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Impacts of rotor slots on interior permanent magnet motors performance

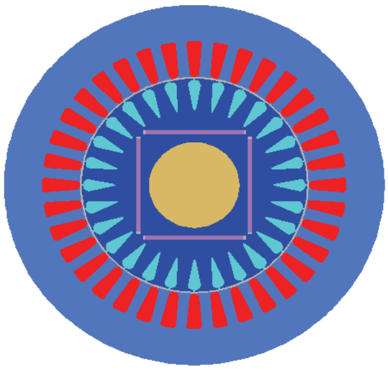
***Abstract**. In this paper, effects of number of rotor slots on the performance of line start interior permanent magnet synchronous motors (LSIPMSMs) are analyzed in details. Magnetic, electrical and mechanical signals of two LSIPMSMs with 28 and 44 rotor slots are calculated, inspected and compared with each other. Influence of the rotor slots on the space harmonics is studied using spectra of the aforementioned signals around the fundamental harmonic and principle slot harmonic. Furthermore impacts of the load variation on the computed signals and their spectra are investigated. Time stepping finite element method is utilized to simulate above mentioned motors.*

***Streszczenie.** W artykule przeanalizowano wpływ liczby żłobków na działanie bezpośredni włączanego silnika synchronicznego z magnesem trwałym. Sygnały elektryczne, magnetyczne i mechaniczne dwóch takich silników z 28 i 44 żłobkami w wirniku zostały obliczone i porównane między sobą. Wpływ żłobków wirnika na harmoniczne przestrzenne został zanalizowany przy użyciu spektrum, wspomnianych wcześniej, sygnałów wokół podstawowej harmonicznej i podstawowej harmonicznej żłobkowej. Co więcej, przebadano też wpływ zmienności obciążenia na obliczane sygnały i ich spektra. Do symulacji silników wykorzystano metodę elementów skończonych z krokiem czasowym. (**Wpływ złobków wirnika na działanie silnika z wewnętrznym magnesem trwałym**)*

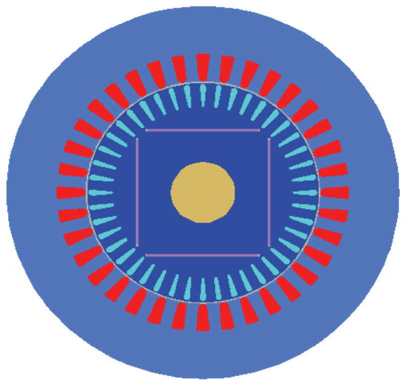
Keywords: IPMSM, rotor slot, TSFEM harmonic analysis.
Słowa kluczowe: silnik synchroniczny z magnesem trwałym, żlobek wirnika, analiza harmoniczna MES

Introduction

Application of permanent magnet (PM) synchronous motors (PMSMs) is increasing due to advanced technology in manufacturing PM, high power density, improved power factor and high efficiency. The PMSMs are classified to surface mounted PM synchronous motors (SPMSM) and interior PM synchronous motors (IPMSMs). In [1], performance of the SPMSM and IPMSM is evaluated by computing electromotive force (EMF), starting current, power factor, cogging torque and speed. It has been illustrated that IPMSM performance is more appropriate than that of SPMSM. In [2], a rotor design of interior-permanent-magnet motors is proposed to reduce harmonic iron losses at high rotational speeds under field-weakening control. First, an optimization method which has been combined with an adaptive finite element method (FEM) is applied to automatically determine the shapes of the magnets and the rotor core. It has been shown that the iron loss of the optimized motor is reduced to nearly half of that of the conventional motor, without a significant decrease in maximum torque. In [3], effects of the space harmonics on the starting charecteristics of a single-phase line start permanent magnet synchronous motors (LSIPMSM) has been investigated. It has been demonstrated that LSIPMSM has a large torque dip at low speed due to a slot effects and many torque ripples are produced due to the difference between the reluctances for d-q-axis. In [4, 5], performance of LSIPMSM has been compared with induction motor (IM). It has been demonstrated that LSIPMSMs have efficiency and power factor larger than IMs and LSIPMSMs also operated at much lower temperatures at rated load and voltage when compared to IMs. In [6], transient performance of IPMSMs in line-start and drive cases has been investigated. It has been demonstrated that stator currents of IPMSMs in drive conditions are distorted. Furthermore, it has been illustrated that increase of supply frequency causes to rise the settling time considerably. It has been exhibited in [7] that a poly phase LSIPMSM can operate on a single-phase supply. Hence, two separate capacitors are required for such an operation: one for starting and the other for steady-state operation. The size of the latter capacitor can be optimized to obtain one of the performance criteria, such as minimum current unbalance, minimum negative sequence current, maximum efficiency, maximum power factor and maximum torque conditions.



