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Core Loss Analysis of Non-oriented Electrical Steel Under Magnetic Induction Including Higher Harmonics

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The actual magnetic induction waveform of cores in electrical machines is not sinusoidal i.e. higher harmonics are always included. Thus the core loss in actual electrical machines is different from the core loss which is measured by the standard method, because the waveform of magnetic induction should be sinusoidal in the standard testing method. Core loss analysis under higher harmonic induction is always important in electric machine design. In this work, we measured the core loss when a hysteresis loop has only one period of an ac minor loop of higher harmonic frequency, depending on the position of the ac minor loop of relative to the fundamental harmonic frequency. From this experiment, the core loss $P(B_0 f_0, B_h, nf_0)$ under a higher harmonic magnetic induction B_h could be expressed by the linear combination the core loss at fundamental harmonic frequency $P_c(B_o, f_o)$, the core loss of ac minor loop at zero induction region of the major hysteresis loop P_{cL} (B_h, nf_o), and the core loss of an ac minor loop in the high induction region of the major hysteresis loop P_{cH} (B_h, nf_o) i.e., P_c (B_o, f_o, B_h, nf_o)=P_c (B_o, f_o)+$(n-1)[k_1$ (B_o) P_{cL} (B_h, nf_o)+$(1-k_1$ $(B_o))$ P_{cH} $(B_h, nf_o)]$. This will be useful formula for electrical machine designers and one of effective methods to predict core loss including higher harmonic induction.

1. Introduction

Under standard measurement conditions, core loss measurements for electrical steels are performed under a sinusoidal waveform of magnetic induction. However, actual magnetic induction waveforms, for example in the stator teeth of an induction motor, are not sinusoidal and always include higher harmonics due to the saturation of cores, phase belts, and rotor slots. The loss values obtained by the standard method are not really applicable to an actual motor design, because the core loss in ferromagnetic materials cannot be easily predicted due to non-linear and hysteresis effects, and the higher harmonics give rise to altered core loss [1-4]. Therefore, this effect must be taken into account for an optimal design of an electrical machine. For the analysis of core loss including higher harmonics, we have generated only one period of a higher harmonics with different relative position in an ac hysteresis loop of fundamental frequency.

2. Measuring System

For the core loss measurement under a given waveform of the magnetic induction, an arbitrary waveform synthesizer and a B-feedback system are necessary. We can calculate the secondary induced voltage waveform for a given waveform of magnetic induction, and the voltage waveform can be synthesized by the arbitrary waveform synthesizer. This voltage can then be applied to the primary winding via a power amplifier. The secondary induced voltage can then be controlled to be the same as the synthesized waveform using the B-feedback system.

For the core loss measurement, a 12-bit two-channel transient recorder with a memory size of 4 kwords per channel was used for the higher harmonic frequency of magnetic induction, one channel for the secondary induced voltage, the other for the voltage across the shunt resistor which is connected in series with the primary winding to measure the magnetic field strength. Fig. 1 shows a block diagram of the core loss measuring system.

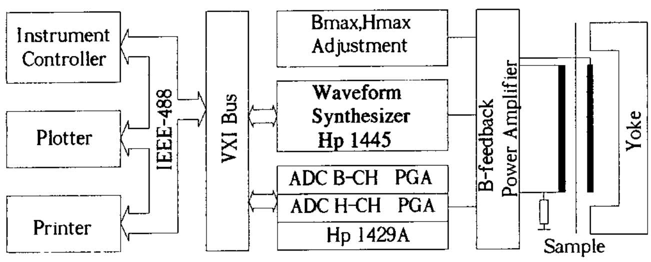

Fig. 1. Schematic diagram of the measuring system for core loss measurement including higher harmonic induction.

