currents (GICs) through the power transmission system and into the transformer through the grounded neutral terminal. An equivalent dc current of 25 A per phase has been observed for several hours from a dc injection of one of the ground electrodes of a HVdc. Comparatively, from GICs, 100 A per phase can be seen for up to 1 min and 50 A for up to 5 min [2]. These can lead to half-cycle saturation leading to a dramatic increase in excitation current, higher harmonic content, over heating (e.g., [3]–[5]), and noise levels [6]. This is illustrated in Fig. 1, which shows the potential for a small dc offset to cause a power transformer to enter half-cycle saturation.

The magnetic properties of electrical steel are usually measured with a sinusoidal magnetic flux density at a fixed level of magnetic induction. Therefore, a preferred parameter for the dc biasing would be an additional constant component of the magnetic induction [7], [8]. In this paper, a method is introduced to measure the magnetic properties of electrical steel with up to a 300% dc offset of the magnetic flux density.

II. EXPERIMENTAL PROCEDURE

A. Samples

Measurements were performed on a single-sheet sample of 3% grain-oriented electrical steel M85-23 with dimensions 100 × 495 mm and mass $m = 84.98$ g. All the measurements were performed in the rolling direction of the material. Initial measurements were performed with a pure sinusoidal flux density at 50 Hz. The power losses at 1.5 and 1.7 T were 0.68 and 0.95 Wkg^{-1}, respectively.

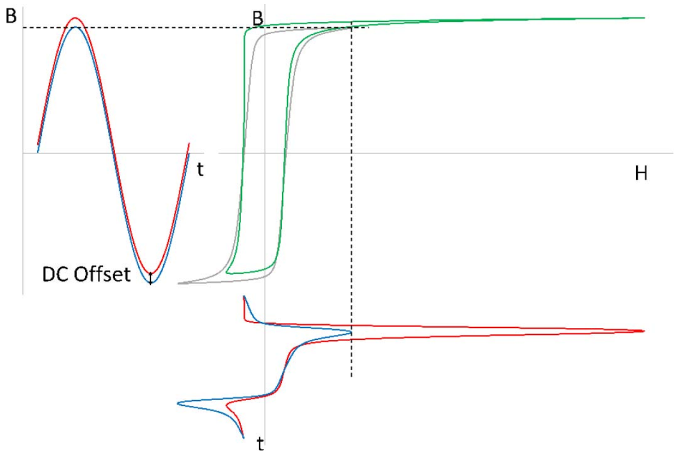

Fig. 1. Effect of the addition of a small dc offset to the magnetic flux density *B* (left) may cause half-cycle saturation (right) and large distortions in the current waveform (bottom).

B. Measurement System

Measurements were performed on a single-strip tester with flux closure around the sample provided by the laminated yokes of grain-oriented electrical steel. The total number of turns in the excitation coil and the search coil was 190 and 285, respectively; a compensation coil was also used. To apply a dc offset, an ideal digital flux density was generated. The makeup of this ideal waveform is shown in Fig. 2(c), which is a summation of a pure sinusoidal wave of five periods [Fig. 2(a)] and a trapezoidal wave [Fig. 2(b)], where the peak of the trapezoidal wave determined the amount of dc offset. Fig. 2(c) shows the second period highlighted from which the results in this paper were derived; in this case, an ac component of magnitude $B_{ac} = 0.5$ T (peak to peak 1 T)

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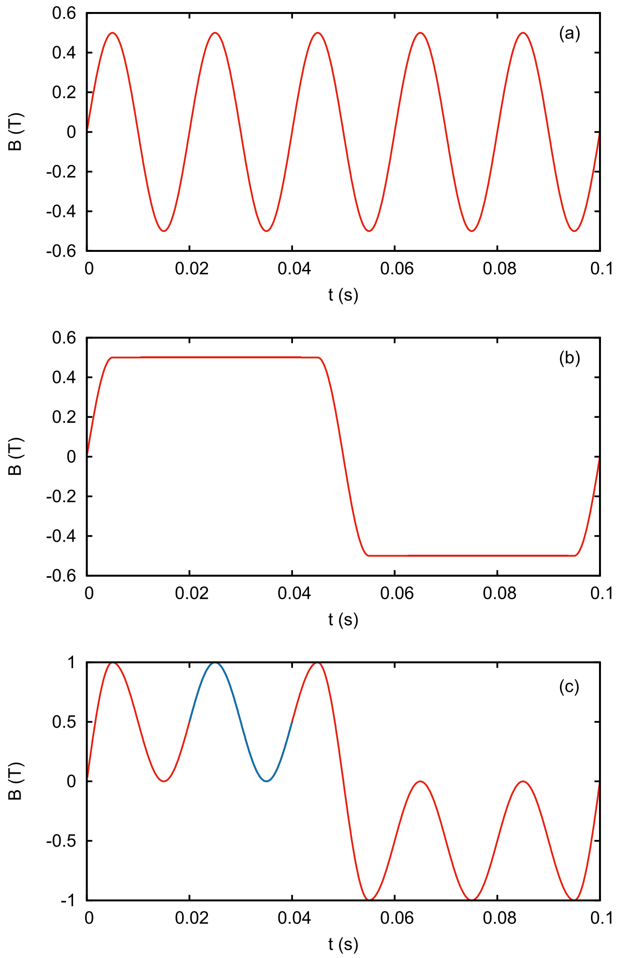

