Simulation Analysis of the Influence of Electrical Steel on the Performance of Air Conditioner Compressor Motors

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The core of an air conditioner compressor motor is made of electrical steel. Reasonably, a proper choice of electrical steel helps enhance the performance of an air conditioner compressor motor and improves its energy efficiency. This work investigates the relationship between the magnetic properties of electrical steel and the performance of air conditioner compressor motors by numerical simulation. Models of a permanent magnet synchronous motor and a single-phase induction motor equipped in commercial air-conditioning compressors were analyzed using finite-element software, in which various grades of electrical steel were employed as the core material in the motor models. Specifically, influences of the iron loss properties and the magnetic induction properties of the electrical steel on the efficiency of the compressor motors were examined.

Keywords: Electrical Steel, Compressor Motor, Air Conditioner

1. INTRODUCTION

Due to global warming, air conditioners have become increasingly indispensable in the daily lives of most people. The air conditioner market is expected to grow at a compound annual growth rate (CAGR) of 14% during 2019–2024(1), and the global energy demand from air conditioners is estimated to triple by 2050(2). It is also reported that air conditioners as well as electric fans already account for about 10% of the present global electricity consumption(2). Therefore, improving the efficiency of air conditioners can be a benefit in the reduction of carbon emission and help stabilize the climate.

In an air conditioner, the compressor motor consumes most of the electricity. The core of the compressor motor is made of electrical steel; consequently, choosing electrical steel with adequate magnetic properties to build the motor core may improve the efficiency of the compressor motor and correspondingly the efficiency of the air conditioner. The compressor motor of an air conditioner is typically a permanent magnet synchronous motor (PMSM) or a single-phase induction motor (single-phase IM). Jacobs *et al.* investigated the performance of a PMSM for a hybrid vehicle and found that high efficiency was achieved by utilizing electrical steel with low iron loss as the core material(3). They also found that using electrical steel with high magnetic induction as the core material raised the output power of the PMSM but didn't guarantee an efficiency increase. Pei *et al.* and Huynh *et al.* separately examined the performance of PMSMs for electrical traction and obtained similar results(4-5). Toda *et al.* reported that for a permanent magnet brushless dc motor, the motor efficiency had a strong correlation with $W_{10/400}$ of the core material (6). On the other hand, Yagisawa *et al.* showed that employing electrical steel with low iron loss as the core material was not always effective in improving the efficiency of a three-phase IM(7). Particularly, for a small-sized three-phase IM operated at a high magnetic flux density, the magnetic induction properties of the electrical steel were more important than its iron loss properties to achieve high motor efficiency. Similar phenomena were described by Toda *et al.*(8-9). Likewise, Honda *et al.* reported that for a single-phase IM to attain low total loss, the Si + Al content of the core material should be decreased with the increase in the magnetic flux density of the core(10).

While previous studies have identified the criteria for selecting electrical steel for the PMSM and the IM, few studies addressed how to choose the electrical steel specifically for the compressor motor of an air conditioner(11). To this end, this work investigates the relationship between the magnetic properties of electrical steel and the performance of air conditioner compressor motors. A computer simulation approach was adopted instead of building and testing real compressor motors to reduce the time and cost for this study. Several grades of electrical steel with different iron losses and magnetic induction were incorporated into the numerical models of a PMSM and a single-phase IM equipped in commercial air-conditioning compressors. The motor models were analyzed by finite-element software to evaluate the performance indices such as the output torque, losses, and efficiency. These performance indices were regressed with the magnetic properties of electrical steel to identify their correlation, from which the influence of electrical steel on the performance of the air conditioner compressor motors was derived. Furthermore, the stack length of the motor models was reduced to examine the effect of motor volume on the correlation outcome. The following sections present details of the simulation setup and the results.