(a)



(b)

Fig. 1. IPMSMs configurations with, (at) 28 rotor slots and (b) 44 rotor slots

It has been indicated that the selection of capacitor rating should not be for maximum torque condition, but should be for maximum efficiency or for maximum power factor condition. In these cases, the variation of capacitor with load is not required and a fixed value of capacitor can be employed.

In this paper, effects of rotor slots numbers on LSIPMSMs are investigated in details. Hence, two LSIPMSMs with almost the same parameters and different rotor slots numbers are modelled using time stepping finite element method (TSFEM).

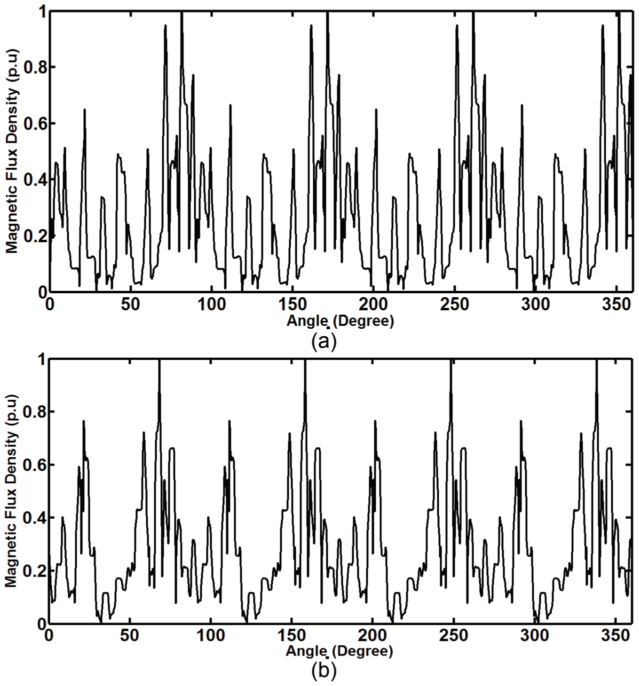


Fig. 2. Magnetic flux density at starting- mode of LSIPMSM, (a) 28 rotor slots and (b) 44 rotor slots

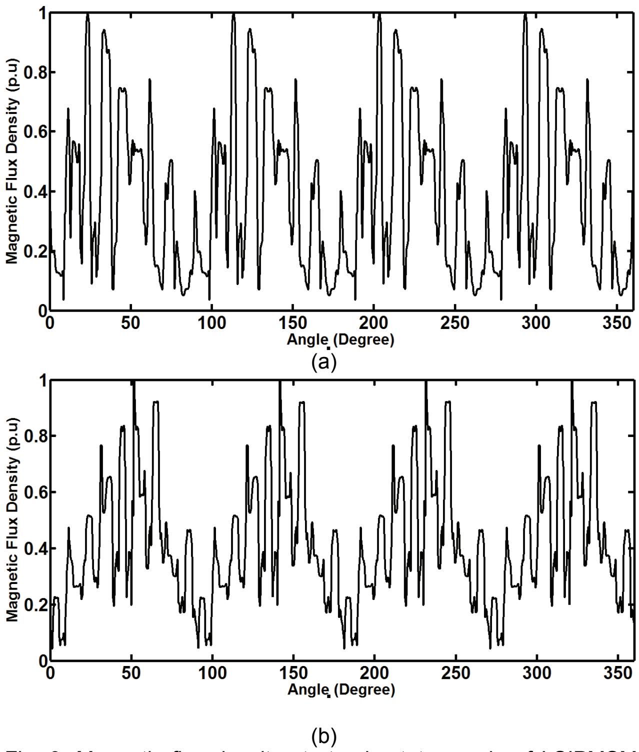


Fig. 3. Magnetic flux density at steady state- mode of LSIPMSM, (a) 28 rotor slots and (b) 44 rotor slots

The magnetic flux density, stator currents, torque and speed of the above mentioned motors are simulated. The performance of the aforementioned motors in the transient and steady-state modes is inspected to analyze rotor slots impacts on LSIPMSMs performance.

