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Efficiency Analysis of a Flux Switching Permanent Magnet Machine with Low Iron Loss Non-Oriented Electrical Steel Materials and Rotor Structure

Zhongxian Chen[1,*], Lei Huang[2], Mingjie Wang[1,3], and Hongxing Zheng[3,*]

[1]*School of Intelligence Manufacturing, Huanghuai University, Zhumadian 463000, China*
[2]*School of Electrical Engineering, Southeast University, Nanjing 450002, China*
[3]*School of Materials Science and Engineering, Shanghai University, Shanghai 200444, China*

ABSTRACT: This study presents a structure design methodology to analyze the operational efficiency of a flux switching permanent magnet machine utilizing non-oriented electrical steel materials. First, iron losses of non-oriented electrical steel materials assembled by bonding and welding stacking methods were tested, and the comparison results demonstrated that the bonded stator core exhibited lower iron losses than the welded stator counterpart. Then, the proposed non-oriented electrical steel material 35SW360 was implemented in the straighted-rotor core of flux switching permanent magnet machine, and the simulation results show that both the amplitudes and harmonics of induced electromotive force with 35SW360 were almost identical to the standard non-oriented electrical steel material DW360_50. Finally, the prototype flux switching permanent magnet machine with straighted-rotor and skewed-rotor including above two non-oriented electrical steel materials was manufactured and tested. Both the simulation analysis and hardware test results revealed that the flux switching permanent magnet machine with skewed-rotor achieved higher efficiency than the straighted-rotor design. Consequently, the proposed non-oriented electrical steel material 35SW360 and skewed-rotor design illustrate a potential solution for efficiency improvement of flux switching permanent magnet machine.

1. INTRODUCTION

Electrical steel is a crucial core material that is usually installed in the stator and rotor sections of permanent magnet synchronous machine. The magnetic permeability and iron loss of electrical steel play an important part in the operational efficiency of permanent magnet synchronous machine [1–3]. Compared with the oriented electrical steel material, non-oriented electrical steel material has the characteristics of isotropic magnetic properties, and thus still struggles to match the rotating magnetic field requirements of permanent magnet synchronous machine, particularly in the low iron loss and high performance applications. Due to the wide operational frequency and speed range, along with high power density and torque, a suitable non-oriented electrical steel material can significantly contribute to the miniaturization and lightweight design of permanent magnet synchronous machine, especially in the application of electric vehicle driving machines and aerospace propulsion systems [4, 5].

In order to decrease the iron loss of permanent magnet synchronous machine, researchers have proposed many kinds of electrical steel materials to investigate the feasibility of such devices by structure design and lamination thickness selection. Ref. [6] proposed the use of both non-oriented and grain-oriented electrical steel materials in the stator section of a permanent magnet synchronous machine, whose aim is to improve power density and reduce iron loss, and the simulation results demonstrate that employing grain-oriented electrical steel materials reduces the total stator iron loss of permanent magnet synchronous machine by up to 54.2%, while experimental tests indicate a 0.9% improvement in the efficiency, both compared to the conventional machine with non-oriented electrical steel materials. By the method of additive manufacturing, [7] successfully fabricated thinner e-6.5Si electrical steel materials, and thus the complex structural design of permanent magnet synchronous machine becomes flexible, and the research results of this reference indicate that the proposed electrical steel materials provide a novel method to simultaneously decrease the iron loss and improve mechanical robustness of high frequency permanent magnet synchronous machine. The cycle efficiency of permanent magnet synchronous machine is increased to 89%, which is a 6% increase over that of the conventional machine using M270-35A material.

Control technology serves as a key factor in enhancing the operational efficiency of permanent magnet synchronous machine that utilizes electrical steel material. Refs. [8] and [9] investigated vector magnetic properties of electrical steel material by the method of DC-biased flux control and multiple frequency magnetic field regulation, and the feasibility and scientificity of vector magnetic hysteresis model were validated by the close agreement between theoretical calculation and test. The results from [8] show a loss error of less than 5% between the theoretical calculation and experimental measurement, and

* Corresponding authors: Zhongxian Chen (chenzhongxian@huanghuai.edu.cn); Hongxing Zheng (hxzheng@shu.edu.cn).

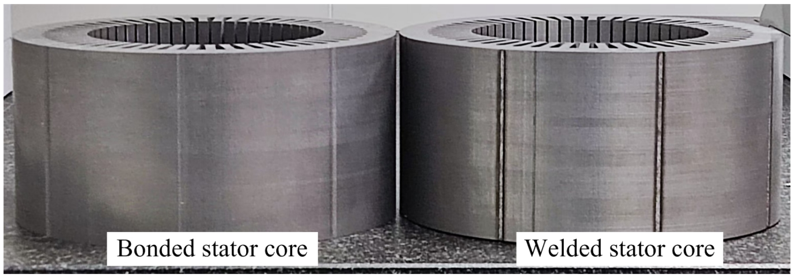

FIGURE 1. The bonded stator core and welded stator core of machine.

this close agreement indicates that the enhanced vector magnetic hysteresis model is well suited for calculating iron losses under DC-biased magnetization (0–0.5 T, 0°–90° , 50–200 Hz). Besides, [9] demonstrated that the enhanced vector magnetic hysteresis model can also accurately calculate the iron loss of electrical steel material. Furthermore, some other control methods such as discrete gradient descent algorithm, grey wolf optimization algorithm, field oriented control, and loss-minimizing model predictive control have been proposed to reduce the iron loss and enhance the operational efficiency of machines [10–13]. However, the aforementioned references primarily investigate and analyze machine efficiency from the perspectives of electrical steel materials and control methods, yet have not considered the additional impact of rotor structure on machine efficiency.

