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A New Squirrel Cage Rotor Structure to Improve the Dynamic Performance of the Single-Phase Induction Motor

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ABSTRACT

Improving the performance of electric machines has been focused on by researchers for many years. Reducing vibration and noise is one of the factors that are effective in improving the performance of electric machines. Electromagnetic forces are produced by the harmonics in the magnetic flux of the air gap, and vibration and electromagnetic noise are produced by the electromagnetic forces exerted on the stator and rotor structures. This paper proposes a new structure of the squirrel cage rotor to improve the distribution of the air gap magnetic flux and reduce the electromagnetic forces and, consequently, the electromagnetic noise in a single-phase induction motor. For this purpose, the rotor bars in the proposed design are located on the rotor in a sinusoidal form. The results show that this rotor structure improves the dynamic behavior and many parameters, such as electromagnetic forces, harmonic distortion of magnetic flux, and torque ripple.

I. Introduction

In general, induction motors are divided into two groups based on rotor structure: squirrel cage motors and slip ring motors (wound rotors). Due to their simple and robust structure, more than 90% of induction motors are squirrel cage rotor types. Single-phase induction motors (SPIM) are the most common type of low-power motors in single-phase systems and are extensively used in domestic and industrial applications [1-2].

With the development and progress of the process of designing and manufacturing electric machines, various technologies of them have been presented for specific purposes. On the other hand, these machines must be able to meet many specific application requirements such as speed, torque, reliability, longevity, low noise and vibration, and maintenance. Therefore, improving the performance of electric machines has always drawn researchers' attention [3-5]. In general, many factors in the process of design, production, and operation of electric machines affect their performance. In [6 - 8], the effect of non-sinusoidal voltage is examined on the steady-state performance of a motor. The results show that harmonic voltages produce non-sinusoidal currents in the stator and rotor, resulting in additional losses and torque ripples. SPIMs have low starting torque. Also, during the transient and steady-state, these motors produce a significant level of torque pulses, which create noise and vibration in the electric machine. In [9], to solve these problems, a pulse width modulation (PWM) inverter has been used to start the motor. In [10-13], by designing the winding and using the pole-change method, reduces the harmonic components of the magnetic flux density air gap. In general, air gap field harmonics play a major role in the performance of electric machines, including the level of electromagnetic forces and the production of noise and vibration in them.

In [14], by injecting a small current into the stator winding, which has a controlled magnitude, frequency, and phase, waves are created that are contrary to the existing harmonics and limit or eliminate them. Also, efforts are made in [15-17] to reduce the field harmonics by using the compensators of the negative current component. In [18-21], the effect of the geometry of the rotor bars and stator slots is investigated on the magnetic field of

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the air gap and the performance of the squirrel cage induction motor. In [22], to improve the starting characteristic of the motor, it is suggested to use skew slots in the stator core instead of the rotor. Another method to improve the performance of SPIM in a specific speed range is to use an adjustable capacitor. In [23], a chaotic pulse width modulation method is proposed to extend the power spectrum of the induction motor drive system. The results show that in this method, carrier, voltage/current, and acoustic switching noise spectrum are dispersed over a chaotic frequency range with no specific frequency concentration.

In [24], the effect of capacitor changes on motor characteristics including efficiency, electromagnetic torque, torque ripple, power factor, and current in a specific speed range is investigated, and the results confirm the improvement of motor performance. In [A], it deals with the reduction of quantization noise in the direct torque control of an induction motor. In the proposed method, by using a random dither signal that is added to the truncating analog-to-digital converter (ADC) outputs, the average error of the ADC reaches zero, and as a result, the integrator output error is reduced. The proposed quantization method can improve the result of the digital converter. Therefore, this method can reduce the current measurement result. Therefore, torque and flux ripples are reduced. To make electric motors with high reliability and low losses, a high-temperature superconducting induction/synchronous motor (HTS-ISM) is studied in [B]. The torque density and structural dimensions of HTS-ISM are optimized using the collective decision optimization algorithm (CDOA).

The results show an increase in torque of about 51.75% through the optimization process. Also, the particle swarm optimization (PSO) algorithm has been used as a common optimization method to compare the results. The results show that CDOA is more capable than PSO in motor design parameter optimization problems. In [25-27], the effects of the combination of different rotor and stator slots on the electromagnetic force are investigated by the finite element method using theoretical analysis. The results show that the coordination of the slots is very important and significant in the design process of low-noise motors. Another effective method of noise reduction is the use of skew slots in the rotor [28-30]. In [28-29], a new type of skew slot is presented and it is compared with previous types to examine the effectiveness of the proposed method. As mentioned, different goals are considered in different machines depending on the type of application for improving their performance.

