Front. Electr. Electron. Eng. 2012, 7(4): 459–466
DOI 10.1007/s11460-012-0217-8

RESEARCH ARTICLE

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Line-start permanent magnet synchronous motors versus induction motors: A comparative study

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Abstract Line-start permanent magnet synchronous motors are suitable candidates for substitution of induction motors in many constant-speed applications. This paper compares steady-state and dynamic performances of these motors. The efficiency, power factor, stator currents, and rotor bars currents are considered for steady-state performance analysis whereas the rotor speed, electromagnetic torque, and stator and rotor currents are investigated for dynamic performance analysis. For this purpose, time stepping finite element method is used to analyze the performance of motors in both full-load and no-load conditions. Results demonstrate the superior performance of the line-start permanent magnet synchronous motor in steady-state condition and the improved dynamic performance of the induction motor. Finally, economic calculations indicate that the extra cost of the line-start permanent magnet synchronous motor with respect to the induction motor is rapidly compensated by energy saving due to a more efficient operation.

Keywords line-start permanent magnet synchronous motors, induction motor, steady-state, dynamic, comparison, finite element method

1 Introduction

Induction motors are widely used in industrial applications. However, the efficiency and the power factor of induction motors especially in low power ratings can hardy meet present and emerging efficiency standards, such as IEC3 and IEC4. In contrast, line-start permanent magnet synchronous (LSPMS) motors are well-suited to these standards [1,2]. In last decades by introducing high energy permanent magnets (PMs) in reasonable prices, extensive researches have been performed in feasibility assessment and economic analysis of these motors [2–5]. Although this kind of motors have a superior performance in the steady-state condition, their dynamic performance during start-up and synchronization suffers from some difficulties caused by braking torque due to PM poles [6]. Several researches have been performed to analyze the performance of LSPMS motors in both steady-state and dynamic conditions [6–12]. Also, some performance aspects of LSPMS motors have been compared with those of induction motors of the same power rate [13–16]. However, the lack of a comprehensive comparison of LSPMS motors and induction motors is felt. Besides, cost analysis of LSPMS motors and their economic values have not been explored.

In this paper, a detailed comparison on steady-state and dynamic performances of a line-start permanent magnet motor and an induction motor is performed. Both motors have the same stator and frame size and are designed for the same output power (2.2 kW). Steady-state performances such as the efficiency, the power factor, and the current level of both motors are compared, and origins of differences are addressed. Dynamic characteristics of both motors are also derived by time-stepping finite element

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Received April 12, 2012; accepted October 8, 2012

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method (FEM), and differences are discussed in detail. Finally, economic merits of using LSPMS motors are described considering the interest and inflation rates.

2 Structure and analysis method

A standard industrial three-phase induction motor with specifications listed in Table 1 is selected in this paper. The cross section of the induction motor is shown in Fig. 1(a). It consists of a stator with 36 slots containing a four-pole single-layer winding and a rotor with 28 deep cage bars. An LSPMS motor is then designed where the stator, the frame, the shaft, and the bearings are kept the same as those of the induction motor. Therefore, a fair comparison of motors is ensured. The LSPMS motor contains a squirrel cage and four permanent magnet poles as shown in Fig. 1(b). Other specifications of the LSPMS motor are listed in Table 1. To analyze the steady-state and dynamic performances of both motors, the circuit-coupled time-stepping finite element method is employed. The commercial software, Cedrat Flux2D, is used for finite element analysis (FEA). Magnetic flux lines in both motors achieved by FEA are shown in Fig. 2. It is seen that flux lines penetrate deeper in the LSPMS motor due to presence of magnet poles. The no-load back electromotive force (back-EMF) voltage of the LSPMS motor considerably affects the steady-state and dynamic performances of the motor. The no-load back-EMF voltage of the LSPMS motor caused by permanent magnets in synchronous speed is depicted in Fig. 3. Its root-mean-square (RMS) value is approximately 185 V, and therefore the back-EMF voltage to the phase voltage ratio is 0.84.