Fig. 2. Digital control waveform used for creating a dc offset. (a) and (b) are summed to create (c), with the highlighted waveform in (c) used in measurements.

and a dc offset of 100%, with $B_{\text{dc}} = 0.5$ T. In all the results presented in this paper, the sinusoidal frequency component was 50 Hz. In all the measurements with a dc offset, the magnetizing waveform was controlled with a digital feedback loop (as developed from the method described in [9]), where the difference in the ideal and measured B and dB/dt is iteratively used to modify the generated output voltage. A block diagram of the digital feedback system is shown in Fig. 3, showing the generated voltage passing through a digital low-pass filter to a power amplifier. The magnetizing current from the power amplifier is passed to the magnetizing coil through a shunt resistor, which allows current measurements. In addition, each iteration is measured over several periods and averaged, which increased the stability of the measurements. Average values between 5 and 10 were used in the measurements as this provided good stability while keeping the overall measurement time to within a few minutes. All the operations in the dc offset system were implemented in the software, and for integration (used to determine B from the induced voltage), low-pass filtering (used in the digital feedback circuit) and Fourier transforms (used to derive total harmonic distortion) of the entire measured wave was used. This was done as the ideal wave function was symmetric and could, therefore, be integrated without adding additional linear components. The total harmonic distortion was <1%, and the peak flux density value and form factor are within 0.1% of the ideal values in all the measurements. Total power losses were also numerically determined by

$$P_{\text{Loss}} = \int_0^T H \cdot \frac{dB}{dt} dt. \tag{1}$$

Fig. 4 shows a comparison between the magnetic properties of the standard measurement and the proposed method with a zero dc offset, with the main figure showing the B–H curves and the inset the power losses. No differences in the B–H curves or the power losses can be seen between the measurement techniques.

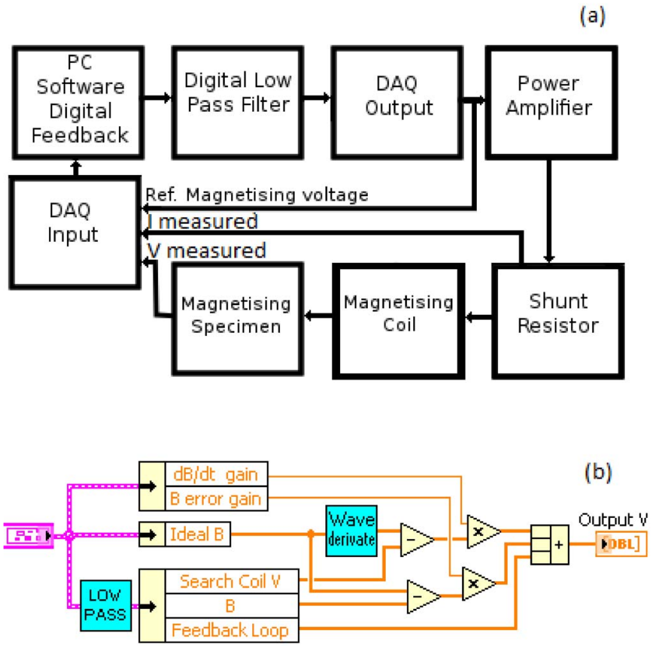

Fig. 3. (a) Block diagram of the digital feedback system. (b) Simplified LabVIEW program showing the process of the PC software digital feedback using the measured voltage, flux density, and reference magnetizing voltage (feedback loop).

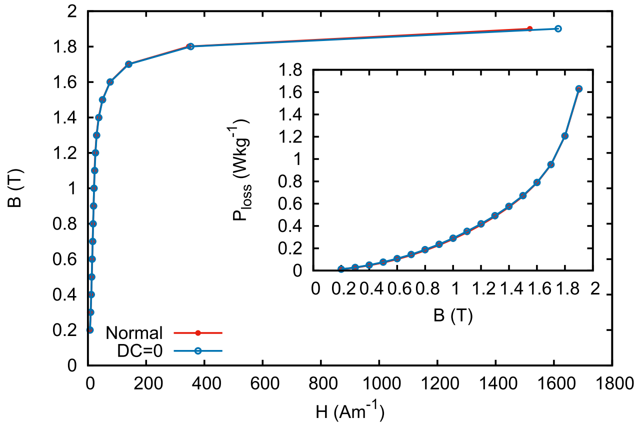

Fig. 4. Peak flux density B as a function of applied field H comparing normal measurement technique (normal) with the dc measurement technique with $B_{\text{dc}} = 0$. Inset: change in measured power loss.