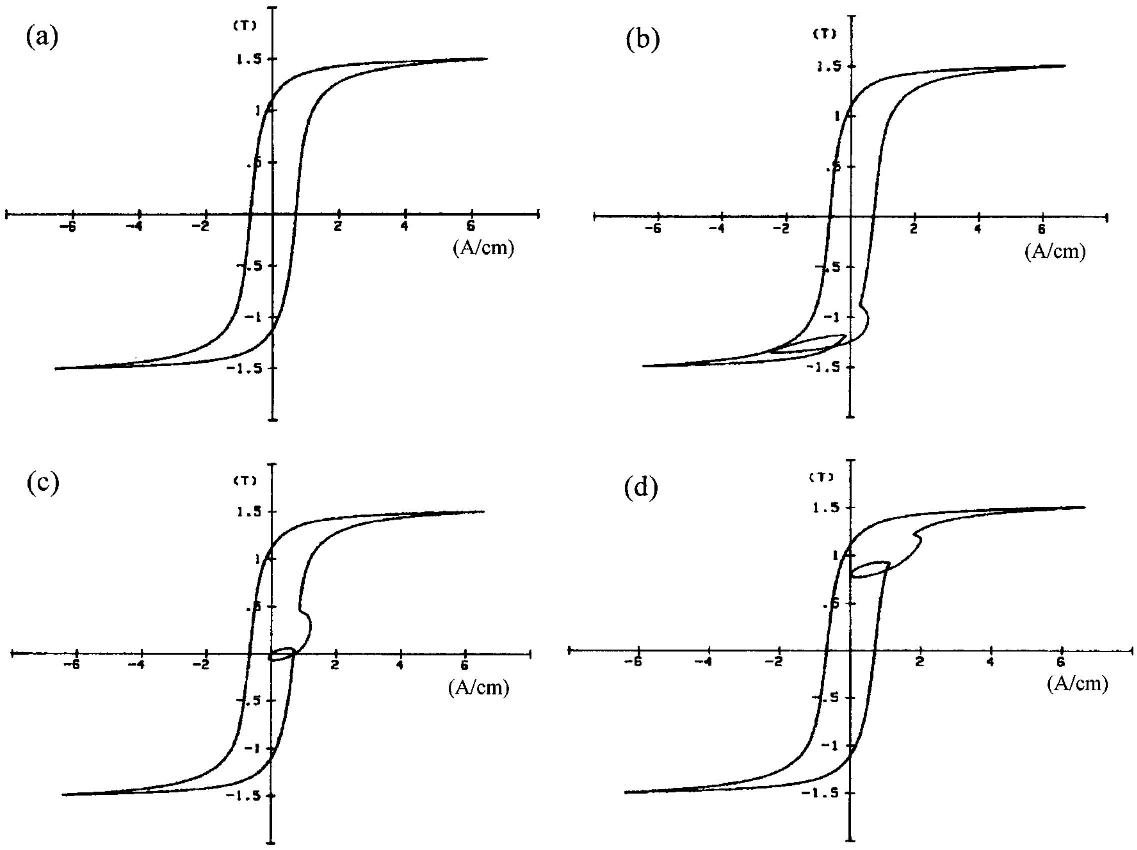

Fig. 2. Ac minor loop shapes depending on the position of the minor loop for 0.35 mm non-oriented electrical steel sheet at a fundamental frequency of 60 Hz and higher harmonic frequency of $23f_0$ (a) without higher harmonics, (b) to (d) with harmonic amplitude of 0.15 T.

3. Experimental Results and Discussion

Fig. 2 shows only one period of an ac minor loop of a higher harmonic frequency at different positions in an ac hysteresis loop of fundamental frequency. The shape of the minor loop at zero magnetic induction and at higher inductions is different because domain movement is dominant in the low induction region and rotation of magnetization is dominant in the high induction region.

Fig. 3 shows the change of core loss depending on the position of the minor loop for different amplitudes of the higher harmonic induction. When the higher harmonic amplitude is very small, the core loss was not changed regardless of the position of the minor loop. However, as the higher harmonic amplitude was increased, the core loss was increased not only depending on the harmonic amplitude but also on the position of the minor loop. When the maximum magnetic induction B_{max} is 1 T, the core loss was not changed depending on the position of the ac minor loop, but when the maximum magnetic induction B_{max} is 1.5 T and the harmonic induction amplitude becomes high, core losses strongly depended on the position of the ac minor loop. This means that we cannot easily predict core loss including higher harmonic induction, and core loss increment due to the ac minor loop located in high induction region of ac major hysteresis loop is different from in the low induction region of ac major hysteresis loop.