Table 1 Stator parameters

parameter	symbol	unit	value
number of slots	Q_s	–	36
turn per slot	Z_s	–	44
stack length	L	mm	90
inner diameter	D_{si}	mm	75
outer diameter	D_{so}	mm	150
slots/pole/phase	q	–	3
conductor area	a_{co}	mm^2	0.3542
parallel conductors	a	–	2
parallel paths	a_p	–	1

3 Steady-state performance analysis

In this section, steady-state performance of the induction motor and the designed LSPMS motor are compared. The efficiency, the power factor, and the steady-state current are selected as comparison criteria. As it is mentioned, all of results are obtained by FEA of both motors where they are directly supplied from grid. Also, the full-load power of these machines is 2.2 kW whereas motors have no output power in no-load condition.

3.1 Current

The phase current of the induction motor and the LSPMS motor for no-load and full-load operations are depicted in Fig. 4. It is seen that, the no-load current of the LSPMS motor is less than that of the induction motor because the magnetization in the LSPMS motor is provided by magnet flux whereas in the induction motor magnetization implies a magnetizing current to the stator windings. This increases the full-load current of the induction motor with respect to the LSPMS motor. The rotor bar current at the full-load condition is depicted in Fig. 5. Although ideally there should be no induced current in rotor bars of the LSPMS motor, filed harmonics cause a high frequency current in rotor bars. However, the magnitude of rotor bar current in the LPMS motor is eight time lower than that in the induction motor which results in a rotor electrical losses approximately 64 times smaller than rotor electrical losses in the induction motor. Another fact is that, all rotor bars in an LSPMS motors do not experience the same inducted current. It is shown in Fig. 6 that the rotor bar located in d-axis experiences a higher level of induced current with respect to the rotor bar located in q-axis.

3.2 Efficiency

Almost 20% of losses in induction motors associate with the rotor cage electrical loss [7]. In LSPMS motors, rotor electrical loss significantly reduces where only electrical loss caused by current harmonics appears in the rotor cage which is almost negligible. In addition, electrical loss of stator which is the largest portion of total loss also reduces due to a significant reduction in the magnetizing current and the input current amplitude. Although iron loss of the LSPMS motor is higher than that of the induction motor due to a higher flux density produced by rotor poles, the LSPMS motor has a higher efficiency value with respect to the induction motor. The full-load efficiencies of both motors along with different loss components are listed in Table 2 that confirms the above discussions.

3.3 Power factor

A low value of power factor causes a reduction in the electrical system distribution capacity by increasing current amplitude and voltage drop. It also causes extra losses in stator windings. The LSPMS motor works with a higher power factor than the induction motor due to a reduction in stator current by decreasing the magnetizing current. The full-load power factors of the LSPMS motor

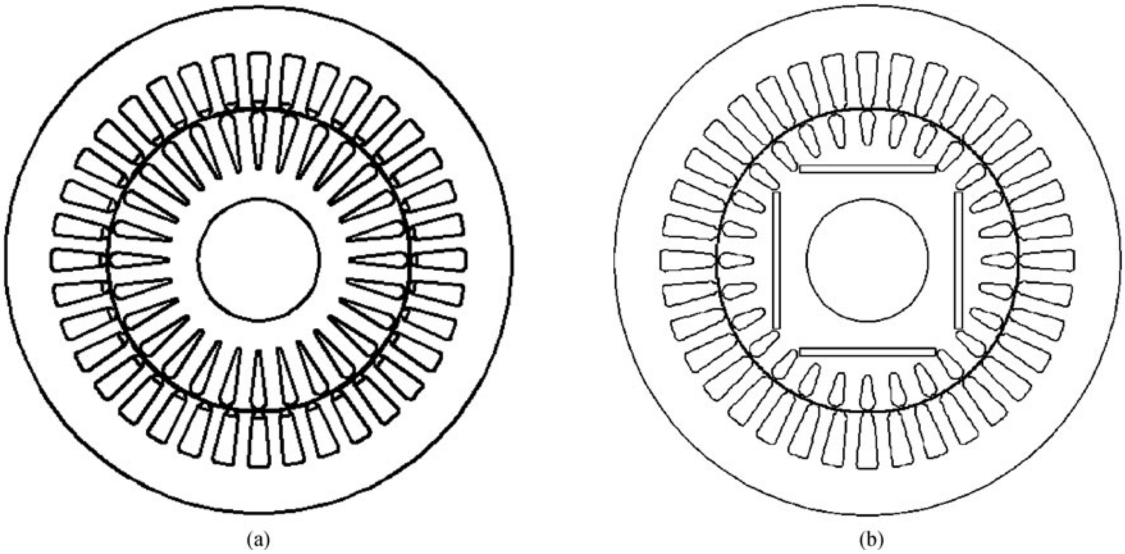

(a) (b)