This paper presents a new structure of the squirrel cage rotor to improve the distribution of the air gap magnetic flux. In the proposed design, by maintaining the composition and geometry of the stator and rotor slots, as well as the identical distribution of the stator winding, the rotor bars are located on the rotor according to a sinusoidal function. For this purpose, the conventional squirrel cage rotor and the proposed designs are simulated in ANSYS Maxwell 2D software. With the new rotor design, the total harmonic distortion (THD) of the magnetic field of the motor is reduced. As a result, the level of electromagnetic forces is reduced. Besides, some dynamic performances such as torque ripple and speed response are improved. The rest of the paper is organized as follows. Section II presents the stator windings. In Section III, the proposed design of a squirrel cage rotor will be introduced. Section IV presents the simulation results. Finally, the conclusion of the paper is provided in Section V.

II. Distributions of Stator Windings

As was already mentioned, one of the factors affecting the electromagnetic forces in electric machines is the distribution of stator winding. The winding distribution can be concentric or lap. However, since this paper aims to investigate the effect of the position of the squirrel cage rotor bars on SPIM on the electromagnetic forces, the distribution of the winding in both conventional and proposed designs is considered to be similar.

In [13], the effect of different types of the stator winding distribution on electromagnetic forces in a SPIM is considered and a new winding is introduced to reduce electromagnetic forces. This paper considers the stator winding in both conventional and proposed designs to be 4-poles and exactly similar to the winding introduced in [13]. This winding type is a lap. The pitch of the main and auxiliary windings equals 7. The widespread design of the stator winding distribution (main and its auxiliary windings) is shown in Fig. 1.

III. Proposed Design of Squirrel Cage Rotor

The cross-sectional of the conventional and proposed designs of the squirrel cage rotor is shown in Figs. 2 and 3, respectively. In the proposed design the distribution of the centers of rotor bars is located on a sinusoidal function. All other parameters such as dimensions, composition, and geometry of the stator and rotor slots are identical in both motors. Also, the shape and area of the rotor bars are kept constant.

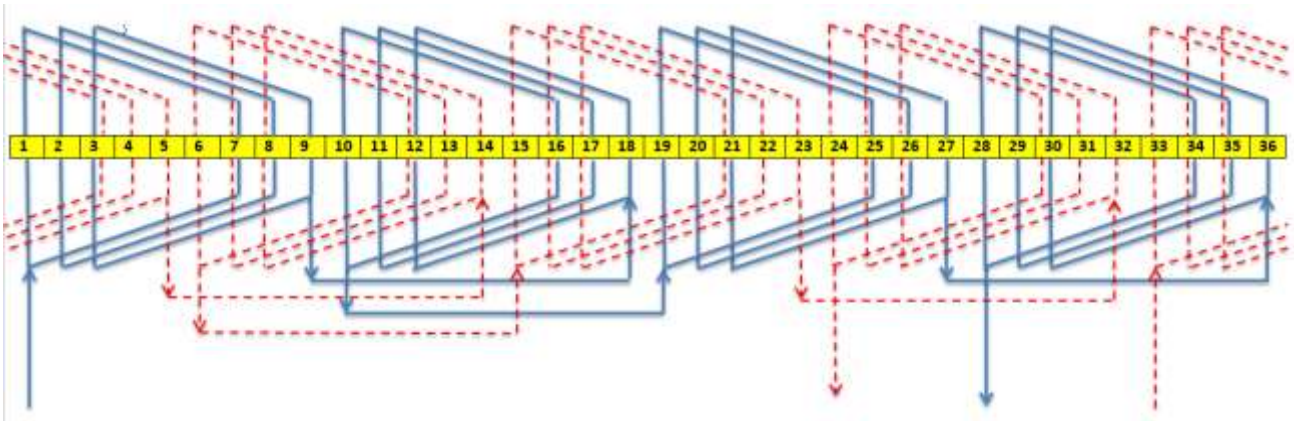

Fig. 1. The widespread design of stator winding: main (solid line) and auxiliary (dashed line) – 4poles [13]