From this experiment, analysis of core loss $P_c(B_o, f_o, B_h, nf_o)$ including higher harmonic induction using the define terms superposition principle

$$P_c(B_o, f_o, B_h, nf_o) = P_c(B_o, f_o) + P_c(B_h, nf_o) \quad (1)$$

where $P_c(B_o, f_o)$ is core loss due to fundamental harmonic induction and $P_c(B_h, nf_o)$ is core loss due to the higher harmonic induction, should be modified. $P_c(B_h, nf_o)$ is the summation of the core loss of ac minor loop at zero induction region of the major hysteresis loop $P_{cL}(B_h, nf_o)$ and the core loss of an ac minor loop in the high induction region of the major hysteresis loop $P_{cH}(B_h, nf_o)$. We can modify Eq. (1) as

$$P_c(B_o, f_o, B_h, nf_o) = P_c\ (B_o, f_o) + (n-1) \\ [k_1(B_o)\ P_{cL}(B_h, nf_o) + k_2(B_o)\ P_{cH}(B_h, nf_o)] \quad (2)$$

where $k_2(B_o) = 1 - k_1(B_o)$ is a function only of the maximum magnetic induction B_0 of the fundamental harmonic induction.

Fig. 4 shows the core loss calculated using Eq. (2) and measured core loss for different thickness of non-oriented electrical steel, different maximum magnetic induction, and parallel and perpendicular to the rolling direction under har-

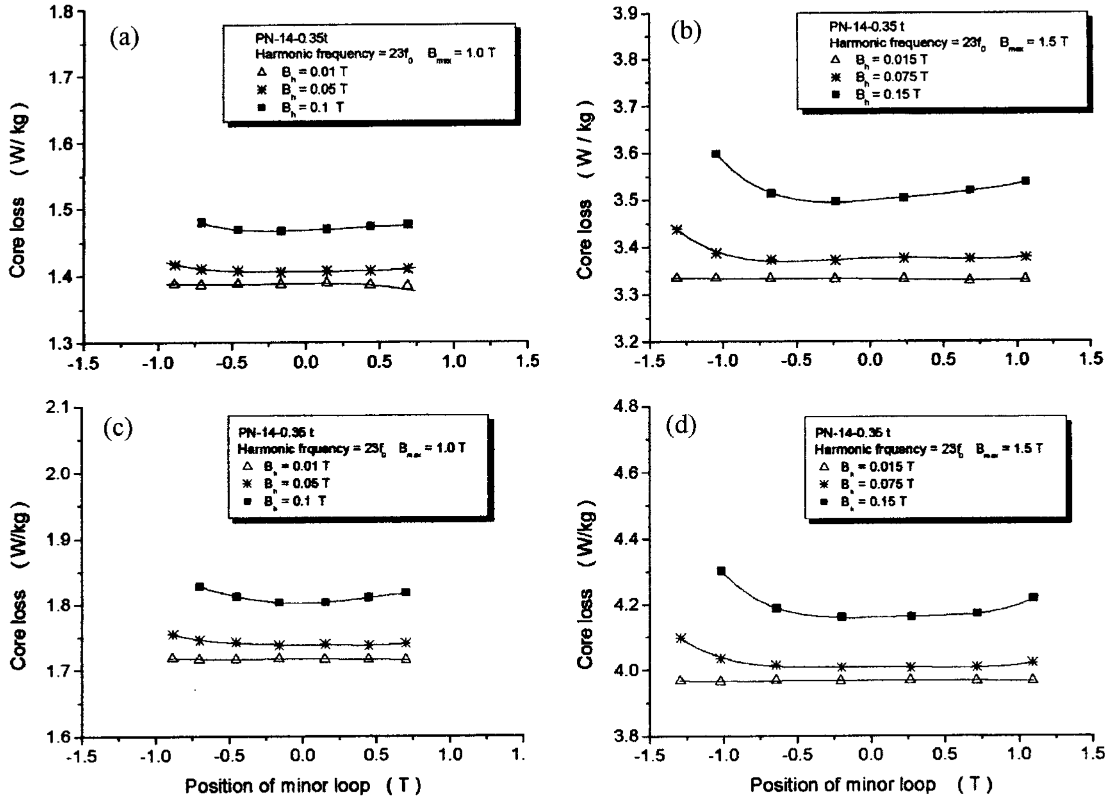

Fig. 3. Core loss with harmonic frequency $23f_0$ depending on the position of the ac minor loop for 0.35 mm sheet with field (a) and (b) parallel, and (c) and (d) perpendicular to the rolling direction at a maximum magnetic induction of 1.0 T and of 1.5 T, respectively.