Fig. 1 Cross sections of (a) three-phase induction motor and (b) LSPMS motor

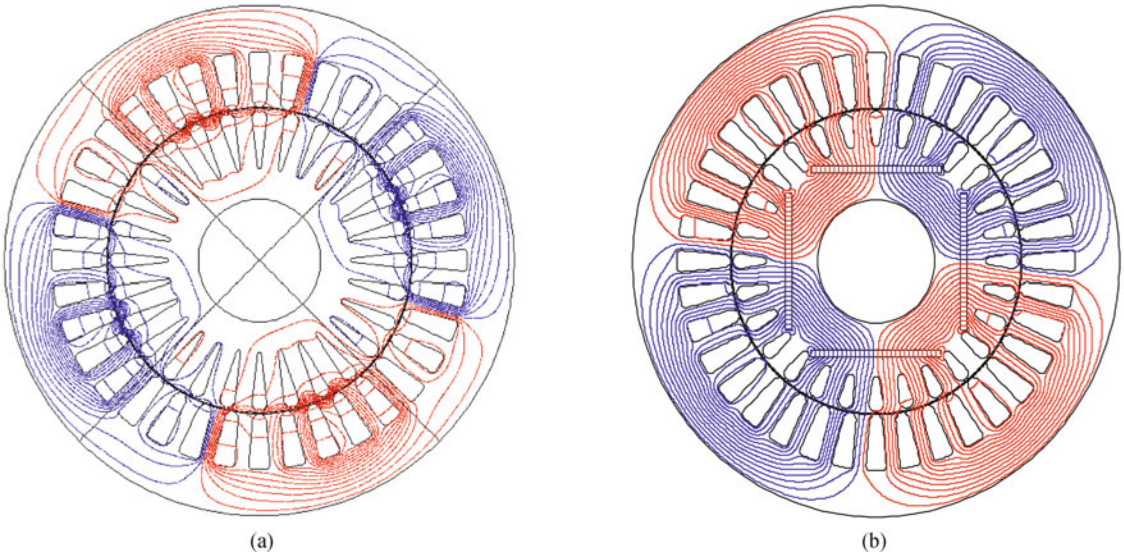

(a) (b)

Fig. 2 Magnetic flux lines in (a) induction motor and (b) LSPMS motor

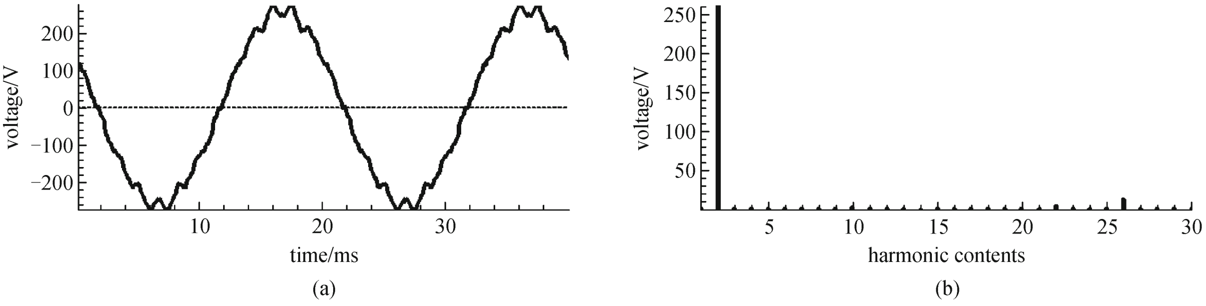


Fig. 3 (a) No-load back-EMF of LSPMS motor and (b) its harmonic contents

and the induction motor are compared in Table 2 which shows that the LSPMS motor has an 18% higher power factor.