In this study, a novel non-oriented electrical steel material was proposed to analyze the efficiency of a flux switching permanent magnet machine. First, based on the stacking methods of bonding and welding, the iron loss of stator core with non-oriented electrical steel material and different magnetic field frequencies was tested, and the comparison results show that the iron loss of bonded stator core is lower than the welded stator core's. Secondly, two kinds of non-oriented electrical steel materials (35SW360 and DW360_50) are applied to the straighted-rotor of flux switching permanent magnet machine. The simulation results show that the amplitudes and total harmonic distortion (THD) of induced electromotive force with 35SW360 were almost identical to DW360_50 (42.5 V at 500rpm, THDs of 6.48% and 6.11% for 35SW360 and DW360_50, respectively). Furthermore, it was found that after the adoption of skewed-rotor structure, the THD of induced electromotive force of flux switching permanent magnet machine was decreased from 6.11% to 2.21%. Finally, a flux switching permanent magnet machine incorporating both straighted-rotor and skewed-rotor with the above two non-oriented electrical steel materials was manufactured and tested, and the analysis and comparison results revealed that the flux switching permanent magnet machine with skewed-rotor exhibited higher efficiency, thus demonstrating its potential as a reliable solution for enhancing the efficiency of permanent magnet machines.

2. IRON LOSS OF NON-ORIENTED ELECTRICAL STEEL MATERIALS

Iron loss is the energy dissipation of ferromagnetic materials under the operational environment of alternating magnetic fields. Typically, iron loss comprises hysteresis loss and eddy current loss, which plays a critical role in the performance and efficiency of permanent magnet synchronous machines, especially in the high frequency operational condition [14, 15]. Therefore, the development of novel non-oriented electrical steel materials and advanced assembly technologies is beneficial for improving the efficiency of permanent magnet synchronous machines.

Figure 1 shows the bonded stator core and welded stator core of the machine. The stator core is made of non-oriented electrical steel material 25SW1300, which is developed and manufactured by ShouGang Zhixin Qian'an Co., Ltd. The outer radius and axial length of stator core are 220 mm and 140 mm, respectively. For non-oriented electrical steel material 25SW1300, the parameter "25" indicates a nominal thickness of 0.25 mm (i.e., 100 times nominal thickness), while the parameter "1300" represents 100 times of the guaranteed iron loss value $P_{1.5/50}$ or $P_{1.0/400}$ (W/kg).

Table 1 shows the iron loss test results of the bonded and welded stator cores. In Table 1, the first subscript of P is magnetic induction intensity (T), while the second subscript represents the magnetic field frequency (Hz). Table 1 reveals that the iron losses increase with the high magnetic field frequencies, and the bonded stator core exhibits lower iron losses than the welded stator core. Furthermore, in order to ensure the measurement accuracy, each stator core fabricated with different stacking methods (bonded or welded) was measured twice, and the results exhibited minimal deviations between two measurements (deviations are less than 5%).

Based on the comprehensive data analysis and comparison in Table 1, it can be concluded that regardless of magnetic field frequencies, the bonded method can effectively reduce the iron loss of non-oriented electrical steel materials. This finding provides a foundation for applying bonded stator core and rotor core in permanent magnet synchronous machines to improve efficiency.

TABLE 1. Iron loss of bonded and welded stator core.

Outer radius/mm	Axial length/mm	Stacking methods	$P_{1.0/50}$ /(W·kg^{-1})	$P_{1.5/50}$ /(W·kg^{-1})	$P_{1.0/400}$ /(W·kg^{-1})
220	140	Welded 1	1.13	2.17	17.5
		Welded 2	1.1	2.09	17.1
		Bonded 1	0.93	1.92	13.6
		Bonded 2	0.98	1.97	14

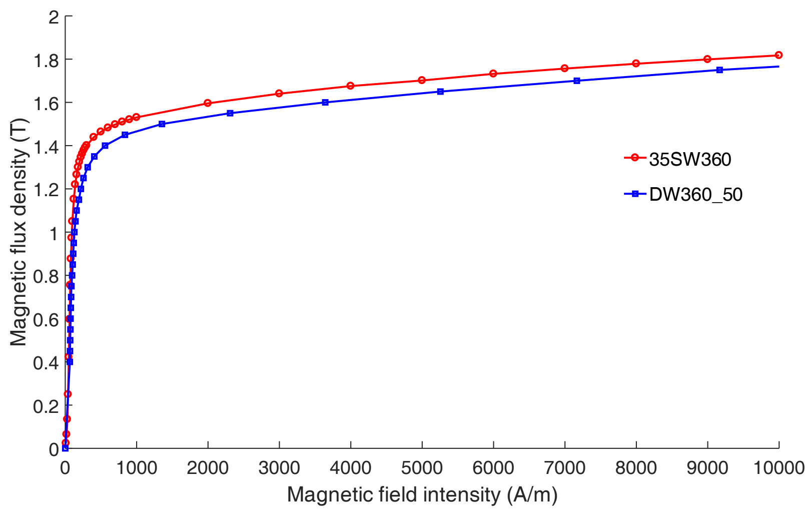

FIGURE 2. Magnetization curves of 35SW360 and DW360_50.