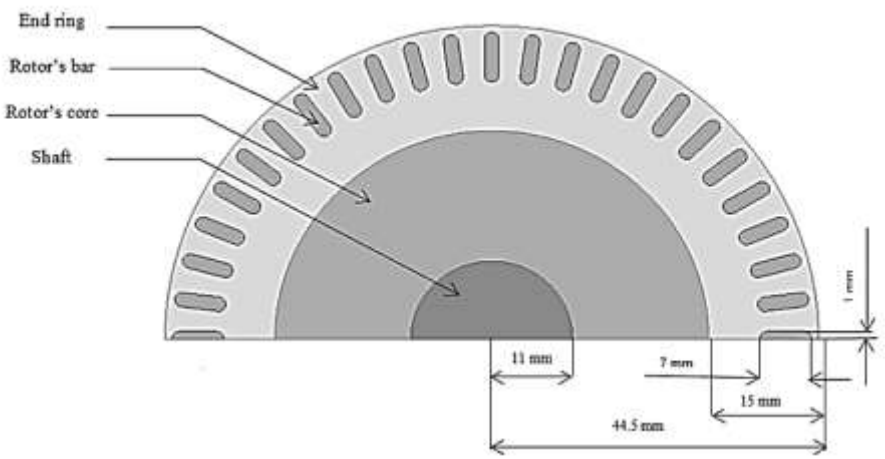

Fig. 2. The cross-sectional of the conventional squirrel-cage rotor

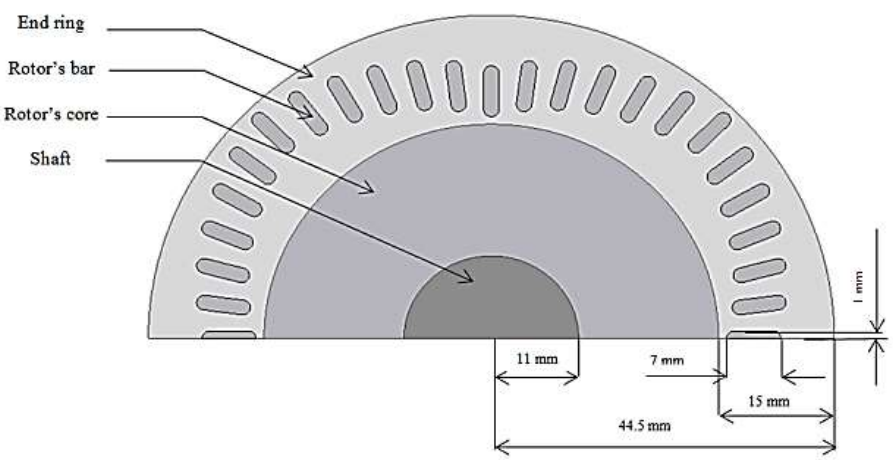

Fig. 3. The cross-sectional of the proposed design of the squirrel cage rotor

IV. Simulation and Results

To evaluate the proposed design and compare it with the conventional design of the squirrel cage rotor, these two designs are simulated in ANSYS Maxwell 2D software. The electrical specifications of the studied single-phase induction motor (run and start capacitor) are presented in Table 1 and its sizing information are according to Table 2. In this

comparison, the stator structure and its winding distribution are the same. Also, the dimensions, geometry, and area of the rotor bars and their core are identical, and the only difference is in the placement of the rotor bars.

TABLE 1
ELECTRICAL SPECIFICATIONS OF THE SINGLE-PHASE INDUCTION MOTOR STUDIED

Parameters	Values
Output power (hp)	0.75
Voltage (V)	220
Phase number	1
Frequency (Hz)	50
Run capacitor (μF)	25
Start capacitor (μF)	160
Pole number	4

TABLE 2
SIZING INFORMATION OF THE SINGLE-PHASE INDUCTION MOTOR STUDIED

Parameters		Values
Stator	Outer diameter (mm)	160.6
	Inner diameter (mm)	89.8
	Length (mm)	66
	Number of slots	36
Air gap(mm)		0.45
Rotor	Outer diameter (mm)	88.9
	Number of bars	48
	Length (mm)	66
	End ring thickness(mm)	5
	End ring height (mm)	15

A. Distribution of Magnetic Field

Figs. 4 and 5 display the magnetic field distribution and flux lines in machines. The curves of the air gap flux density variations in the conventional and proposed designs are shown in Fig. 6. According to these curves, the average variations of flux density amplitude in conventional and proposed designs are 0.43 Tesla and 0.56 Tesla, respectively. Also, the Fast Fourier Transform (FFT) analyses of these waveforms in conventional and proposed models are depicted in Figs. 7 and 8, respectively. Accordingly, the total harmonic distortion (THD) percentages in these designs are 71 and 52, respectively. To investigate the effect of the proposed structure on the air gap field, the effect of the rotor field in the conventional and proposed designs has been independently analyzed. Fig. 9 displays the flux density change curves due to only the rotor field in these designs. According to these curves, the average variations of flux density magnitude in conventional and proposed designs are 0.35 Tesla and 0.41 Tesla, respectively. The FFT of these curves is also shown in Figs. 10 and 11, respectively. Accordingly, the THD percentages in these designs are 83 and 61, respectively. As is seen in these figures, the new placement of rotor bars increases the magnetic field generated by the rotor. As a result, as the magnitude of the air gap magnetic field increases, its distortion decreases.

