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Measurement of Stator Core Loss of an Induction Motor at Each Manufacturing Process

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Abstract – The measurement of stator core loss for an induction motor at each manufacturing process is carried out in this paper. Iron loss in the stator core of induction motor changes after each manufacturing process due to the mechanical stress, which can cause the deterioration of the magnetic performances. This paper proposes a new iron loss measuring system of the stator core in an induction motor, which can be applied to the case when the distribution of magnetic flux density is not uniform along the magnetic flux path. In the system, the iron loss is calculated based on the induced voltage of the *B*-search coil and exciting current.

Keywords: Induction motor, Iron loss measurement, Manufacturing process, Stator core loss

1. Introduction

Nowadays, much attention has been paid to improve the efficiency of rotating electric machines because of the globalized energy saving policy in many countries. There have been many investigations for improving the efficiency of rotating electric machines such as optimal design of stator and/or rotor core, employing electrical steel sheet (ESS) with better magnetic performance and lower iron loss, and so on [1]. Especially in the induction motor, it is well known that the iron loss in the stator core is a significant factor, which plays a vital role in the total iron loss [1-3]. Therefore, for the development of high efficiency induction motors, it is very essential to investigate how the iron loss in stator core changes in each manufacturing process since each manufacturing process is not a matter foreign to the question of efficiency via mechanical stress [4-5]. For example, the extra loss of ESS is related to the residual stress and additional stress during the manufacturing process of stator core and its initial state [4].

In general, the manufacturing process of a stator core of induction motor, as shown in Fig. 1, includes four steps: punching, laminating, winding and varnishing, and housing processes. Since these steps involve interlocking, welding, and local heating for housing, they may deteriorate the magnetic properties of ESS and eventually increase iron loss of stator core.

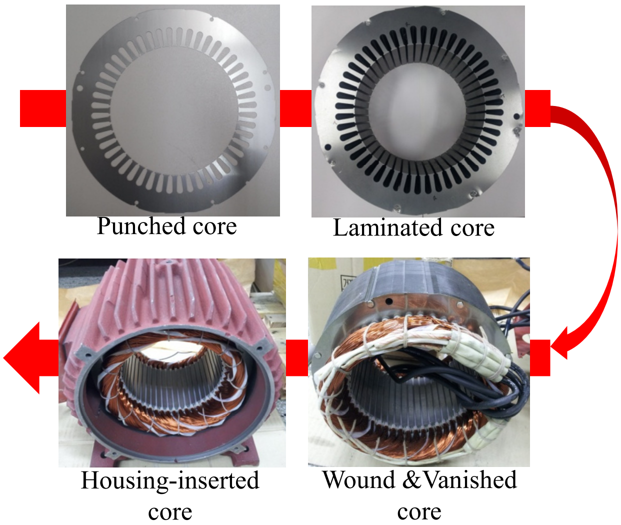

Fig. 1. Manufacturing process of stator core of induction motor.

It may be concluded, therefore, that measurement and comparison of iron loss at each manufacturing stage are essential to clarify the deterioration of magnetic performances of ESS and variation of iron loss in stator core [6]. Although there have been a lot of investigations on the design of stator core of induction motor, including shape optimal design, the influences of the manufacturing process on the variation of stator core loss have not been fully investigated yet. The stator core loss of an induction motor, unfortunately, cannot be measured using conventional methods such as the Epstein frame test (EFT) [7], the single sheet tester (SST) [8], and the ring type method [9].

In this paper, stator core loss of an induction motor is measured and compared at each manufacturing process by adopting the auxiliary inner core method, proposed in [10], and developing the *e-I* method for iron loss calculation.