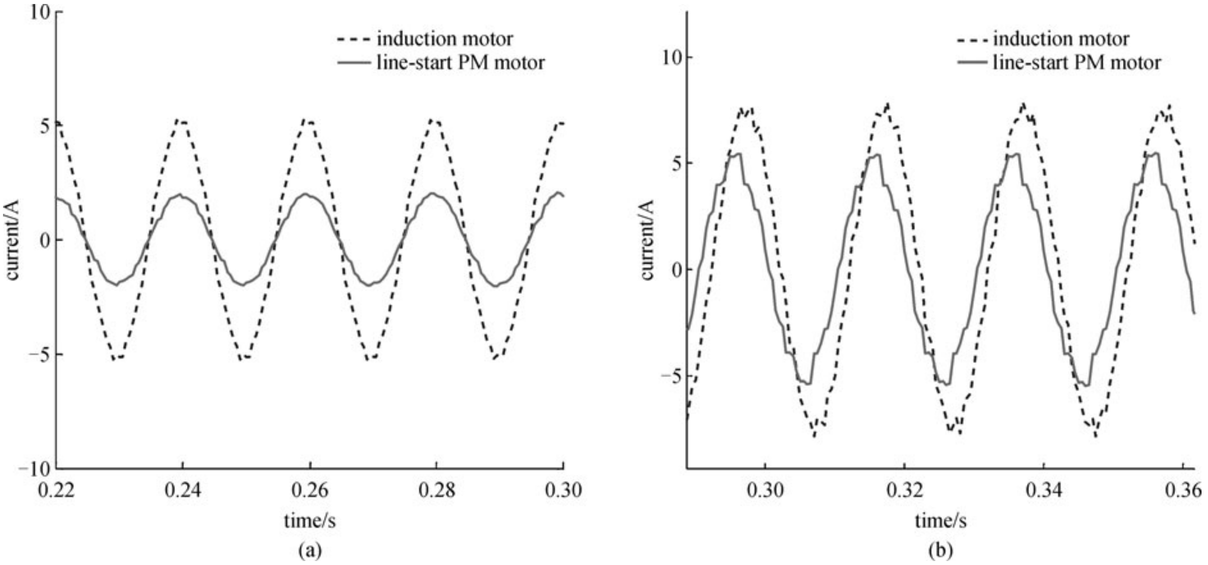
Measurement of some steady-state performance of the induction motor has been performed and listed in Table 2. A photo of experimental setup is shown in Fig. 7. Experimental results validate the accuracy of the results obtained by FEM.

4 Dynamic performance analysis

In contrast to the steady-state operation, LSPMS motors have some drawbacks with respect to induction motors in their dynamic behavior especially in starting under a load. In LSPMS motors, permanent magnet poles and magnetic saliency produce a synchronous pulsating torque with a negative average, so-called breaking torque [3]. Braking torque deteriorates the asynchronous operation of LSPMS motors with respect to induction motors. Dynamic performance of the LSPMS motor and the induction motor by analyzing speed, torque, and current are compared in this section.