3. INDUCED ELECTROMOTIVE FORCE ANALYSIS OF FLUX SWITCHING PERMANENT MAGNET MACHINE

By bonding stacking method, this section adopts two non-oriented electrical steel materials named 35SW360 and DW360_50 to calculate and analyze the induced electromotive force characteristic of a flux switching permanent magnet machine. Among these two non-oriented electrical steel materials, 35SW360 was developed and manufactured by Shougang Zhixin Qian'an Co., Ltd., while DW360_50 is a commercially available standard product. Similar to the previously mentioned non-oriented electrical steel 25SW1300, 35SW360 also has a low iron loss grade. This paper adopts 35SW360 and DW360_50 for analyzing machine's induced electromotive force, and the main reason is that theirs static electromagnetic properties are essentially identical.

3.1. Magnetization Characteristic of 35SW360 and DW360_50

Magnetization characteristic (B-H curve) is a fundamental characteristic of electrical steel material that reflects its magnetic behavior under varying magnetic field frequencies. For example, the B-H curve of electrical steel material directly determines hysteresis loss, which constitutes a major component of iron loss in a permanent magnet synchronous machine.

Figure 2 compares the B-H characteristic curves of non-oriented electrical steel materials 35SW360 and DW360_50 across the same magnetic field frequency. Under the same frequency, the B-H curves of 35SW360 and DW360_50 exhibit identical trends. However, when the magnetic field intensity exceeds 400 A/m, the magnetic flux density of 35SW360 is higher than that of DW360_50 (the increases are between 2.5% and 6.5%).

The comparison of magnetic field intensity in Figure 2 demonstrates the superior field performance of non-oriented electrical steel materials 35SW360 in permanent magnet synchronous machine, particularly under magnetic saturation conditions in both the stator teeth and rotor teeth.

3.2. Induced Electromotive Force of Flux Switching Permanent Magnet Machine

The amplitude and harmonic of induced electromotive force critically determine the operational efficiency, power density, and torque ripple of permanent magnet synchronous machine. Therefore, analysis and optimization of induced electromotive force are crucial for ensuring both the scientific research and high efficiency in permanent magnet synchronous machine design. Based on the non-oriented electrical steel materials 35SW360 and DW360_50, the structural configuration and design parameters of flux switching permanent magnet machine are summarized in Figure 3 and Table 2.

The topology of flux switching permanent magnet machine in Figure 3 has been extensively investigated by experts, and its operation principle was detailed in [16, 17]. In this paper, the rotor core structure of the proposed flux switching permanent magnet machine is designed in both skewed (5 deg) and straight types, respectively.

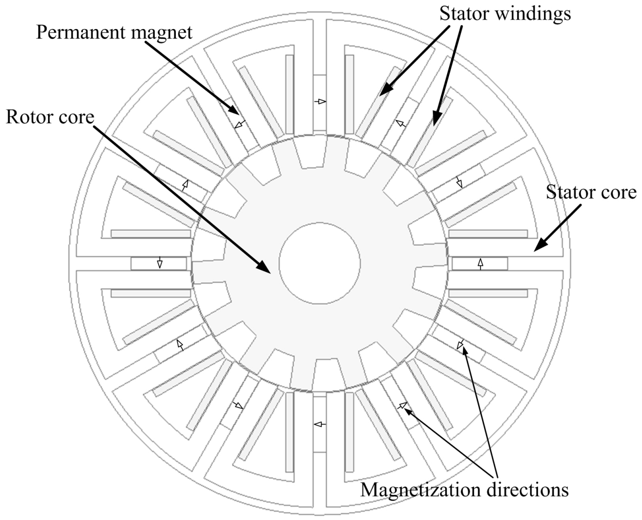

FIGURE 3. Radial cross-section of flux switching permanent magnet machine.

Through finite element analysis (FEA) simulation and analytical softwares, Figure 4 shows the waveforms and harmonics of induced electromotive forces of flux switching permanent magnet machine, and the operational speed of rotor is 500 rpm. As shown in Figure 4(a), the induced electromotive force of the straighted-slot rotor using non-oriented electrical steel material 35SW360 is nearly identical to that of DW360_50 under the same operational speed. This comparison result preliminarily validates the effectiveness of the proposed 35SW360 material. Furthermore, as indicated in Figure 4(a), the skewed-rotor design significantly improves the sinusoidal quality of the induced electromotive force. Corresponding harmonics analysis are provided in Figure 4(b) and Table 3.

In Table 3, the total harmonic distortion (THD) of induced electromotive forces by skewed-rotor and straighted-rotors are 2.21%, 6.11%, and 6.48%, respectively. Considering the minor computational variations inherent in FEA simulation software, the THD of induced electromotive forces generated by straighted-slot rotors using non-oriented electrical steel materials 35SW360 and DW360_50 can be considered identical. Notably, the skewed-rotor configuration reduces the THD of induced electromotive forces to 2.21%, and this near-sinusoidal waveform significantly benefits machine control and operation, particularly under the high speed operational conditions.

Furthermore, Figure 4(a) demonstrates that the electromotive force amplitude of the skewed-rotor decreases by approximately 5% compared to the straighted-slot rotor, which will adversely affects both the efficiency and power density of flux switching permanent magnet machine. Therefore, during the design and optimization process of flux switching permanent magnet machine, the efficiency and operational stability (or more precisely, controllability) should be considered comprehensively.

Besides, other skew angles of the rotor core, such as 3° and 7° were investigated by [18]. The comparison results demonstrate that the induced electromotive forces of flux switching permanent magnet memory machine with 5° skew angle are the best.