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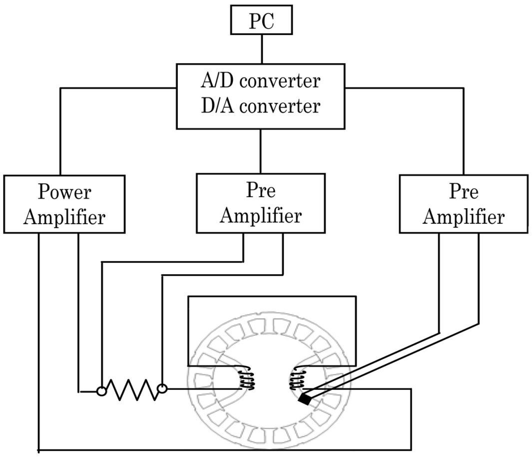
2. Conventional Stator Core Loss Measurement System [10]

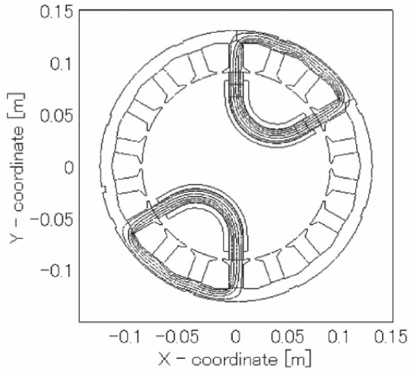
The configuration of the stator core loss measurement system proposed in [10] is shown in Fig. 2(a), where PC, interfacing unit, pre-amplifier, power amplifier, shunt resistance, and auxiliary inner cores are major components. The two auxiliary inner yokes are set to be attached to the stator core by clamping. As shown in Fig. 2(b), the system is developed with the assumption that magnetic flux density should be almost uniform because of nearly same width along the magnetic flux path.

The system specification is summarized as follows:

- The measuring frequency is 50 Hz;
- Axial heights of the auxiliary yokes are set to be same with that of the stator core;
- The *B*-search coil has 5 turns at the back yoke of the inner core;
- B-waveform control is carried out to make the waveform of magnetic flux density sinusoidal using the digital feedback method [11];
- The exciting current is measured assisted by a shunt resistance.



(a) Measuring system



(b) Analyzed result of magnetic flux line distribution

Fig. 2. Conventional measurement system proposed in reference [10].

In this system, the exciting voltage waveforms for the two inner yokes are dependently controlled using *B*-waveform control method [11] so that the following two conditions may be satisfied:

1) *B*-waveform at the inner yokes should be sinusoidal,
2) No magnetic flux links the two inner yokes at the same time as shown in Fig. 2(b).

The magnetic flux density, which is assumed to be uniformly distributed along the magnetic flux path, is measured via the induced voltage from the *B*-search coil:

$$B(t) = -\frac{1}{\left(N_2 A\right)} \int_0^t e(\tau) d\tau \quad [\mathrm{T}] \tag{1}$$

where $e(\tau)$ is the induced voltage of the *B*-search coil and $(N_2 A)$ is the area-turn of the *B*-search coil.

On the other hand, the magnetic field intensity is measured by using Ampere's circuital law via current measurement as follows:

$$H(t) = N_1 i(t)/l \quad [\mathrm{A/m}] \tag{2}$$

where $i(t)$ is the exciting current measured from the shunt resistance, N_1 is the number of exciting coil turns and l is the effective magnetic path length. As shown in Fig. 2(b), l is estimated by assuming to be average length of the inner yoke and the stator core.

Stator core loss for a specific *B*-waveform is calculated as follows:

$$P_s = \frac{1}{\rho T} \int_T H(t) \cdot \frac{dB(t)}{dt} dt \quad [\mathrm{W/kg}] \tag{3}$$

where ρ is the mass density of the ESS and T is time period.

It should be noted that this method should be applied only under the assumption that the magnetic flux density along the flux path is uniform.