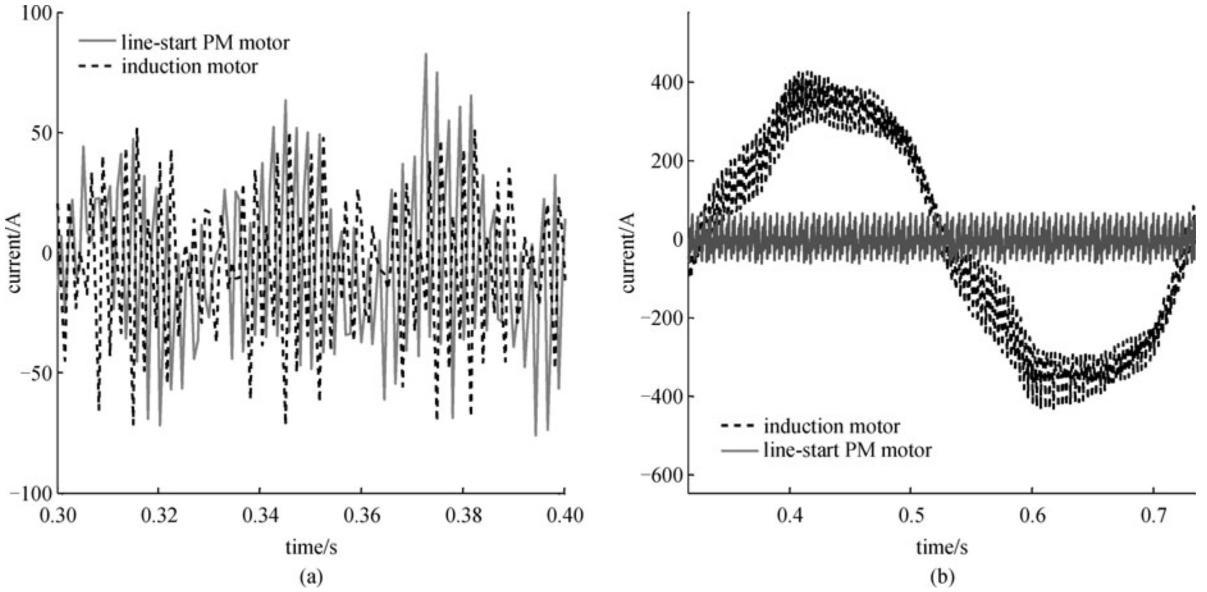
4.1 Speed

The speeds of the induction motor and the LSPMS motor under no-load and full-load starting conditions are depicted



(a) (b)

Fig. 4 (a) No-load and (b) full-load stator currents of induction and LSPMS motors



(a) (b)

Fig. 5 (a) No-load and (b) full-load rotor currents of induction and LSPMS motors

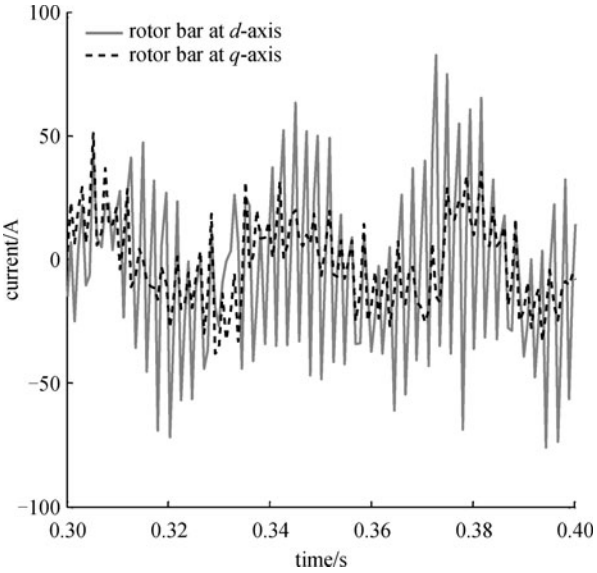


Fig. 6 No-load current of LSPMS motor in different rotor bars

Table 2 Induction and LSPMS motors characteristics

parameters	induction (FEM)	induction (experiment)	LSPMS (FEM)
efficiency	0.81	0.795	0.88
power factor	0.8	0.807	0.98
full-load current/A	5.33	5.4	3.65
no-load current/A	3.30	3.18	1.46
rotor iron loss/W	18	–	15.6
stator iron loss/W	60	–	60
rotor electrical loss/W	110.9	–	6.6
stator electrical loss/W	230.1	–	121.5
mechanical loss/%	3	–	3

Fig. 7 Experimental setup

in Fig. 8. It is observed that, the dynamic of the induction motor is faster than that of the LSPMS motor. The rise time of the induction motor is roughly half of the rise time of the LSPMS motor at full-load condition and around two-thirds of the rise time of the LSPMS motor at no-load condition. Also, the speed of the LSPMS motor has some dips due to a synchronous pulsating torque during the asynchronous operation of the motor. An overshoot observed in the speed of the LSPMS motor is also caused by this pulsating torque.

4.2 Torque

The starting torques of both motors under no-load and full-load conditions are depicted in Fig. 9. It is observable that, the positive peaks of starting torques at no-load condition are approximately equal for both motors but the LSPMS motor suffers from higher negative torque peak caused by magnet pulsating torque. Both positive and negative peaks of starting torque of the LSPMS motor at full-load condition are greater than those of the induction motor.