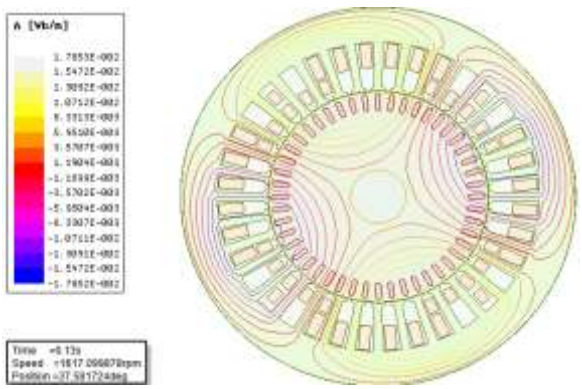

Fig. 4. Magnetic flux distribution in conventional design

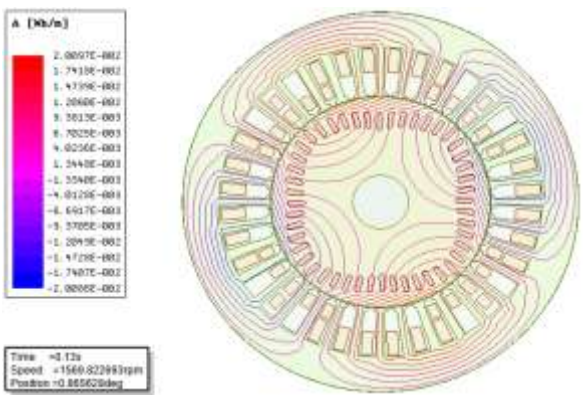

Fig. 5. Magnetic flux distribution and flux lines in proposed design

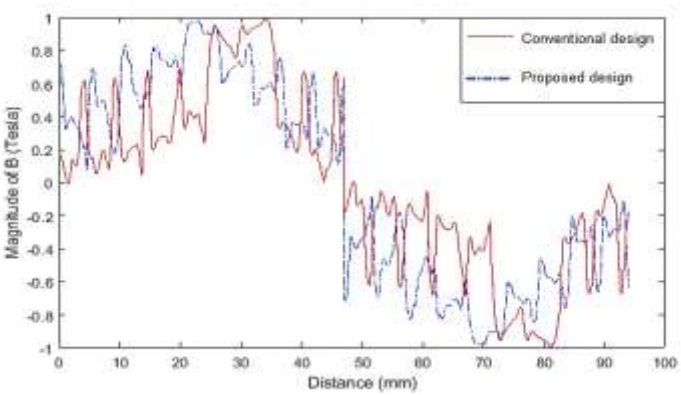

Fig. 6. Air gap flux density curves

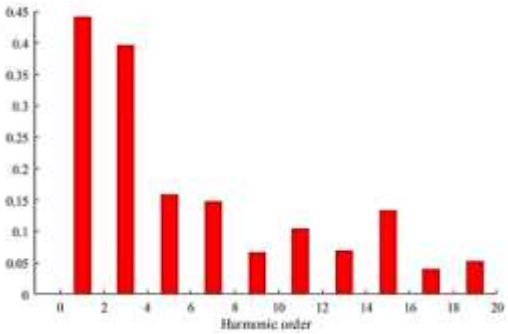

Fig.7. FFT of the air gap flux density in the conventional design

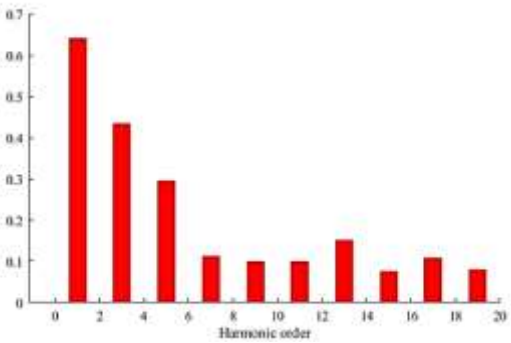

Fig. 8. FFT of the air gap flux density in the proposed design

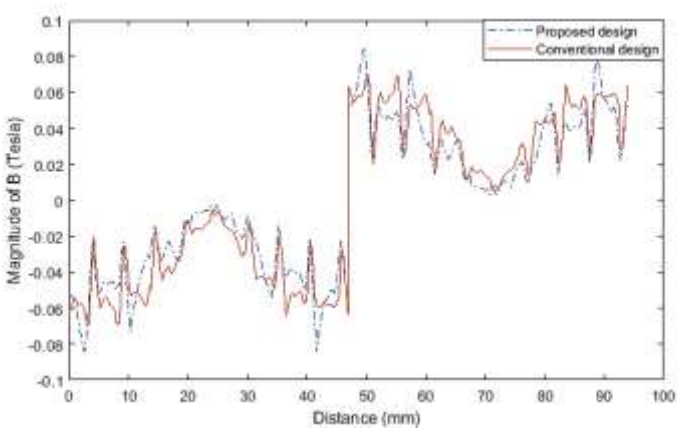

Fig. 9. Rotor field curves

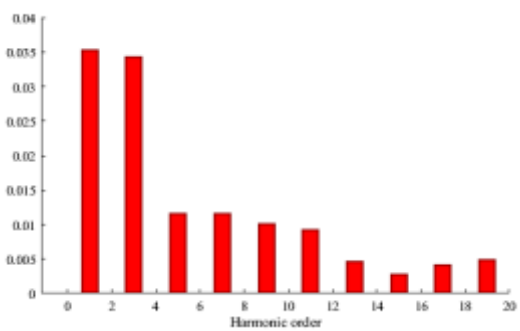

Fig. 10. FFT of the rotor field in the conventional design

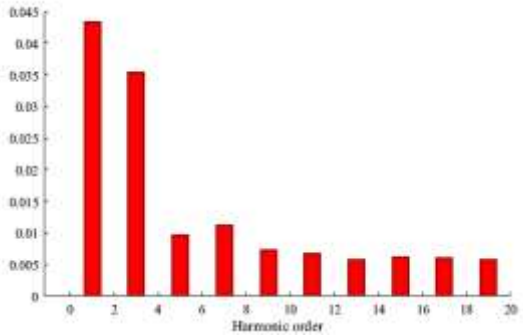

Fig. 11. FFT of the rotor field in the proposed design

B. Electromagnetic Forces in Induction Motor

The harmonics in the magnetic flux in the air gap are the main cause of electromagnetic noise and vibration in electric machines. Recently, reducing noise and vibration in electric machines to improve their performance has been highly regarded by researchers. In general, radial and tangential electromagnetic forces are two major sources of electromagnetic vibration. Radial electromagnetic forces are the main source of electromagnetic noise in electric machines.