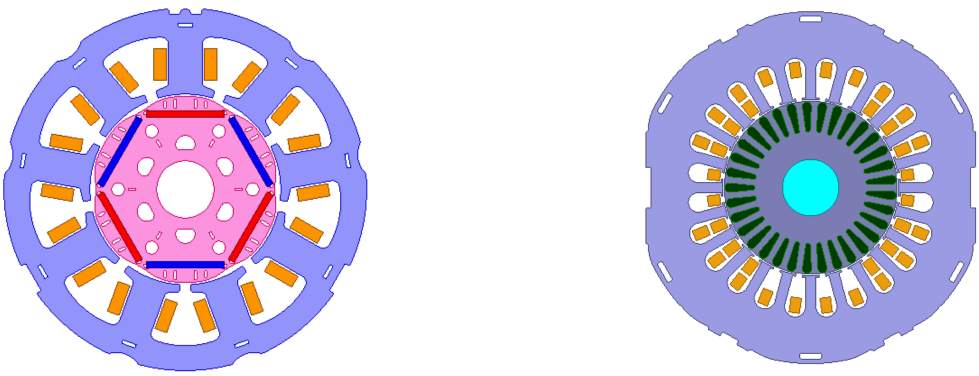
2. EXPERIMENTAL METHOD

Finite-element models of a PMSM and a single-phase IM (Fig.1) for air-conditioning compressors were created using ANSYS Maxwell3D. Table 1 lists some major specifications of the two motors. The PMSM was analyzed at five rated speeds with a constant input current at each speed. The current vector was positioned on the q-axis of the rotor. The single-phase IM was analyzed at a single rated speed with a 50 Hz, 220 V input voltage. Several kinds of annealed electrical steel, with the range of the magnetic induction properties and iron loss properties shown in Table 2, were imported as the core materials of the motor models. Correlation coefficients between the magnetic properties of the electrical steel and the simulated performance indices of the motors were calculated using Excel.

3. RESULTS AND DISCUSSION

3.1 Correlation analysis of the PMSM for an air-conditioning compressor

Table 3 displays the correlation coefficients between the magnetic properties of electrical steel and the



(a) (b)

Fig.1. Layouts of (A) the PMSM and (B) the single-phase IM for air-conditioning compressors.

Table 1 Some major specifications of the PMSM and the single-phase IM

Specifications \ Motor type	PMSM	Single-phase IM
Phases	3	1
Input voltage (V)	Not a constant	220
Outer diameter (mm)	101.1	112.2
Stack length (mm)	50	95.5
Number of poles	6	2
Number of stator slots	9	24
Rated speed (RPM)	1300/2300/3100/ 5000/6550	2897
Electrical frequency at rated speed	65/115/155/250/327.5	50
Nominal torque at rated speed (N·m)	1.43/1.29/1.80/1.97/2.09	2.72

performance indices of the PMSM at the lowest and the highest rated speeds. The copper loss and the mechanical loss were not included in the correlation analysis since they were constants at a given rated speed. Table 3 indicates that the rated efficiency of the PMSM was significantly negatively correlated with $W_{15/50}$ and $W_{10/400}$ of the electric steel at the lowest rated speed and the highest rated speed, respectively. B_{50} or B_{10} of the electric steel was significantly positively correlated with the output torque of the PMSM but showed negligible correlation with the rated efficiency, agreeing well with the results presented in[3-6]. Additionally, B_{50} or B_{10} of the electric steel was somewhat correlated with motor core loss, probably because a higher B_{50} or B_{10} led to an elevated magnetic flux density in the core and consequently a higher motor core loss[3]. The weighted efficiency, which was a weighted average of the efficiencies at all rated speeds, similarly exhibited a significant negative correlation with $W_{10/400}$ or $W_{15/50}$ and showed almost no correlation with B_{10} and B_{50} (Table 4 and Fig.2).

3.2 Correlation analysis of the single-phase IM for an air-conditioning compressor

Table 2 Ranges of the magnetic properties of the electrical steel

Magnetic properties \ Motor type	PMSM	Single-phase IM
B_{10} (T)	1.49–1.59	1.54–1.6
B_{50} (T)	1.66–1.76	1.7–1.76
$W_{15/50}$ (W)	2.11–2.44	2.55–3.56
$W_{10/400}$ (W)	16.3–18.98	25.6–41.16

Table 3 Correlation coefficients between the magnetic properties of electrical steel and the performance indices of the PMSM at the lowest and the highest rated speeds

Magnetic properties \ Performance indices	1300 RPM, 1.43 N·m			6550 RPM, 2.09 N·m		
	Torque	Core loss	Efficiency	Torque	Core loss	Efficiency
B_{10}	0.974	0.691	-0.186	0.964	0.421	0.000
B_{50}	0.984	0.658	-0.140	0.976	0.392	0.033
$W_{15/50}$	-0.152	0.750	-0.974	-0.169	0.656	-0.721
$W_{10/400}$	0.075	0.757	-0.839	-0.001	0.973	-0.964