4.3 Current

Stator current characteristics of both motors are depicted in Fig. 10. It is observed that peak values of starting currents of both motors are close. However, this transient current is damped sooner in the induction motor due to its faster dynamic. Starting currents in rotor bars of both motors are also compared in Fig. 11 which shows that the amplitude of rotor bar current in the LSPMS motor is much higher than that in the induction motor because of a stronger magnetic field in the air gap of the LSPMS motor. It is seen that the amplitude of starting rotor bar current in the LSPMS motor is more than 150% of that of the induction motor.

5 Energy saving

In this section, the energy saving and economic aspects of the LSPMS motor are investigated. Annual energy saving of the designed LSPMS motor with respect to the original induction motor is given by [3]

$$S = P_{\text{out}} \times L \times hr \times C \times \left[\frac{1}{E_{\text{ind}}} - \frac{1}{E_{\text{LS}}}\right], \qquad (1)$$

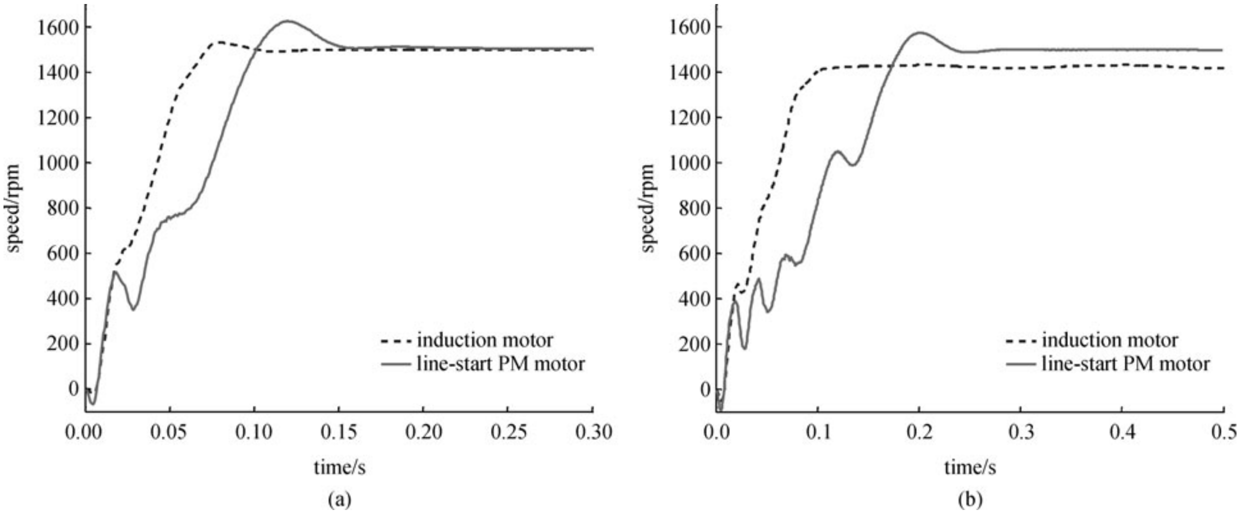
where S is the annual saving, P_{out} is the motor rated power, L is the load factor, hr is the annual operating hours, C is the average energy cost, and E_{ind} and E_{LS} are induction and LSPMS motors efficiencies, respectively. Taking into account of an interest rate and an energy inflation rate in the analysis, the payback period for extra cost of the LSPMS motor is given by [3]

$$n = \frac{\ln\left[1 - \frac{E(i-j)}{S}\right]}{\ln\frac{1+j}{1+i}}, \tag{2}$$

where i and j are the interest rate and the inflation rate of energy cost, respectively. Also, E stands for the extra cost of the designed LSPMS motor with respect to the induction motor. The extra cost of the designed LSPMS motor with respect to the original induction motor is around 20 $ which shows near 15% of cost increasing. Assuming 3000 h annual working at nominal power, the interest rate of 0.05, the energy inflation rate of 0.03, and the energy cost rate of 0.08 $/kWh, the annual energy saving is roughly 52 $ resulting in a very short payback period which is less than 5 months. This duration is very short with respect to the motor life time which is around 20 years. Therefore, the LSPMS motor can save more than 1050 $ during its life time which is worth eight times of its initial cost.