Today, with the development of the process of designing and manufacturing electric machines, the harmonic components affecting vibration and noise have been reduced greatly. However, various factors caused by internal/external defects of the motor such as power supply, load, stator core structure, rotor, etc. can cause serious problems that affect the normal performance of the motor [33-35].

Electromagnetic pressure (Maxwell pressure) or in other words electromagnetic forces (Maxwell forces) per unit area (Pm) can be calculated by Eq. (1).

$$P_m(\theta.t) = \frac{b_r^2(\theta.t) - b_t^2(\theta.t)}{2\mu_0} \quad (1)$$

In Eq. (1), θ is the mechanical angular position in degree, t is time, μ_0 is the magnetic permeability in the air gap, $b_r(\theta.t)$ and $b_t(\theta.t)$ 000.00000000000000000…..are the radials the tangential components of flux density in the air gap, respectively. In general, the radial component is much larger than the tangential component, so in most cases, the tangential component is ignored.

C. Analysis of The Dynamic Characteristics

Fig. 12 depicts the curve of the electromagnetic force applied to the rotor and stator cores in the conventional and proposed designs. For example, according to this figure, the mean value of the variation of the electromagnetic force in the conventional and proposed models by a numerical method under loading condition 2 N.m is equal to 4.58 N and 0.59 N,

respectively. Also, the curves of speed, main winding current, and torque are shown in Figs. 13, 14, and 15 respectively.