Table 4 Correlation coefficients between the magnetic properties of electrical steel and the weighted efficiency of the PMSM

Magnetic properties	B_{10}	B_{50}	$W_{15/50}$	$W_{10/400}$
Correlation coefficient	-0.126	-0.083	-0.908	-0.947

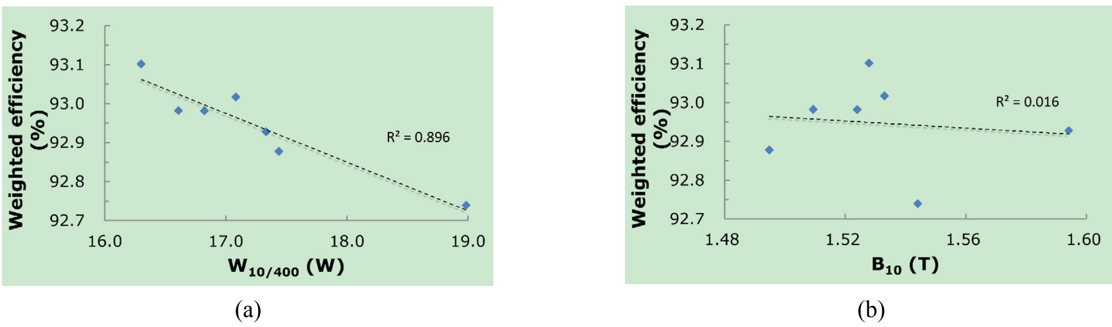


Fig.2. Linear regression of the weighted efficiency of the PMSM on (A) $W_{10/400}$ and (B) B_{10} of the electrical steel.

Table 5 presents the correlation coefficients between the magnetic properties of electrical steel and the performance indices of the single-phase IM. The mechanical loss was not included in the correlation analysis since it was a constant at the rated speed. As expected, the motor copper loss was negatively correlated with B_{50} or B_{10} of the electrical steel, the output torque was positively correlated with B_{50} or B_{10} of the electrical steel, and the motor core loss was positively correlated with $W_{15/50}$ of the electrical steel. The rated efficiency of the single-phase IM exhibited a stronger correlation with $W_{15/50}$ than with B_{50} or B_{10} (Fig.3).

3.3 Effect of reducing motor stack length

The stack length of the PMSM and the single-phase IM were decreased respectively from 50 mm to 45 mm and 95.5 mm to 85 mm. Table 6 displays the correlation coefficients of the magnetic properties of electrical steel and the performance indices of the PMSM with reduced stack length at the lowest and the highest rated speeds. Similar to Table 3, the rated efficiency of the PMSM with reduced stack length exhibited a significant negative correlation with $W_{10/400}$ or $W_{15/50}$. Likewise, the weighted efficiency of the PMSM with reduced stack length presented a significant negative correlation with $W_{10/400}$ or $W_{15/50}$ and showed almost no correlation with B_{10} and B_{50} (Table 7 and Fig.4).

Table 8 presents the correlation coefficients between the magnetic properties of electrical steel and the performance indices of the single-phase IM with reduced stack length at the rated speed. In contrast to Table 5, Table 8 indicates that the rated efficiency was more correlated with B_{50} or B_{10} than with $W_{15/50}$ (Fig.5). The single-phase IM with reduced stack length was more magnetically

Table 5 Correlation coefficients between the magnetic properties of electrical steel and the performance indices of the single-phase IM at the rated speed

Magnetic properties / Performance indices	B_{10}	B_{50}	$W_{15/50}$	$W_{10/400}$
Torque	0.971	0.980	-0.486	-0.287
Copper loss	-0.985	-0.987	0.231	-0.007
Core loss	-0.084	-0.139	0.977	0.990
Efficiency	0.549	0.597	-0.950	-0.849