TABLE 2. Design parameters of flux switching permanent magnet machine.

Design parameters	Value or material
Stator outer radius	65.5 mm
Stator inner radius	35 mm
Stator tooth width	8.22 deg
Axial length of stator	75 mm
Number of stator slots	12
Stator core material	DW360_50
Rotor outer radius	34.5 mm
Rotor tooth width	10 deg
Axial length of stator	75 mm
Number of rotor teeth	14
Rotor core material	DW360_50 or 35SW360
Permanent magnet thick (NdFeB35)	3.5 mm
Permanent magnet length (NdFeB35)	15 mm
Air-gap length (mm)	0.5mm
Turns of armature winding per phase	140
Phase number	3

4. EFFICIENCY SIMULATION BASED ON NON-ORIENTED ELECTRICAL STEEL MATERIALS AND ROTOR STRUCTURE

Based on the structure and design parameters of flux switching permanent magnet machine described in Figure 3 and Table 2, and under the control methods and parameter settings listed in Table 4, the efficiency simulation results of the flux switching permanent magnet machine are shown in Figure 5. In Table 4, the parameter settings for rated speed (400 rpm) and maximum speed (800 rpm) are determined by the hardware limitations and experimental conditions. The inverter switching frequency, control method, and measurement accuracy have a significant influence on the operational speed range of flux switching permanent magnet machine.

The comparison between Figure 5(a) and Figure 5(b) reveals that in the case of a straighted-rotor structure, the efficiency distributions of flux switching permanent magnet machine are nearly identical (using non-oriented electrical steel materials 35SW360 and DW360_50, respectively). The detailed efficiency distributions of Figure 5 are listed in Table 5, which align with the earlier observations in Figure 4 and Table 3 regarding the induced electromotive force amplitudes and THDs of straighted-rotors. However, after adoption of the skewed-rotor (5 deg), the efficiency distribution of the flux switching permanent magnet machine improves significantly, particularly in the efficiency ranges $\geq 85\%$ and $\geq 87\%$, where the efficiency distribution increases by 14.15% and 84.15%, respectively compared to the straight-rotor using non-oriented electrical steel material DW360_50.

It should be noted that although the skewed-rotor structure enhances the efficiency distribution of the flux switching permanent magnet machine, it also reduces the output torque amplitude from 10 N·m to 9 N·m. This phenomenon is consistent with the induced electromotive force comparison presented in Figure 4(a) (that is to say, lower induced electromotive force amplitude corresponds to lower output torque amplitude).

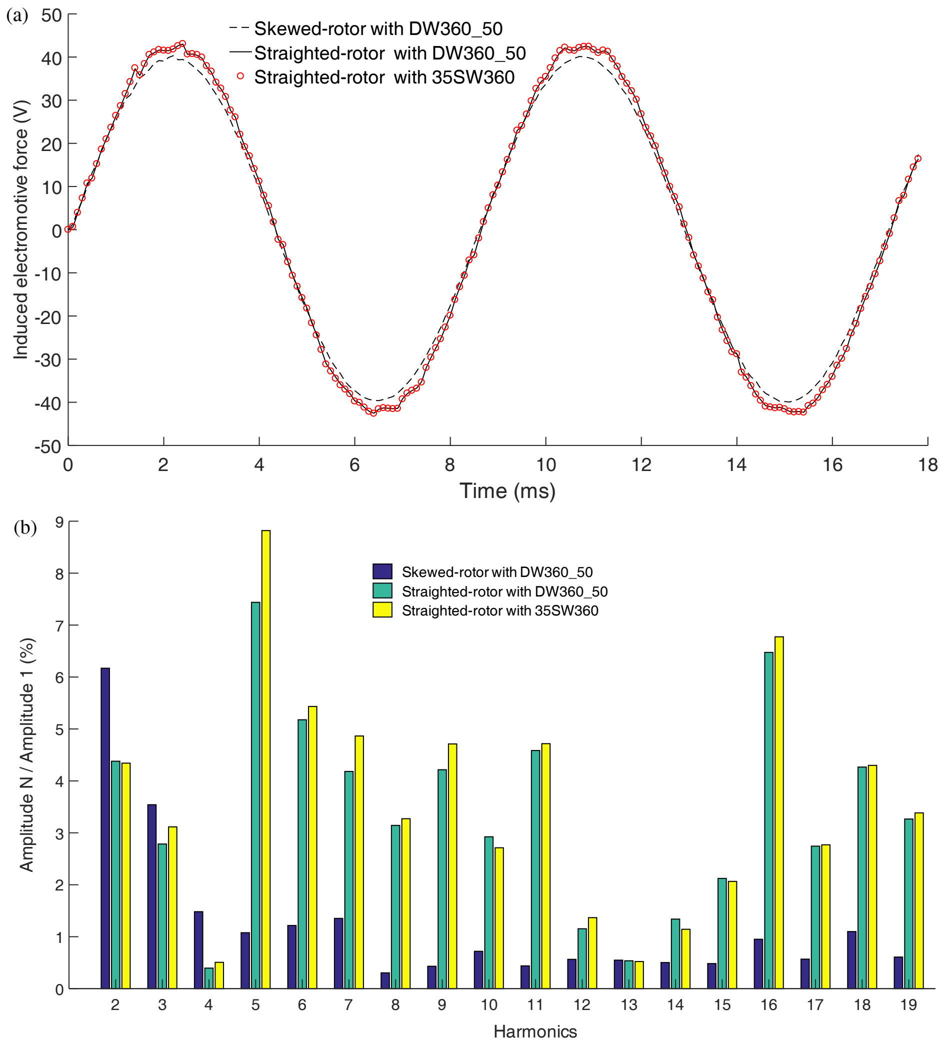

FIGURE 4. Induced electromotive forces of flux switching permanent magnet machine. (a) Waveform comparison. (b) Harmonic comparison.