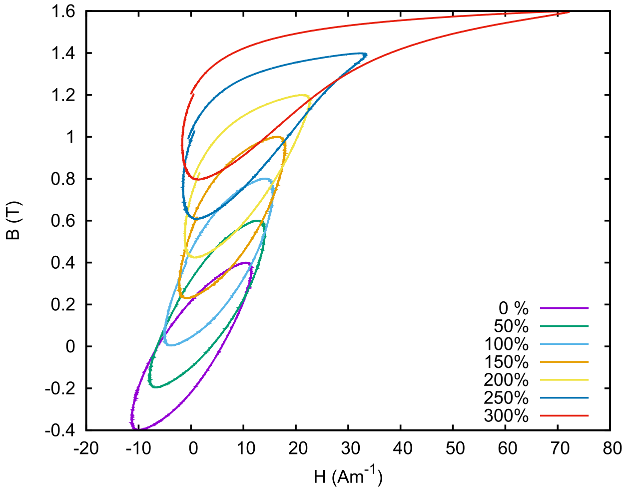

Fig. 5. Hysteresis loops of magnetic flux density B as a function of applied magnetic field H for varying amount of dc offsets.

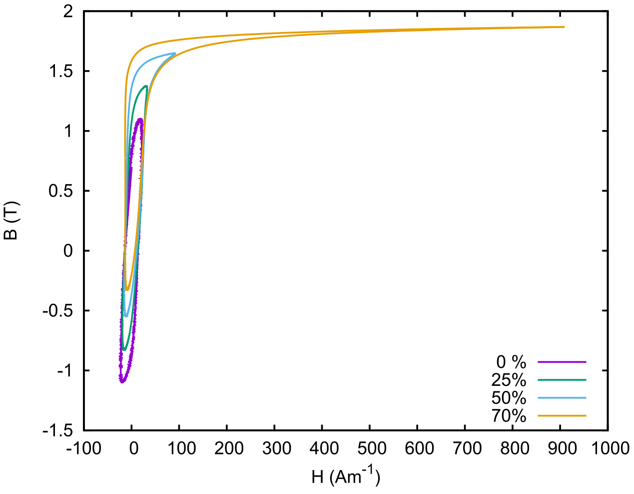

Fig. 6. Hysteresis loops of magnetic flux density B as a function of applied magnetic field H for varying amount of dc offsets.

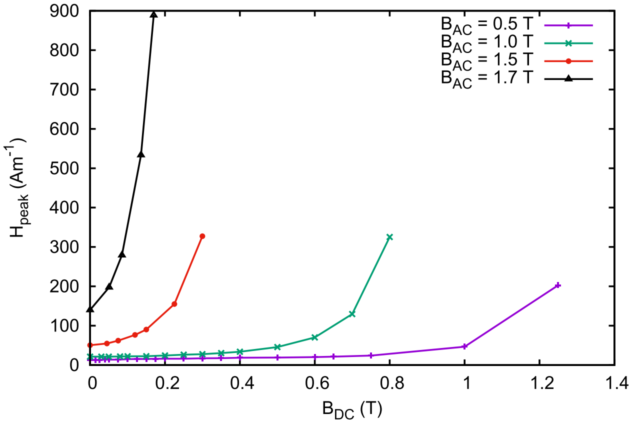

Fig. 7. Peak applied field H_{peak} for varying applied dc offsets B_{dc}. Results are shown for fixed peak sinusoidal flux densities B_{ac}.

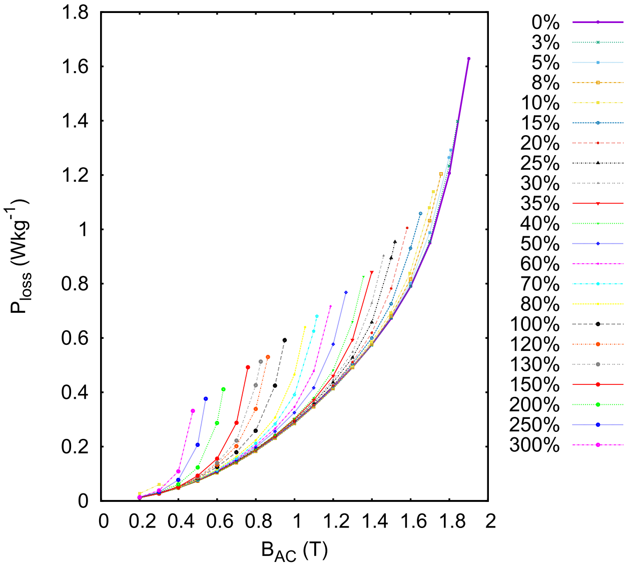

Fig. 8. Total power losses as a function of peak sinusoidal flux density B_{ac} for varying dc offset percentages.