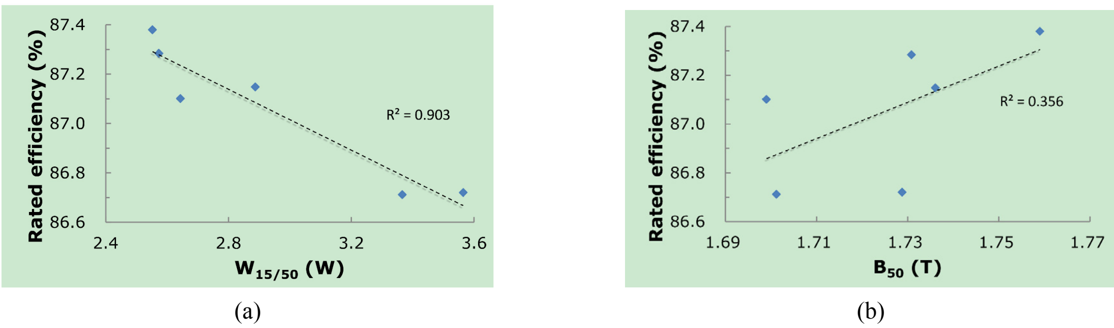


Fig.3. Linear regression of the rated efficiency of the single-phase IM on (A) $W_{15/50}$ and (B) B_{50} of the electrical steel.

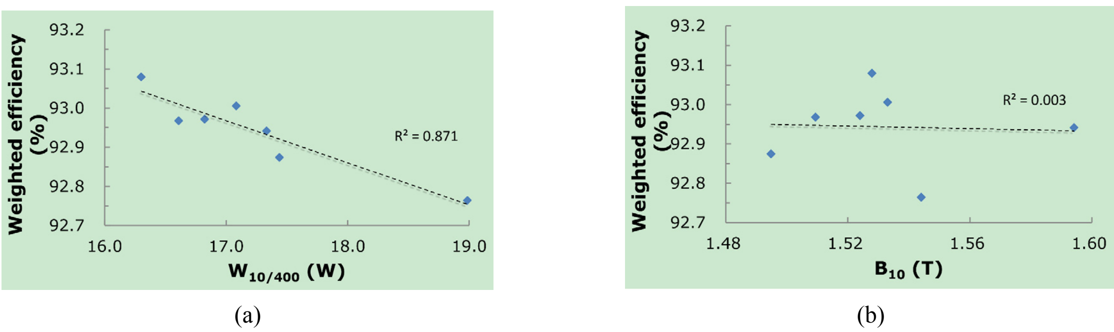


Fig.4. Linear regression of the weighted efficiency of the PMSM with reduced stack length on (A) $W_{10/400}$ and (B) B_{10} of the electrical steel.

Table 6 Correlation coefficients between the magnetic properties of electrical steel and the performance indices of the PMSM with reduced stack length at the lowest and the highest rated speeds

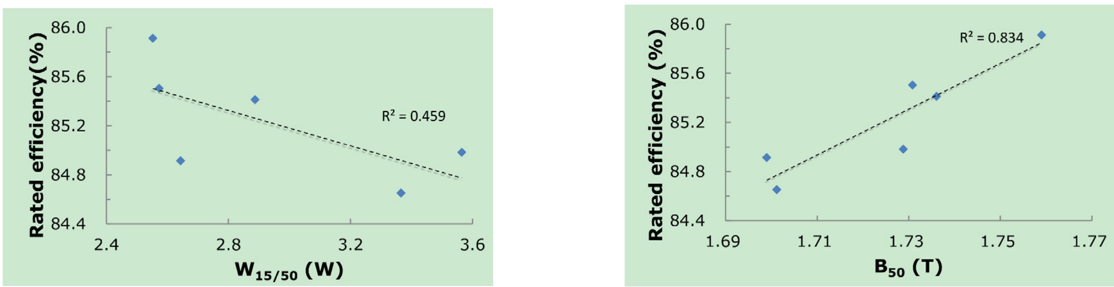
Magnetic properties \ Performance indices	1300 RPM, 1.43 N·m			6550 RPM, 2.09 N·m		
	Torque	Core loss	Efficiency	Torque	Core loss	Efficiency
B_{10}	0.975	0.686	-0.068	0.968	0.417	0.032
B_{50}	0.985	0.653	-0.021	0.979	0.389	0.065
$W_{15/50}$	-0.145	0.754	-0.982	-0.160	0.657	-0.722
$W_{10/400}$	0.084	0.762	-0.821	0.017	0.973	-0.956

Table 7 Correlation coefficients between the magnetic properties of electrical steel and the weighted efficiency of the PMSM with reduced stack length

Magnetic properties	B_{10}	B_{50}	$W_{15/50}$	$W_{10/400}$
Correlation coefficient	-0.052	-0.009	-0.911	-0.933