Therefore, based on the comparison and analysis presented in Figure 5 and Table 5, it can be concluded that the proposed novel non-oriented electrical steel material 35SW360 can be effectively applied in flux switching permanent magnet machine. Furthermore, the skewed-rotor design contributes to an increase in the efficiency of flux switching permanent magnet machine.

5. EXPERIMENTAL VALIDATION

In order to validate the simulation analysis described in the previous sections, an efficiency test rig of flux switching permanent magnet machine has been designed and built, as shown in Figure 6(a). A digital signal processing (DSP)-based digital controller is adopted and implemented to drive the flux switching permanent magnet machine, and a brake and corresponded controller is used as variable load. In order to evaluate the input electrical power and output mechanical power of flux switching permanent magnet machine, a dynamometer is mounted between the inverter and flux switching permanent magnet machine by three-phase three-wire method, and a torque/speed measuring instrument is installed between the flux switching permanent magnet machine and brake.

Figure 6(b) is the prototype of flux switching permanent magnet machine, and the main design parameters are given in Table 2. In Figure 6(b), two kinds of rotors are installed in the stator and tested respectively, and the rotors are designed by different non-oriented electrical steel materials and structures. Besides, both the rotor core and stator core are assembled using bonded method, which aims to decrease the iron loss. Figure 6(c) describes the proportional-integral (PI) control method of flux switching permanent magnet machine, where the parameter setting $i_d = 0$ (Id current minimization) is consistent with the efficiency simulation process in Section 4.

The measured efficiency distributions are shown in Figure 7. From Figure 7 it can be seen that the measured efficiency distributions do not agree well with the simulation results described in Figure 5. The primary reason for this phenomenon lies in the fact that during the hardware test process, the obtained efficiency distribution data are affected by multiple factors including frictional losses, dimensional accuracy of flux switching permanent magnet machine, instrument measurement pre-

TABLE 3. Harmonic analysis of induced electromotive force.

Normalization of harmonic	Skewed-rotor with DW360_50	Straighted-rotor with DW360_50	Straighted-rotor with 35SW360
2^{th}	0.62%	0.44%	0.43%
3^{th}	0.35%	0.28%	0.31%
4^{th}	0.15%	0.04%	0.05%
5^{th}	0.11%	0.74%	0.88%
6^{th}	0.12%	0.52%	0.54%
7^{th}	0.14%	0.42%	0.49%
8^{th}	0.03%	0.31%	0.33%
9^{th}	0.04%	0.42%	0.47%
10^{th}	0.07%	0.29%	0.27%
11^{th}	0.04%	0.46%	0.47%
12^{th}	0.06%	0.12%	0.14%
13^{th}	0.05%	0.05%	0.05%
14^{th}	0.05%	0.13%	0.11%
15^{th}	0.05%	0.21%	0.21%
16^{th}	0.10%	0.65%	0.68%
17^{th}	0.06%	0.27%	0.28%
18^{th}	0.11%	0.43%	0.43%
19^{th}	0.06%	0.33%	0.34%
Total harmonic distortion (THD)	2.21%	6.11%	6.48%

TABLE 4. Control methods and parameters setting of efficiency simulation.

Methods or Parameters	Methods or value
Control method	Id current minimization
Inverter switching method	SVPWM (space vector pulse width modulation)
DC voltage	220 V
Line current	6.5 A (root mean square)
Rated speed	400 rpm
Maximum speed	800 rpm
Windage lossed	5 W
Friction losses	5 W

TABLE 5. Efficiency ratio of flux switching permanent magnet machine.

Rotor structure and materials	Efficiency	Ratio
Straighted-rotor with DW360_50	$\geq$ 80%	61.65%
	$\geq$ 85%	35.01%
	$\geq$ 87%	1.88%
Straighted-rotor with 35SW360	$\geq$ 80%	61.65%
	$\geq$ 85%	33.92%
	$\geq$ 87%	1.27%
Skewed-rotor with DW360_50	$\geq$ 80%	63.05%
	$\geq$ 85%	40.78%
	$\geq$ 87%	9.83%

cision, inverter self-protection mechanisms, and control parameters setting. For instance, as the flux switching permanent magnet machine's operating frequency increases (i.e., in the condition of higher speed), the measurement accuracy of the dynamometer decreases. Nevertheless, this does not affect the validity of the test data in verifying the theoretical simulation results.

Further analysis from the measured results illustrates that when the rotor core is designed with straight structure and non-oriented electrical steel material 35SW360, the flux switching permanent magnet machine exhibits efficiency ranges $\geq$ 78% and $\geq$ 80% by the coverage ratios of $\geq$ 19.4% and $\geq$ 14.6%, respectively, as illustrated in Figure 7(a). Nevertheless, the implementation of skewed-rotor with non-oriented electrical steel material DW360_50 leads to a substantial improvement in the efficiency distribution of flux switching permanent magnet machine, where the efficiency ranges $\geq$ 78% and $\geq$ 80% are achieved by coverage ratios of $\geq$ 34.05% and $\geq$ 26.6%, respectively, as shown in Figure 7(b).