3. Proposed Stator Core Loss Measurement System

Based on the system proposed in [10], a stator core loss-measuring system of which configuration is shown in Fig. 3 is developed. In the system, DAQ Board (PCI 6110 DAQ board, NI Co. Ltd.), low pass filter of NF P-82, two power amplifiers of NF 4520 and isolation amplifier of NF P-62A are employed. Table 1 summarizes specifications of the system. The auxiliary inner cores are designed, as shown in Fig. 4, so that the width of magnetic flux path is almost same along the flux path and fixed to the stator core using a spring located between auxiliary inner cores. Other specifications of the system are summarized as follows:

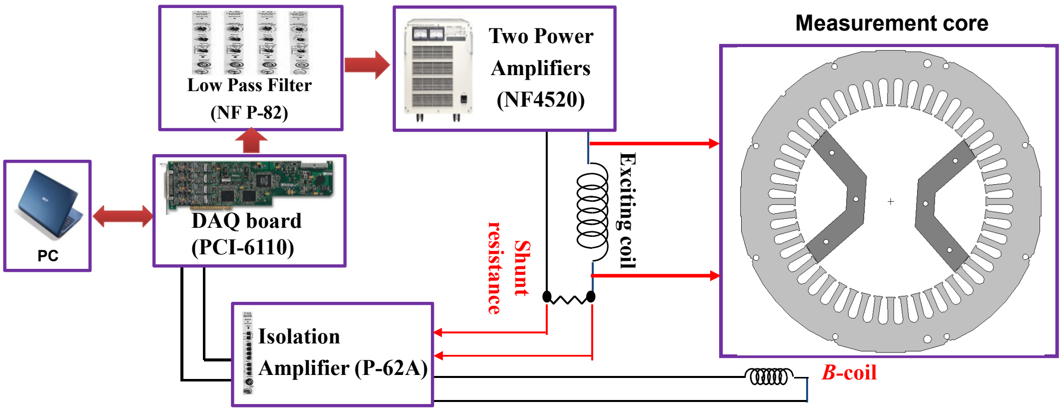


Fig. 3. Proposed measuring system for stator core loss.

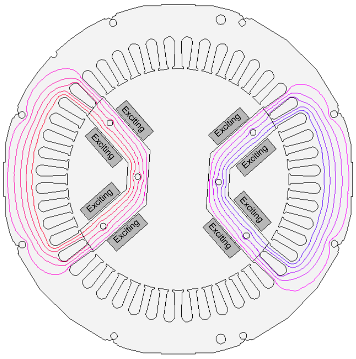


Fig. 4. Distribution of magnetic flux lines.

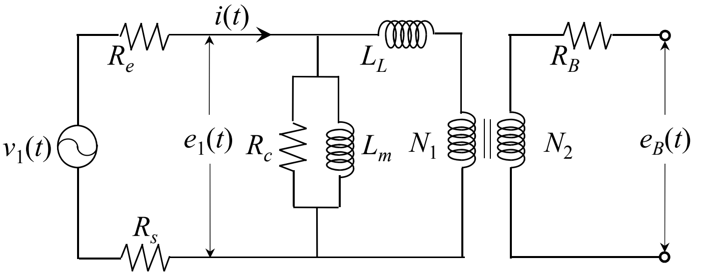


Fig. 5. Circuit for measuring induced voltage $e_B(t)$ and current $i(t)$.

Table 1. Specification of the proposed measurement system.

	Items	Value
Stator core	Outer diameter	260 mm
	Inner diameter	163 mm
	Height(Laminated)	105 mm
	Thickness(Sheet)	0.5 mm
	Mass density	7.85 g/cm^3
Exciting coil	Coil diameter	1.5 mm
	Number of turns	120
	Other	3 layers in series
B-coil	Coil diameter	0.13 mm
	Number of turns	2
	Position	On inner core
Others	Specimen	50PN1300
	Frequency	50 Hz
	Shunt resistance	0.05 Ω
	Yoke type	Inner core method

1) The measuring frequency is 50 Hz,
2) Auxiliary inner core is made of same ESS (50PN1300) and set to have same height with the stator core,
3) *B*-search coil locates on the inner yoke under the exciting coil. It has width of 18.34 mm and 2 turns [12].