Table 8 Correlation coefficients between the magnetic properties of electrical steel and the performance indices of the single-phase IM with reduced stack length at the rated speed

Performance indices \ Magnetic properties	B_{10}	B_{50}	$W_{15/50}$	$W_{10/400}$
Torque	0.991	0.997	-0.381	-0.171
Copper loss	-0.987	-0.986	0.191	-0.042
Core loss	-0.073	-0.127	0.973	0.993
Efficiency	0.886	0.913	-0.678	-0.491



(a) (b)

Fig.5. Linear regression of the rated efficiency of the single-phase IM with reduced stack length on (A) $W_{15/50}$ and (B) B_{50} of the electrical steel.

saturated than the original motor (Fig.6), and the copper loss increased much more than the motor core loss (Table 9). The copper loss is associated with the magnetic induction properties of electrical steel, justifying the significant correlation between B_{50} or B_{10} and the rated efficiency in Table 8. This result matches those of the previous studies[7-10].

3.4 Discussion

The magnetic properties of the electrical steel employed in the motor core have a direct consequence on the performance of the motor. Therefore, the results of the correlation analysis imply that the iron loss properties of electrical steel affect the rated efficiency of the permanent-magnet-type compressor motor much more than the magnetic induction properties of the electrical steel. Decreasing the motor volume doesn't change this relationship. In contrast, both the iron loss properties and

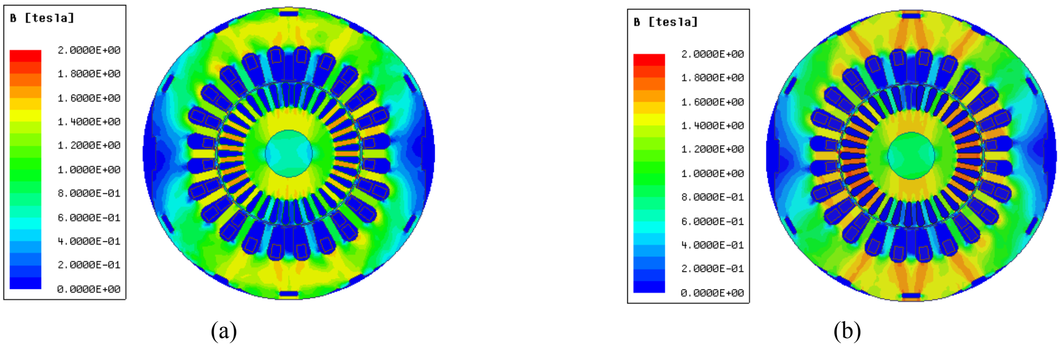


Fig.6. Magnet flux density plots of the (A) the original single-phase IM and (B) the single-phase IM with reduced stack length. The core material is annealed 50A400.

Table 9 An example of the performance indices of the single-phase IM with the original stack length or with the reduced stack length

Core material	Annealed 50A400	
Stack length (mm)	95.5	85
Torque (N·m)	2.717	2.814
Speed (RPM)	2897	
Output power (W)	824.144	853.823
Stator copper loss (W)	77.885	102.389
Rotor copper loss (W)	32.117	36.567
Core loss (W)	12.033	12.710
Mechanical loss (W)	Not included	
Efficiency (%)	87.102	84.916

the magnetic induction properties of the electrical steel can exert influence on the rated efficiency of the induction-type compressor motor. If the volume of the induction-type compressor motor is decreased, electric steel influences the rated efficiency of the motor mainly through the magnetic induction properties.

4. CONCLUSIONS

This work investigates the influence of the magnetic properties of electrical steel on the performance; especially on the rated efficiency of air conditioner compressor motors by a simulation approach. A permanent magnet synchronous motor and single-phase induction motor used in air-conditioning compressors, with various grades of electrical steel set as the core material, were analyzed by finite element software. A clear correspondence between the rated efficiency of the permanent-magnet-type compressor motor and the iron loss properties of the electrical steel was observed regardless of the motor volume. In contrast, the rated efficiency of the induction-type compressor motor may be affected by the iron loss properties or the magnetic induction properties of the electrical steel, depending on the volume or the operating magnetic flux density of the motor. The above results may assist manufacturers of air-conditioning compressors in selecting a proper grade of electrical steel as the core material to improve the efficiency of the compressor motor as well as the air conditioner.

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