Time stepping Finite Element Modelling

The magnetic field distribution within the motor can be evaluated by FEM. The stator currents, torque and speed of the motor can be then determined using other specifications of the motor. A 2D scheme of the simulated IPMSM has been depicted in Fig. 1. In Fig 1a, an IPMSM with 28 open rotor slots and in Fig. 1b, an IPMSM with 44 rotor slots have been revealed. However, the used materials and number of stator slots in the two motors are identical. IPMSM modelling consists of the three following parts.

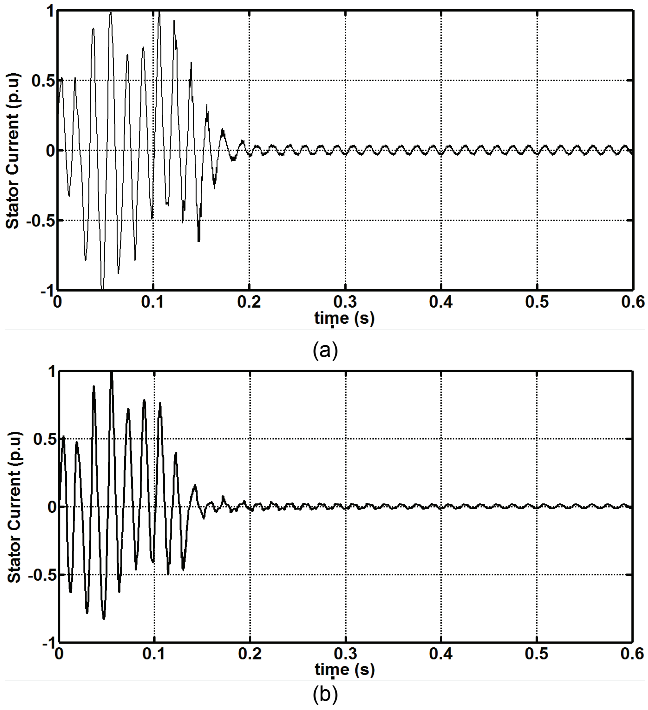


Fig. 4. Stator current profiles of the LSIPMSM, (a) 28 rotor slots and (b) 44 rotor slots

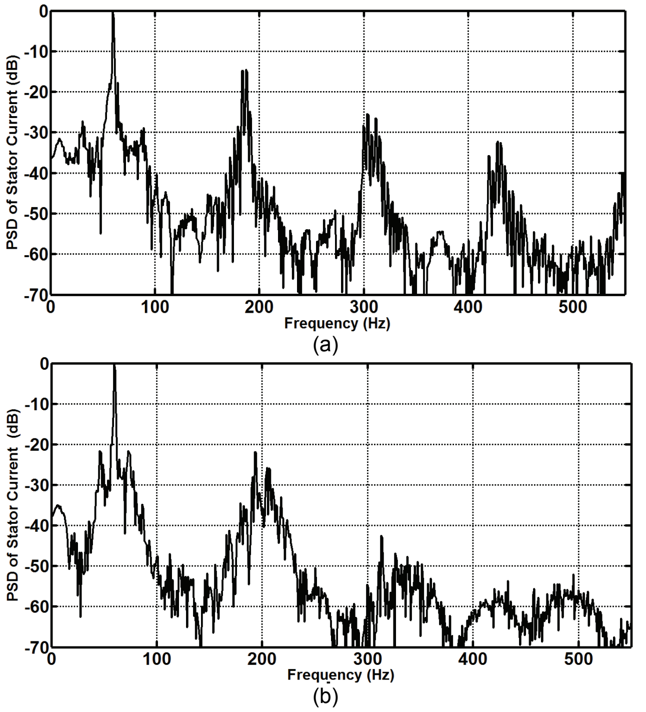


Fig. 5. Stator current spectra of LSIPMSM around fundamental harmonic, (a) 28 rotor slots and (b) 44 rotor slots

Modelling Motor Elements

Accuracy of the simulation approaches depends on the physical characteristics of the machines materials [8]. The reason is the noticeable impacts of the materials characteristics on the machine performance. In this modelling, non-linear characteristics of the PMs, stator and rotor cores and spatial harmonics due to the stator and rotor slots have been taken into account. The stator consists of laminated M-19 sheets and has 36 slots filled with copper. The motor has radially magnetized Nd-Fe-B PMs buried in the rotor core. Winding configuration has considerable impacts on the fault diagnosis precision. The reason is related to the windings distribution impacts on the harmonics of the line currents and voltages which affect the aforementioned signals spectra. In this modelling, two-layer stator windings and their spatial distribution is reckoned and a three-phase voltage supply is used in the simulations.