Therefore, the hardware test results further confirm that the proposed non-oriented electrical steel material 35SW360 can be effectively applied to flux switching permanent magnet machine, and the skewed-rotor structure improves the operational efficiency of flux switching permanent magnet machine to some extent. Moreover, as part of the hardware test process, the output torque of flux switching permanent magnet machine can

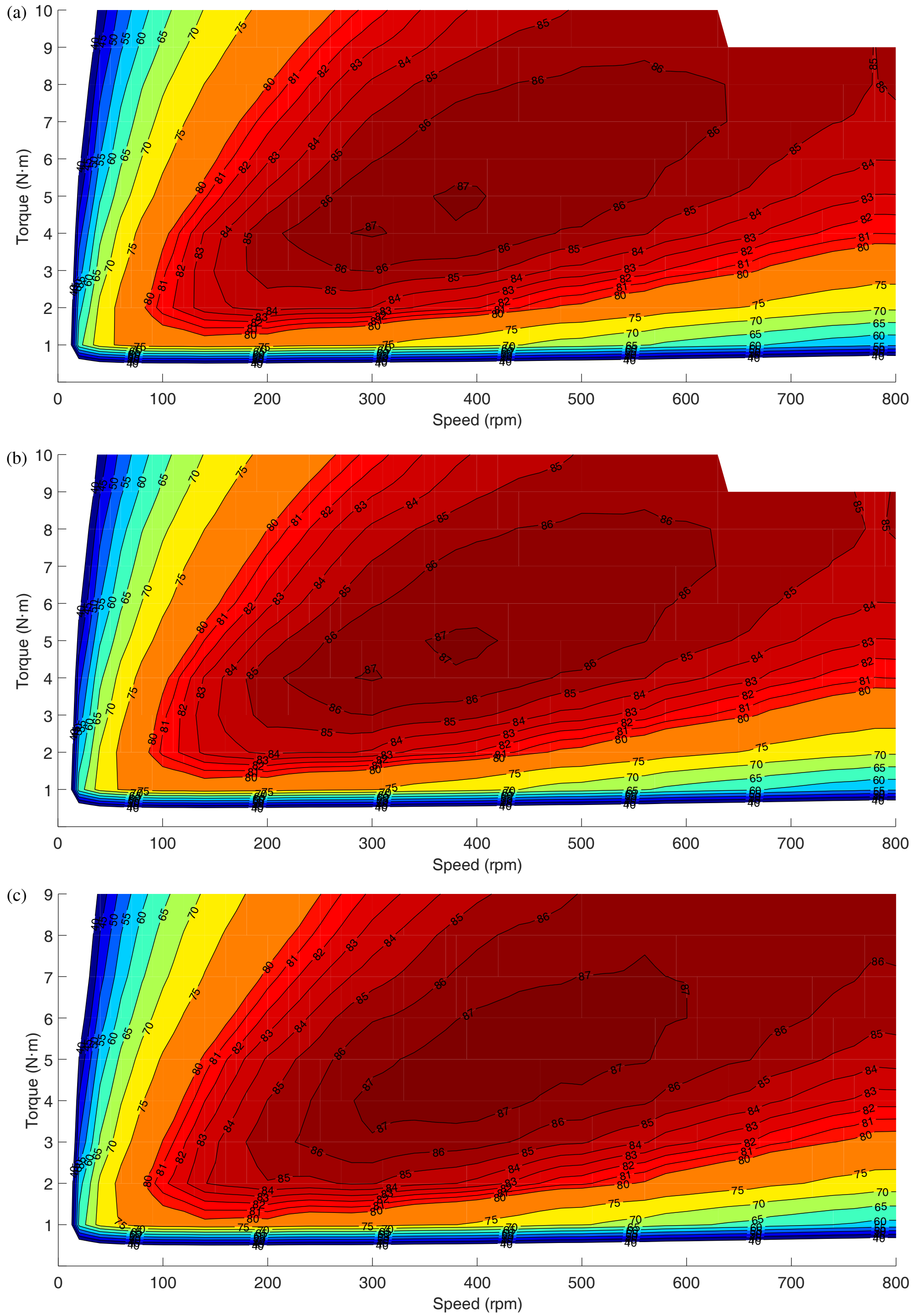

FIGURE 5. Efficiency simulation of flux switching permanent magnet machine. (a) Straighted-rotor with DW360_50. (b) Straighted-rotor with 35SW360. (c) Skewed-rotor with DW360_50.

be increased from the simulated value of 9 N·m to 10 N·m by raising the three-phase line current, as illustrated in Figure 7(b).

6. DISCUSSIONS

Both the simulation and hardware test results show that the overall efficiency of flux switching permanent magnet machine is lower than the conventional permanent magnet synchronous motor. There are several reasons for this case:

(1) Both the stator core and rotor core are designed by salient-pole structures, which inherently lead to the higher harmonic of air-gap magnetic field, and the iron losses (eddy current loss and hysteresis loss) increase. Therefore, in order to suppress the iron loss caused by higher harmonic of air-gap magnetic field,