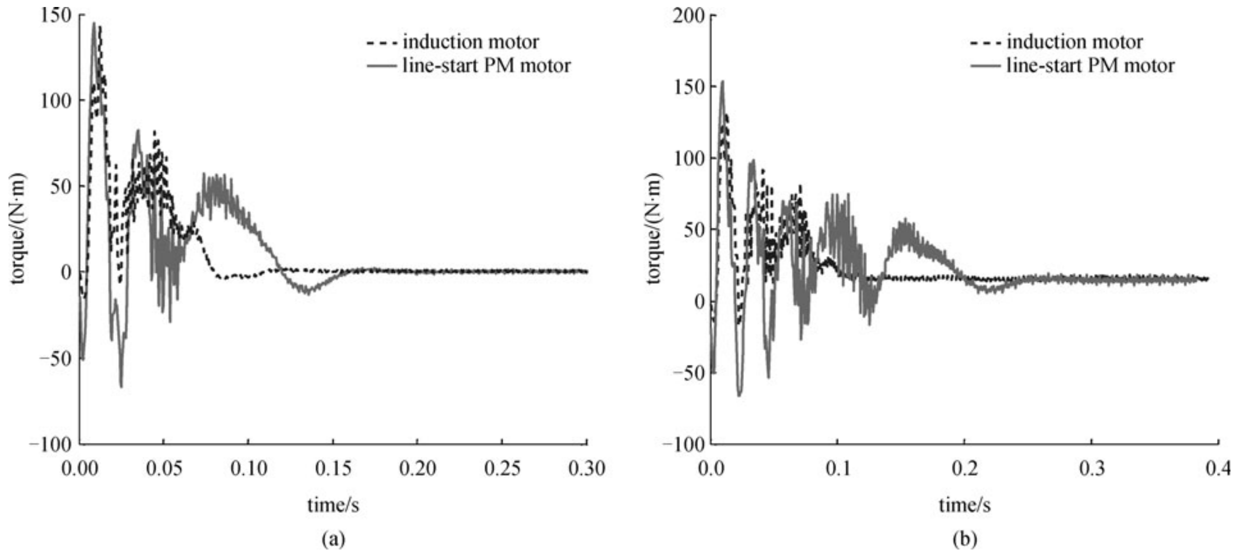
6 Conclusion

Steady-state and dynamic performances of an induction motor and a LSPMS motor are investigated in detail using FEM. Both motors have the same output power, frame, stator, shaft, and bearings. It is seen that the LSPMS motor has 7% higher efficiency and 18% higher power factor. Also, it benefits from 38% lower full-load stator current and 60% lower no-load stator current. Furthermore, the current level in the rotor bars of the LSPMS motor is near 0.13 of that in the induction motor resulting in a substantial reduction in rotor electrical losses. However, it is seen that



(a) (b)

Fig. 8 Speeds of induction and LSPMS motors at starting under (a) no-load and (b) full-load conditions



(a) (b)

Fig. 9 Torques of induction and LSPMS motors at starting under (a) no-load and (b) full-load conditions