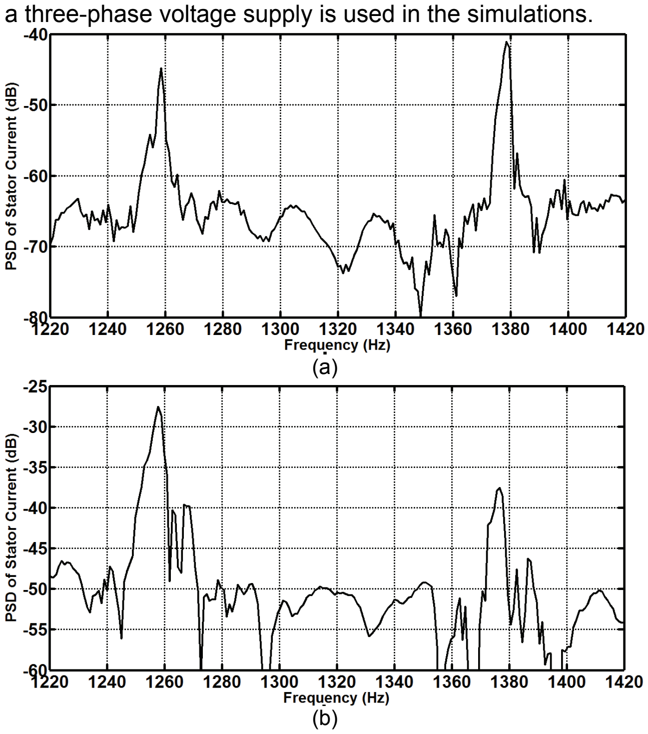


Fig. 6. Stator current spectra of LSIPMSM around PSH, (a) 28 rotor slots and (b) 44 rotor slots

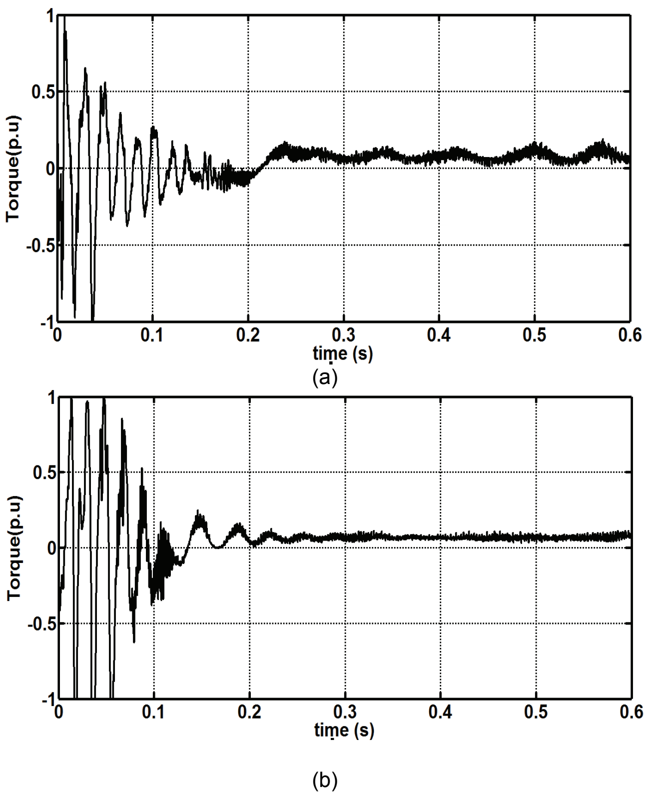


Fig. 7. Stator current profiles of full-load LSIPMSM, (a) 28 rotor slots and (b) 44 rotor slots