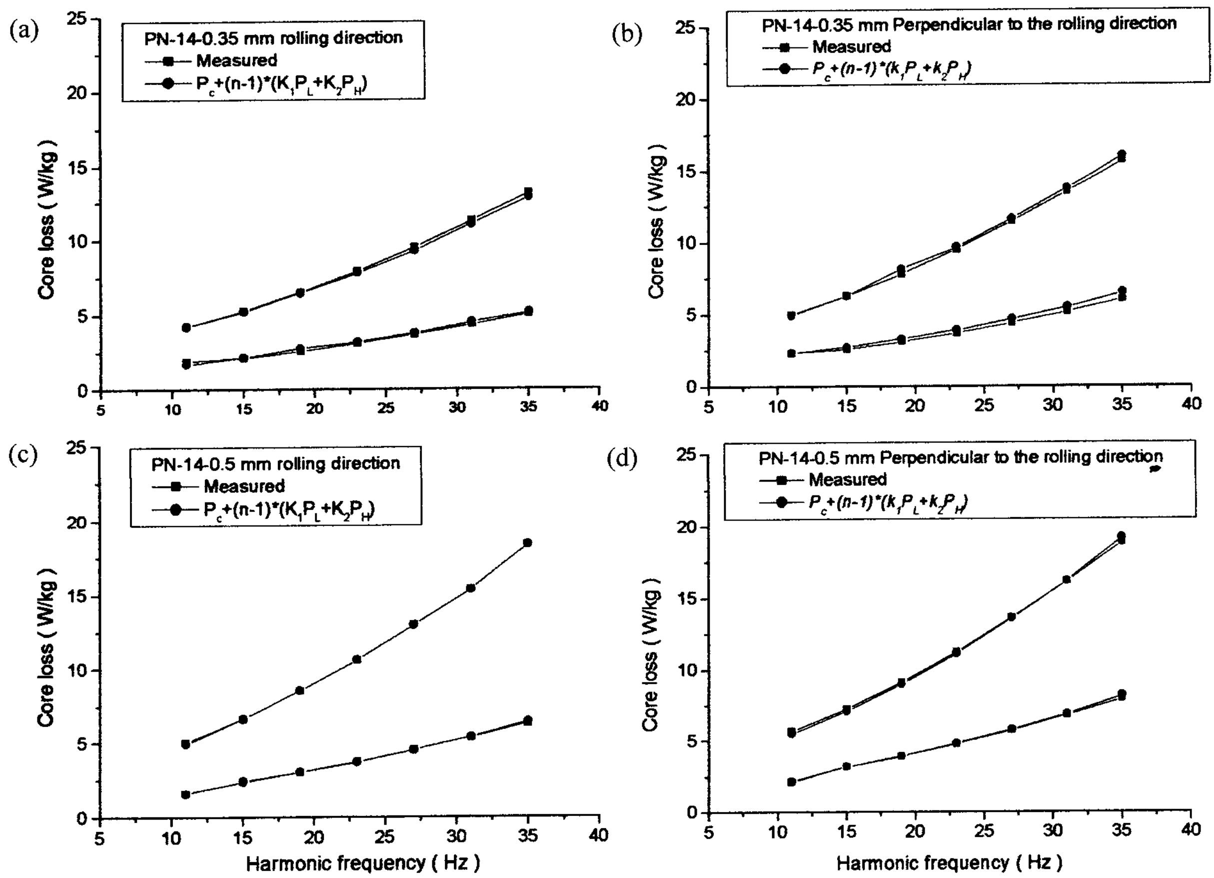

Fig. 4. Core loss depending on the higher harmonic frequencies with harmonic amplitude 10% of maximum magnetic induction 1.0 T, 1.5 T; plotted as suggested formula (●) $P_c=P_{cf_0}+(n-1)(k_1 P_{cL}+k_2P_{cH})$, and measured (■) for sheet thickness 0.35 mm {(a) and (b)} and 0.5 mm {(c) and (d)}.

monic frequencies ranging from $11f_o$ to $35f_o$. From this experimental results, we can predict core loss including higher harmonic induction using Eq. (2) satisfactorily.

4. Conclusion

For the analysis of core loss including higher harmonic induction, we have generated only one period of a minor loop of higher harmonic frequency in a major hysteresis loop of the fundamental frequency, and the core losses depending on the harmonic amplitude and the position of minor loop relative to the major loop were studied in this work. We conclude that the core loss including the higher harmonic induction can be predicted by the equation

$$P_c(B_o, f_o, B_h, nf_o) = P_c(B_o, f_o) + (n-1)$$
$$[k_1(B_o)\ P_{cL}(B_h, nf_o) + (1-k_1(B_o))\ P_{cH}(B_h, nf_o)].$$

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