Fig. 4 shows different widths along magnetic flux path, in this system, at inner yoke, teeth and return yoke. It is found that the magnetic flux density along the flux path is not uniform. For this reason, the estimation of stator core loss using (3) is thought to be unreasonable in this measuring system.

Fig. 5 shows an electric circuit of the measuring system, where R_e, R_B are resistances of exciting and *B*-search coils, respectively; e_1, e_B are induced voltage of primary and *B*-search coil respectively; R_s is shunt resistance, L_m and L_L are magnetizing and leakage inductances; R_c represents the iron loss; N_1 and N_2 are the winding turns of exciting coil and *B*-search coil respectively.

The iron loss in the stator core and auxiliary inner yokes can be expressed as follows:

$$P = \frac{1}{T}\int_T e_1(t)\cdot i(t)\,dt \quad [\mathrm{W}] \tag{4}$$

With the assumption of no leakage flux between the exciting and *B*-search coils, iron loss in (4) is measured as:

$$P = \frac{1}{T}\frac{N_1}{N_2}\int_T e_2(t)\cdot i(t)\,dt \quad [\mathrm{W}] \tag{5}$$

If the leakage inductance L_L cannot be ignorable, it may significantly affect measurement accuracy. For this matter, in this paper, *B*-search coils are located under the exciting coil. Table 2 compares the proposed stator core loss

Table 2. Comparison of measuring systems

	Conventional	Proposed
B-distribution	should be uniform	-
Loss unit	W/kg	W
Material density	necessary	unnecessary
Effective magnetic path length	necessary	unnecessary

evaluation with that proposed in [10].

4. Experiment and Results

By rotating the inner yokes, the iron loss is measured at 12 positions with the interval of 15 degree as shown in Fig. 6. The iron loss, at each position, is measured at the range of magnetic flux densities at the inner yoke from 0.4 T to 1.775 T under the condition of sinusoidal *B*-waveform using *B*-waveform control method. Fig. 7 shows the exciting voltage waveform together with that of magnetic flux density at the position of 45 degree at B= 1.775 T. It is obvious the voltage waveform is far from sinusoidal one.

Fig. 8 shows the distribution of iron losses at different positions and manufacturing processes when the magnetic flux density is 1 T. In the figure, the unstressed core is obtained through thermal annealing for 5 hours at the temperature of 850 ºC to remove the residual mechanical stress during the punching process [4, 13]. From the figure, following investigations are found:

1) All the processes, except the housing, increase the iron loss. It is because that each process will give mechanical stress to the ESS.
2) The iron loss is not perfectly symmetric along the azimuthal direction. It is thought because of the holes for laminations and interlocking.
3) The lamination process increases the iron loss much more than other processes.
4) The housing process, although it is expected to give much mechanical stress to the ESS, slightly reduces the iron loss because the housing made of magnetic material decreases the magnetic flux density at the stator core.

Fig. 9 shows the iron losses, which is averaged for all the positions in Fig. 6, at each manufacturing process. It is found that the lamination process makes dominant increment of iron loss.

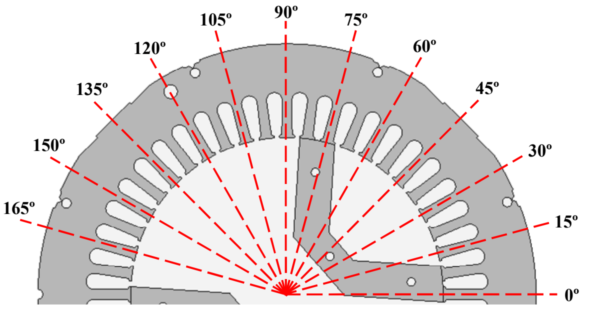


Fig. 6. Distribution of measured position.