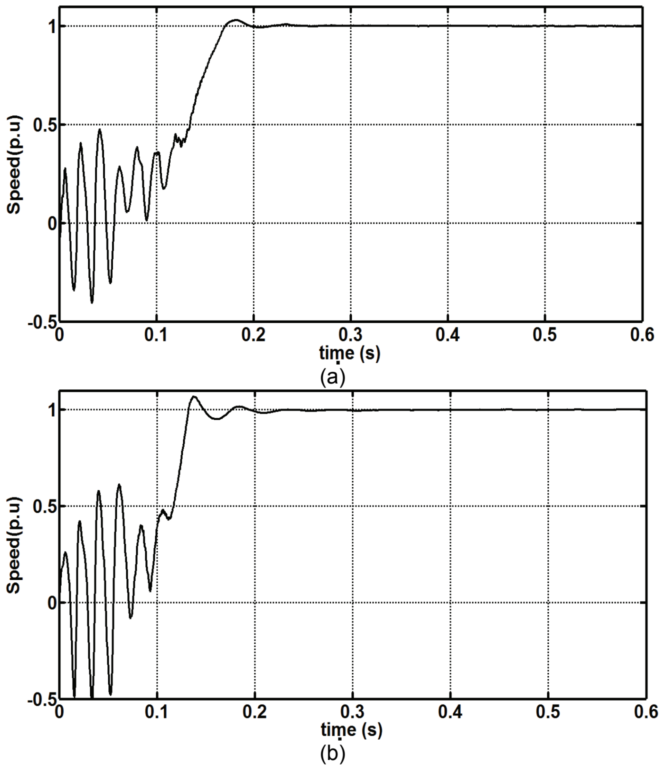


Fig. 8. Stator current profiles of full-load LSIPMSM, (a) 28 rotor slots and (b) 44 rotor slots

Solution Method

In this simulation, transient analysis of rotating machines (RM) is employed for modeling and analyzing PMSM with mechanical coupling. RM program is a transient eddy current solver which has been extended to include the effects of rigid body (rotating) motion [9]. The solver also provides for the use of the external circuits and coupling to the mechanical equations. In the modelling of PMSM, three-phase sinusoidal voltages are applied to the motor terminals as inputs, magnetic flux density and torque are predicted as the signals for processing and feature extraction. In this modeling, electrical equations due to the external circuits which exhibit supply and electrical circuits are combined with magnetic field equation in FEM and motion equations of the mechanical coupling. Fig. 2 depicts magnetic flux distribution of different LSPMSMs in the starting-mode at 75% rated load. Comparison between Fig. 2a and 2b illustrates that variation rate of the flux density in the motor with 28 rotor slots is larger than that of the motor with 44 rotor slots. The reason is skewing angle which is larger for motor with 28 rotor slots in comparison with another motor. Thus, total harmonic distortion (THD) of the flux density in the motor with 28 rotor slots is larger than that of the motor with 44 rotor slots. According to Fig. 3, this fact is seen in the aforementioned motors with 75% rated. Comparison Fig. 2 and Fig. 3 illustrates that variation rate of the flux density in the motor with 75% rated load is sharper than that in the no-load case.

Performance Analysis

Stator Currents

Fig. 4 exhibits the stator current of the motors in the no-load case. It is seen that variation rate of the stator currents in transient mode of the motor with 28 slots is larger than that of the 44slots. Moreover, magnitude of the stator currents in the steady-state case in the motor with 28 slots is larger than that the other motor. It is due to the variation rate of the inductances profiles which is sharper for the motor with 28 slots. Fig. 5 shows the spectra of the motor stator currents. It is seen that harmonic components in the stator current spectrum of the motor with 28 slots are larger than that of the 44 slots. This fact is expected due to explained physical concepts. Fig. 6 shows the spectrum of the stator current around PSH. According to Fig. 6, magnitude of the harmonic components around PSH in motor with 28 slots is larger than that the second motor; this phenomenon has been justified above.

Torque

Developed torque of two motors is presented in Fig. 7 for the full-load case. It is seen that variation rate of the motor torque with 28 slots is larger than motor with 44 slots. Since electromagnetic torque relates to square of magnetic flux density and variation rate of the flux density for motor with 28 slots is larger than the motor with 44 slots, variation rate of the motor torque is sharper in motor with 28 slots.

Speed

Speed profiles of the two full-load motors have been depicted in Fig. 8. It is seen that speed ripples for motor with 28 slots is larger than the motor with 44 slots. It is obvious when variation rate of the magnetic flux density, stator currents and torque of motor with 28 slots is larger than that of the second motor, its speed ripples is larger than that motor with 44 slots.

Conclusion

In this paper, TSFEM was used for modelling and analyzing two LSIPMSMs with different number of rotor slots. Impacts of number of rotor slots were investigated on the stator currents, torque and speed of these motors. Spectra of the stator currents were employed to justify the obtained results. It was illustrated that magnitude of the harmonic components in motor with 44 rotor slots is larger than that motor with 28 rotor slots.

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