III. Results and Discussion

The magnetic properties were measured for the increasing values of dc offset from 0% to 300% and up to a total peak flux density $B = B_{\text{ac}} + B_{\text{dc}} = 1.9$ T. An example of the B–H loop for peak $B_{\text{ac}} = 0.4$ T (peak to peak $B = 0.8$ T) is shown in Fig. 5 and for $B_{\text{ac}} = 1.1$ T (peak to peak $B = 2.2$ T) in Fig. 6, showing the effect on the loop shape and the area for varying dc offsets. In Fig. 7, the maximum applied field H_{peak} is shown for varying values of B_{dc}. The value of H_{peak} increases with increasing B_{dc}, with a 500% increase in H_{Peak} observed with $B_{\text{dc}} = 0.17$ and 0.3 T for $B_{\text{ac}} = 1.7$ and 1.5 T, respectively. By comparing the results of Figs. 7 with 4, the value of H_{peak} at B_p ($=B_{\text{ac},p} + B_{\text{dc},p}$) can be directly related to B_p of the zero dc offset. This could allow for extrapolation beyond $B = 1.9$ T of these measurements [10] allowing the study of saturation values observed during the GIC events. The total power losses for all the measured dc offsets are shown in Fig. 8. The total power losses for several fixed peak-to-peak flux densities are shown in Fig. 9. At high peak-to-peak ac flux densities, even a small addition of dc component can greatly increase the power losses by 10% dc increasing losses by 0.13 Wkg^{-1} or 13% at $B_{\text{ac}} = 1.7$ T. At $B_{\text{ac}} = 1.5$ T, at 10% dc offset, the increase in losses is only 0.02 Wkg^{-1} or 4%. As the dc offset increases to 25%, the increase in power losses increases to 0.22 Wkg^{-1} or a change in 33%. At low peak-to-peak flux densities of $B_{\text{ac}} = 0.4$ and 0.5 T, no discernible change in power loss is seen below a dc field of $B_{\text{dc}} = 1$ T. This relates to a 200% and 250% dc offset.

The effect on power loss with increasing dc bias shows a similar trend to previous measurements [7], [8], [11] when the offset is applied to the magnetic flux density. From Fig. 7, to determine a dc offset in the applied magnetic field at 200 Am^{-1}, $B_{\text{ac}} = 0.7$ T shows a 100% increase in power loss, whereas at $B_{\text{ac}} = 1.7$ T, the losses only increase by 2%. Results where the dc biasing is to the applied magnetic field [12] have shown similar results with a 100%–200% increase in power losses at $B_{\text{ac}} = 0.7$ T for $H_{\text{dc}} = 100$–400 Am^{-1} and as peak-to-peak flux densities

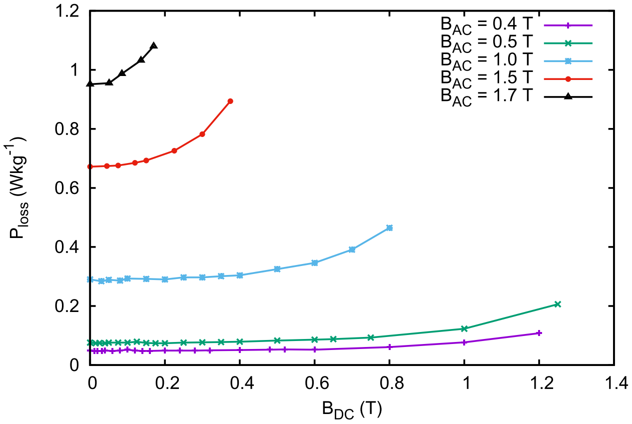

Fig. 9. Total power losses for varying applied dc offsets B_{dc}. Results are shown for fixed peak sinusoidal flux densities B_{ac}.

approach saturation; the difference between no dc and applied dc power losses reduces to 10% or less.

IV. CONCLUSION

A measurement system has been presented to allow the measurements of sinusoidal magnetic flux densities with a dc component of up to 300% for the measurement of magnetic steel sheets. The technique has been used to show that consideration need to be made for systems operating above 1.5 T, where the dc offsets of the order of 25% can cause large additions to the power losses and large increases to the magnetizing current.

ACKNOWLEDGMENT

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