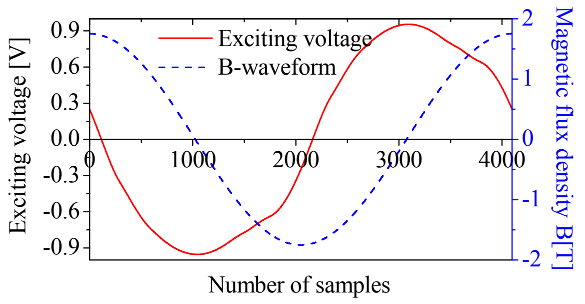


Fig. 7. Waveforms of exciting voltage and magnetic flux density.

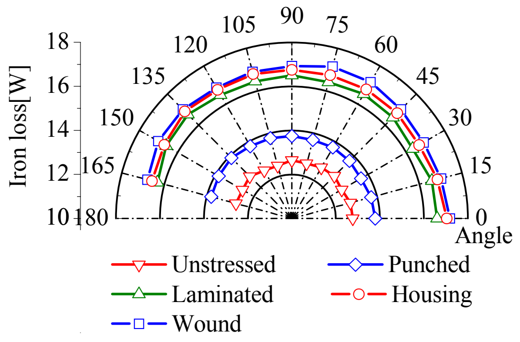
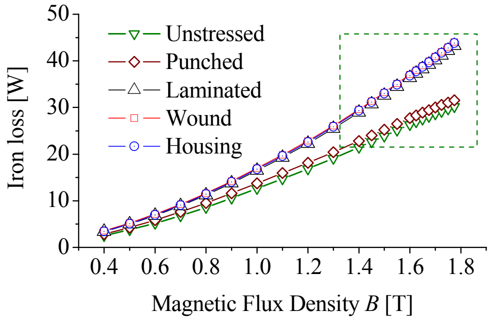
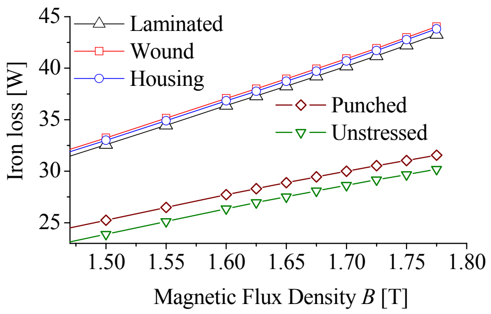


Fig. 8. Iron loss distribution at each manufacturing process when the magnetic flux density is 1.0 T.



(a) Iron loss increase



(b) Iron loss increase in the selected region

Fig. 9. Iron losses at each manufacturing process.

Table 3. Increment of iron losses at each process

B (T)	Process	Iron loss increment (%)
1.400	punching	6.28
	laminating	26.94
	winding	2.23
	housing	-0.8
1.775	punching	4.54
	laminating	37.1
	winding	1.77
	housing	-0.48

Table 3 compares the increment of the iron loss at each process from its previous one, which is defined as follows:

$$P_R = (B - A)/A \times 100\% \tag{6}$$

where A and B represent the iron losses at the previous and current processes, respectively.

5. Conclusion

A comparative study on the stator core loss at each manufacturing process is suggested for an induction motor. For this a measuring system of relative stator core loss is developed. From the experimental results, the followings are concluded:

1) All the process, except the housing process, increases the iron loss,
2) The iron loss is not perfectly symmetrical along the azimuthal direction because of the holes for laminations and interlocking,
3) Among the processes, i.e., punching, lamination, winding with varnishing and housing, the iron loss increases most during the lamination process,

It is also found that the housing made of magnetic material slightly decreases the iron loss.

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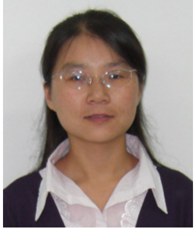

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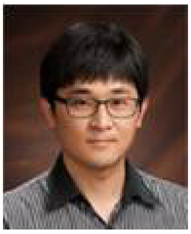

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