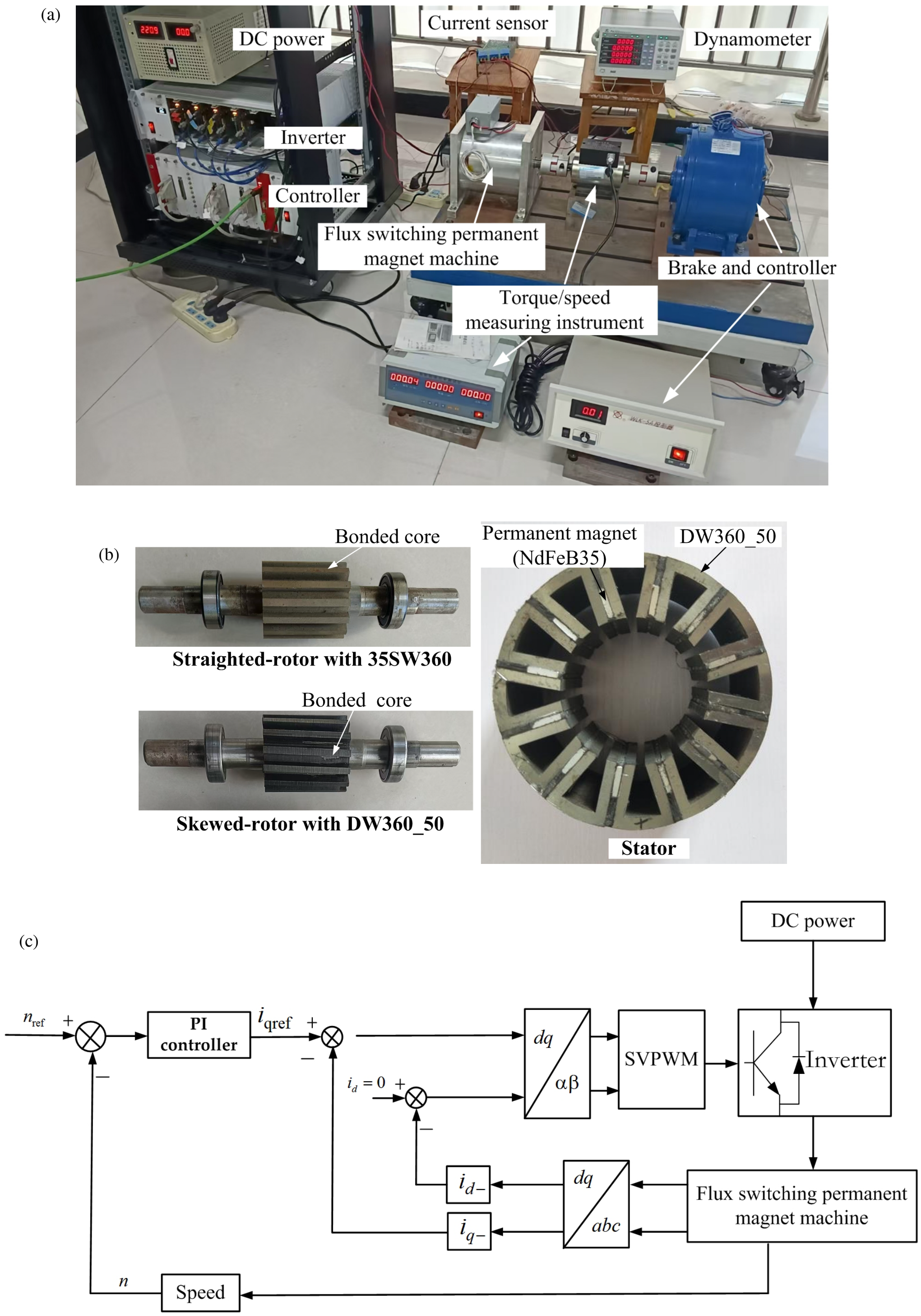

FIGURE 6. The efficiency test system of flux switching permanent magnet machine. (a) Test rig. (b) Prototype. (c) Control method.

this paper adopts the structure of bonded stator core and rotor core to decrease the iron losses.

(2) As shown in Figure 3 and Figure 6(b), the permanent magnets of flux switching permanent magnet machine are embedded in the stator core and directly exposed to high frequency alternating magnetic fields, resulting in the eddy current losses of permanent magnets.

(3) If the assembly accuracy of the flux switching permanent magnet machine is insufficient, the mechanical friction losses and leakage flux of flux switching permanent magnet machine will increase.

(4) Compared with the conventional permanent magnet synchronous machines, the control strategies for flux switching permanent magnet machine need further improvement. Some methods such as harmonic current injection and maximum