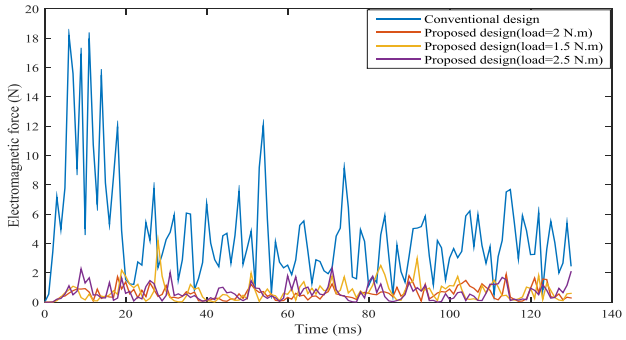

Fig. 12. Electromagnetic force-time curves

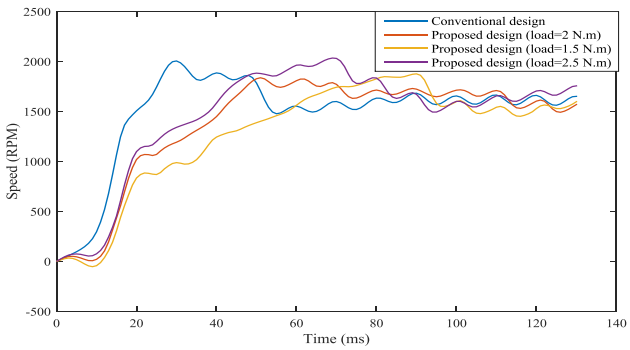

Fig. 13. Speed-time curves

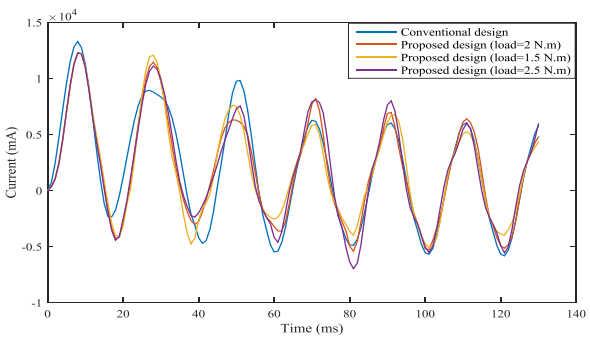

Fig. 14. Main winding current - time curves

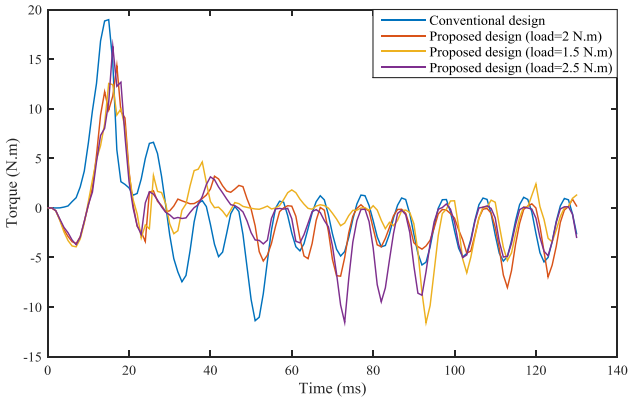

Fig.15. Torque-time curves

Table 3 shows the comparison of losses in two conventional and proposed models under different loading conditions. According to this table, core losses and copper losses under different loading conditions including 100%, 80% and 60% of nominal load have been calculated and compared. The total losses in the proposed design are smaller than the conventional design. This means that the efficiency of the proposed motor has been modified.

TABLE 3
COMPARISON OF LOSSES IN CONVENTIONAL AND PROPOSED DESIGN

Losses / Design	Core loss (W)	Copper loss (W)	Total losses (W)
Conventional (load=1.5 N.m)	12	82	94
Conventional (load=2 N.m)	12	104	114
Conventional (load=2.5 N.m)	12	148	160
Proposed (load=1.5 N.m)	14	64	78
Proposed (load=2 N.m)	14	83	97
Proposed (load=2.5 N.m)	14	120	134

V. Conclusion

In this paper, it was determined that if the position of the rotor bars follows the sinusoidal distribution, the first harmonic component of the air gap magnetic flux will increase and other harmonic components will decrease. Therefore, it can be achieved with less electromagnetic force and noise. Also, the single-phase induction motor will show better behavior in transient operations. The analytical and simulation results by Maxwell software of both simulated models are summarized in Table 4.

TABLE 4
COMPARISON OF PARAMETERS IN CONVENTIONAL AND PROPOSED DESIGN

Motor / Quantity		Conventional design	Proposed design
Stator winding Current (A)	Main	6	5
	Auxiliary	5	4
Winding Resistance (Ω)	Main	3.9	
	Auxiliary	4	
Torque ripple (N.m)		2.50	2.25
The calculated average of Maxwell radial force magnitude by numerical method (N)		4.58	0.59
The calculated average of Maxwell radial force magnitude by analytical method (N)		12.06	2.68
The variations average of flux density amplitude (Tesla)		0.43	0.56
The THD of flux density (%)		71	52
Total copper consumed (gram)		235	

References

[1] Khan, M. A., Khan, F., Rahman, L. U., & Fatima, A. "Analysis and electromagnetic noise suppression of three-phase squirrel cage induction motor", In 2018 International Conference on Computing, Electronic and Electrical Engineering (ICE Cube), pp. 1-5, 2018.