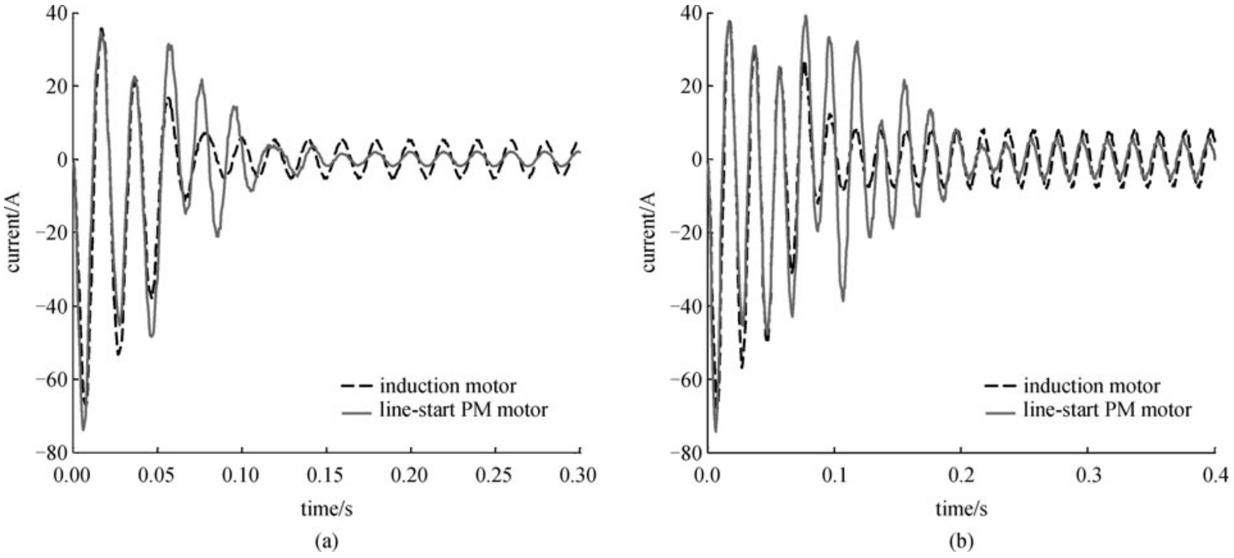


Fig. 10 Currents of induction and LSPMS motors at starting under (a) no-load and (b) full-load conditions

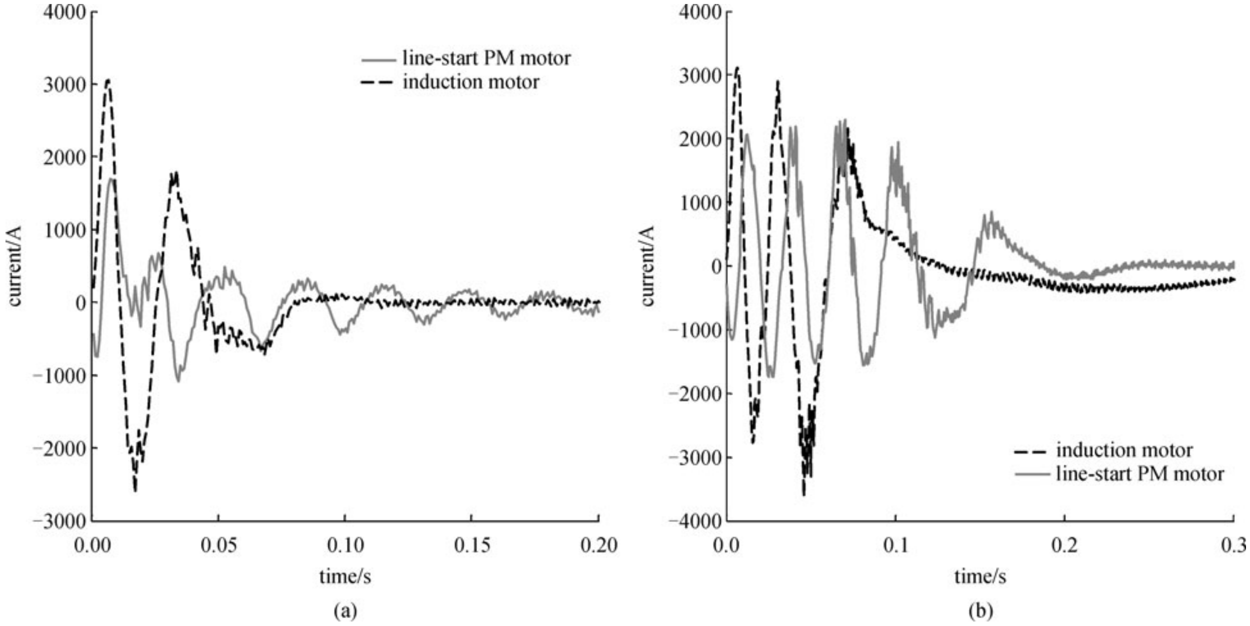


Fig. 11 Currents in rotor bars of induction and LSPMS motors at starting under (a) no-load and (b) full-load conditions

the induction motor benefits from a faster dynamic. The speed rise time of the LSPMS motor in full-load condition is more than twice of that of the induction motor. Amplitudes of starting torque and starting stator current in the LSPMS motor are close to those of the induction motor whereas the amplitude of starting rotor bar current is much higher in the LSPMS motor. Economic analysis for using the LSPMS motor instead of the induction motor shows that the extra cost of the LSPMS motor is shortly compensated by energy saving.

Acknowledgements The authors wish to thank SAMA Technical and Vocational College, Islamic Azad University, Khomeinishahr Branch, for partial support of this work.

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