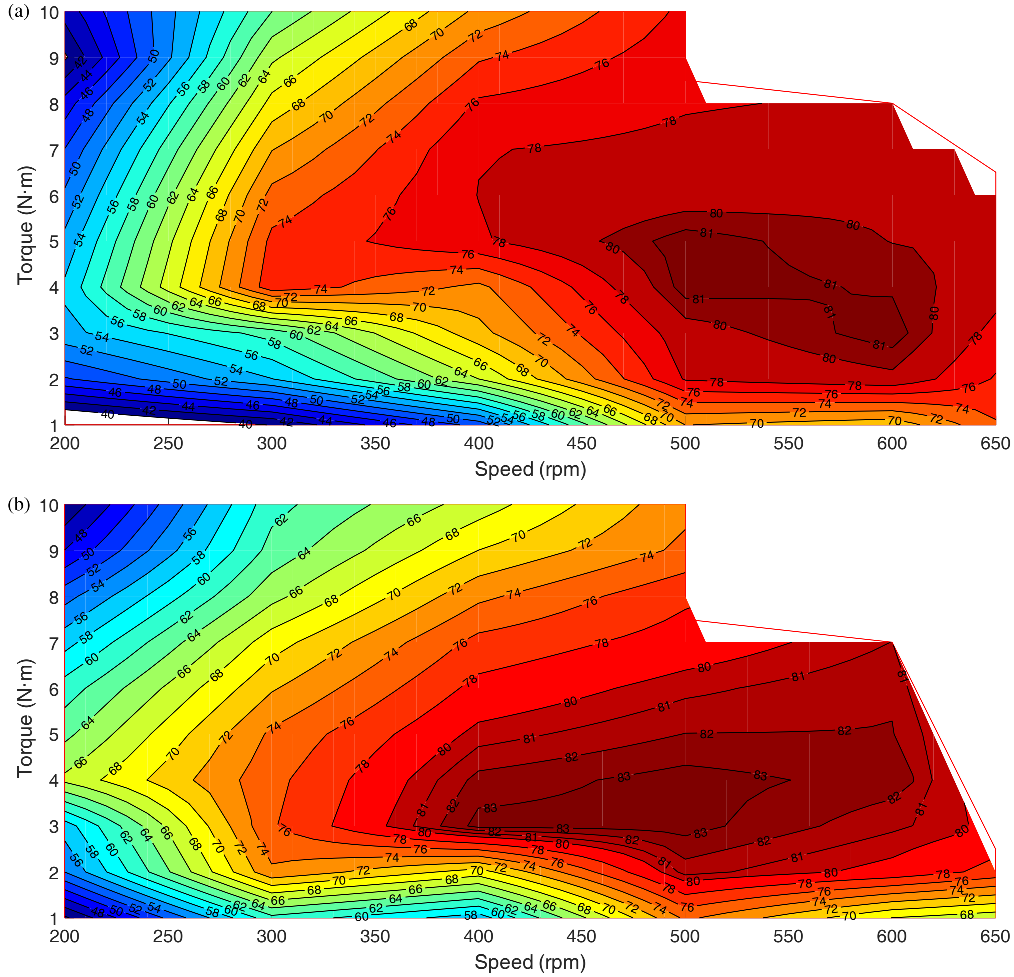

FIGURE 7. Efficiency test of flux switching permanent magnet machine. (a) Straighted-rotor with 35SW360. (b) Skewed-rotor with DW360_50.

TABLE 6. Active power measurement error of dynamometer.

Frequency f	Read error E1 and range error E2
Direct current (DC)	± (0.1*E1 + 0.2*E2)%
$0.5\,\text{Hz} \leq f < 45\,\text{Hz}$	± (0.3*E1 + 0.2*E2)%
$45\,\text{Hz} \leq f < 66\,\text{Hz}$	± (0.1*E1 + 0.05*E2)%
$66\,\text{Hz} \leq f < 1\,\text{kHz}$	± (0.2*E1 + 0.2*E2)%
$1\,\text{kHz} \leq f < 10\,\text{kHz}$	± (0.1*E1 + 0.3*E2)% ± (E1*(0.067*(f-1))%
$10\,\text{kHz} \leq f < 100\,\text{kHz}$	± (0.5*E1 + 0.5*E2)% ± (E1*(0.07*(f-10))%

torque per ampere (MTPA) control can be implemented to enhance the efficiency of flux switching permanent magnet machine.

(5) In the hardware test of this paper, the efficiency of flux switching permanent magnet machine was compromised by several factors: inverter's self-protection mechanisms, low-resolution encoder (1024 counts/revolution), control method, and the limited high-frequency measurement accuracy of the dynamometer. For the inverter, a higher switching frequency or a shorter software program scanning cycle can lead to larger currents, which may cause the inverter to stop working. The low-resolution encoder (1024 counts/revolution) compromises the effective implementation of control method and the speed stability of machines. Table 6 shows the active power measurement error of dynamometer (source: user's manual). From Table 6, it can be concluded that the higher frequency f is, the greater active power measurement error is (comprising the total of read error E1 and range error E2).

Nevertheless, some prior research results demonstrated that flux switching permanent magnet machine have a competitive advantages in some specific applications (e.g., high-speed operation and reliability of electric vehicle) due to its high torque density and robust construction (with permanent magnets installed in the stator core). In the future, investigations and improvements may be achieved through magnetic circuit optimization (e.g., asymmetric rotor design) and advanced control algorithms to further enhance the efficiency of flux switching permanent magnet machine.

7. CONCLUSION

In this paper, the operational efficiency of a flux switching permanent magnet machine was investigated through simulation and test by employing different rotor structures and non-oriented electrical steel materials. First, iron loss test and comparison show that the bonded stator core exhibits lower iron losses than welded stator core. Based on the bonding stacking method of stator and rotor cores, a non-oriented electrical steel material named 35SW360 was proposed and installed in the straighted-rotor of flux switching permanent magnet machine. The simulation results demonstrated that the induced electromotive force and efficiency of flux switching permanent magnet machine with 35SW360 were nearly identical to those of the standard non-oriented electrical steel material DW360_50. Besides, a skewed-rotor with 5 deg was adopted and implemented in the flux switching permanent magnet machine, and the simulation results show that skewed-rotor design improves efficiency. Furthermore, a prototype flux switching permanent magnet machine and its corresponding test rig were constructed. The hardware test results confirmed that the flux switching permanent magnet machine with skewed-rotor achieved higher efficiency, which aligned with the simulation results. Hence, employing the non-oriented electrical steel material 35SW360 (bonding stacking method) and skewed-rotor design can enhance the efficiency of flux switching permanent magnet machine.

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