[2] Cho, D. H., & Kim, K. J. "Modelling of electromagnetic excitation forces of small induction motor for vibration and noise analysis", IEE Proceedings-Electric Power Applications, vol. 145, no. 3, pp. 199-205, 1998.

[3] Bendaas, Ismail, and Farid Naceri. "A new method to minimize the chattering phenomenon in sliding mode control based on intelligent control for induction motor drives." Serbian journal of electrical engineering, vol. 10, no. 2, pp. 231-246, 2013.

[4] Nahilia, H., Boudour, M., Cardenas, A., Agbossou, K., & Doumbia, M. L. "Doubly fed induction wind generators model and field orientation vector control design and implementation on FPGA", International Journal of Dynamics and Control, vol. 7, no. 3, pp. 1005-1014, 2019.

[5] Stojić, Đorđe M., and Milić R. Stojić. "Induction motor IFOC based speed-controlled drive with asymptotic disturbance compensation." Serbian Journal of Electrical Engineering, vol. 9, no. 3, pp. 301-314, 2012.

[6] Vamvakari, A., Kandianis, A., Kladas, A., Manias, S., & Tegopoulos, J. "Analysis of supply voltage distortion effects on induction motor operation", IEEE Transactions on Energy Conversion, vol. 16, no. 3, pp. 209-213, 2008.

[7] El Daoudi, S., Lazrak, L., El Ouanjli, N., & Lafkih, M. A. "Improved DTC-SPWM strategy of induction motor by using five-level POD-PWM inverter and MRAS SF estimator", International Journal of Dynamics and Control, vol. 9, no. 2, pp. 448-462, 2021.

[8] Kong, W., Guo, H., Tang, G., & Zhong, Z. "Optimized Non-Sinusoidal Power Supply in High-Power Multiphase Induction Motor Drive Based on Harmonic Parameter Analysis", Journal of Electrical Engineering & Technology, vol. 15, no. 6, pp. 2627-2638, 2020.

[9] Olarinoye, G. A., Yusuf, J., & Jimoh, B. "Improvement of Torque Production in Single-Phase Induction Motors", Nigerian Journal of Technological Development, vol. 14, no. 2, pp. 39-45, 2017.

[10] Nam, H., Jung, S. K., Kang, G. H., Hong, J. P., & Jung, T. U. "Design of pole change single-phase induction motor for household appliances", In 38th IAS Annual Meeting on Conference Record of the Industry Applications Conference, vol. 2, pp. 1126-1133, 2003.

[11] Jung, T. U., Yun, C. H., Cha, H. R., Chae, M. G., & Kim, H. M. "Improved design for driving characteristics in single phase induction motor with concentrated winding", In 2007 IEEE Power Electronics Specialists Conference, pp. 2418-2422, 2007.

[12] Tessarolo, A., Mezzarobba, M., & Contin, A. "A stator winding design with unequally-sized coils for adjusting air-gap space harmonic content of induction machines", In The XIX International Conference on Electrical Machines-ICEM 2010, pp. 1-7, 2010.

[13] Shadfar, H., & Izadfar, H. R. "Improvement of Electromagnetic Forces in a Single-Phase Induction Motor by Providing a New Winding Distribution", Iranian Journal of Electrical and Electronic Engineering, vol. 16, no. 1, pp. 74-84, 2020.

[14] Cassoret, B., Corton, R., Roger, D., & Brudny, J. F. "Magnetic noise reduction of induction machines", IEEE Transactions on power electronics, vol. 18, no. 2, pp. 570-579, 2003.

[15] Sadigh, A. K., & Hagh, M. T. "Elimination of instantaneous backward mmf in single phase induction motors", In 2009 5th IEEE GCC Conference & Exhibition, pp. 1-6, 2009.

[16] Zhong, H., Wang, X., Leng, X., & Wang, D. "A new type single-phase induction motor with negative sequence compensatory winding", In 2007 2nd IEEE Conference on Industrial Electronics and Applications, pp. 82-85, 2007.

[17] Zhong, H., Wang, X., Wang, D., & Qiao, D. "Analysis and design of a new type high-efficiency single-phase induction motor based on negative sequence magnetic field compensation", In 2008 International Conference on Electrical Machines and Systems, pp. 3962-3966, 2008.

[18] Makhetha, E., Muteba, M., & Nicolae, D. V. "Effect of Rotor Bar Shape and Stator Slot Opening on the Performance of Three Phase Squirrel Cage Induction Motors with Broken

Rotor Bars", In 2019 Southern African Universities Power Engineering Conference/Robotics and Mechatronics/Pattern Recognition Association of South Africa (SAUPEC/RobMech/PRASA), pp. 463-468, 2019.
[19] Brojboiu, M. A. R. I. A. "Concerning the influence of the rotor bar geometry on the induction motor performances", In 5th International Conference on Telecommunications in Modern Satellite, Cable and Broadcasting Service. TELSIKS 2001. Proceedings of Papers (Cat. No. 01EX517), Vol. 2, pp. 647-650, 2001.
[20] Kim, Y. S. "Effects of rotor bar shape for squirrel cage induction motor in transient state using moving band technique", IEEE transactions on applied Superconductivity, vol. 24, no. 3, pp. 1-4, 2013.
[21] Iqbal, M. A., & Singh, G. "A review on influence of rotor geometry on the performance of single-phase capacitor-run Induction motor", International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, vol. 3, pp. 10216-10224, 2014.
[22] Kim, B. T., Kim, D. K., Kwon, B. I., & Lipo, T. A. "Optimal skew angle for improving of start-up performance of a single-phase line-start permanent magnet motor", In 2008 IEEE Industry Applications Society Annual Meeting, pp. 1-6, 2008.
[23] Kim, J. H., & Jung, Y. G. "Spreading Power Spectrum of an Induction Motor Drive System by Chaotic Pulse Width Modulation Method", Journal of Electrical Engineering & Technology, pp. 1-10, 2021.
[24] Hekmati, P., Yazdanpanah, R., Monfared, J. M., & Mirsalim, M. "Adjustable capacitor for the single-phase IM performance improvement", In The 5th Annual International Power Electronics, Drive Systems and Technologies Conference (PEDSTC 2014), pp. 7-12, 2014.
[25] Taheri, Asghar, and Amir Ghasemian. "Quantization Noise Reduction Using Random Dither in Direct Torque Control of an Induction Motor." International Journal of Industrial Electronics Control and Optimization, vol. 3, no. 4, pp. 439-445, 2020.
[26] Niaz Azari, Milad, Vasiye Lohrasbi, and Seyed Abdolah Mousavi. "Optimum Design of High-Temperature Superconducting Induction/Synchronous Motor to Increase Torque Density Using Collective Decision Optimization Algorithm." International Journal of Industrial Electronics Control and Optimization, vol. 3, no. 2, pp. 137-145, 2020.
[27] Liu, C., Xu, Y., & Feng, J. "Low Electromagnetic Noise Squirrel Cage Motor Analysis and Optimization of Slot Coordination", MECHANICS, vol. 4, no.1100, pp. 1100, 2015.
[28] Kobayashi, T., Tajima, F., Ito, M., & Shibukawa, S. "Effects of slot combination on acoustic noise from induction motors", IEEE Transactions on Magnetics, vol. 33, no.2, pp. 2101-2104, 1997.
[29] Le Besnerais, J., Lanfranchi, V., Hecquet, M., & Brochet, P. "Optimal slot numbers for magnetic noise reduction in variable-speed induction motors", IEEE Transactions on Magnetics, vol. 45, no. 8, pp. 3131-3136, 2009.
[30] Zhu, H., Zhou, G., Chen, J., & Liu, H. "Analysis and study of skewed slot tooth distance on low electromagnetic noise of three-phase induction motor with squirrel cage rotor", In 2012 Sixth International Conference on Electromagnetic Field Problems and Applications, pp. 1-4, 2012.
[31] Wang, C., Bao, X., Xu, S., Zhou, Y., Xu, W., & Chen, Y. "Analysis of vibration and noise for different skewed slot-type squirrel-cage induction motors", IEEE Transactions on Magnetics, vol. 53, no. 11, pp. 1-6, 2017.
[32] Wang, L., Bao, X., Di, C., & Li, J. "Effects of novel skewed rotor in squirrel-cage induction motor on electromagnetic force", IEEE Transactions on magnetics, vol. 51, no. 11, pp. 1-4, 2015.
[33] Hilgert, T. G., Vandevelde, L., & Melkebeek, J. A. "Numerical analysis of the contribution of magnetic forces and magnetostriction to the vibrations in induction machines", IET Science, Measurement & Technology, vol. 1, no. 1, pp. 21-24, 2007.
[34] Hirotsuka, I., Tsuboi, K., & Ishibashi, F. "Effect of slot-combination on electromagnetic vibration of squirrel-cage induction motor under loaded condition", In Proceedings of Power Conversion Conference-PCC'97, vol. 2, pp. 843-848, 1997.
[35] J. F. Gieras, C. Wang, and J. C. Lai, "Noise of polyphase electric motors",Boca Raton, FL: CRC Press, 2005.

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