Yuzuncu Yil University
Journal of the Institute of Natural & Applied Sciences

https://dergipark.org.tr/en/pub/yyufbed

Research Article

Performance and Harmonic Analysis of a Three-Phase Induction Motor with Various Coil Pitch Configurations

Atilla DÖNÜK*[1], Osamah AL-DORI[2]

[1] Aydın Adnan Menderes University, Engineering Faculty, Electrical and Electronics Department, Aydın, Turkey
[2] Gaziantep University, Engineering Faculty, Electrical and Electronics Department, Gaziantep, Turkey
Atilla DÖNÜK, ORCID No: 0000-0001-9468-8456, Osamah AL-DORI, ORCID No: 0000-0002-3295-4218
*Corresponding author e-mail: adonuk@adu.edu.tr

Article Info

Received: 18.04.2022
Accepted: 07.09.2022
Online April 2023

DOI:10.53433/yyufbed.1105237

Keywords
Coil pitch,
Finite element analysis,
Harmonics,
Induction motor,
Stator winding

Abstract: In this work, analyses of the effect of full-, under-, and over-pitched stator winding configurations on the efficiency, output power, torque characteristics, and current and voltage harmonic components are carried out on a three-phase, squirrel cage induction motor. Performance analyses have been performed both via Ansys/RMxprt and Maxwell/2D software by modelling the stator winding with coil pitches of 100°, 120°, 140°, 160°, 180°, 200°, 220°, 240°, and 260°. Current and voltage harmonics analyses have been performed in Matlab using the data obtained from Maxwell/2D simulations. Maxwell/2D results showed that the maximum efficiency is attained at 200° over-pitched configuration, which is 0.73% higher than the efficiency when the motor is full-pitched. The maximum output power and torque are attained at 240° over-pitched configuration, which is 7.96% and 7.45% more than the power and torque obtained when the motor is full-pitched, respectively. Harmonic analysis results showed that both under-pitched and over-pitched coils can be used to eliminate harmonics in the current and voltage waveforms. However, over-pitched coils performed better in eliminating the phase current harmonics. The minimum total harmonic distortion (THD) of the phase current and induced voltage are reached at 260° over-pitched and 120° under-pitched configurations, which is 52.39% and 74.36% lower than the THD when the motor is full-pitched, respectively. Over-pitched coils provide slightly higher efficiency, output power, and torque than the under-pitched coils. There is no unique coil pitch configuration to eliminate all harmonic components. Therefore, in order to eliminate a specific harmonic component, a specific coil-pitch must be applied.

Üç Fazlı Bir Asenkron Motorun Çeşitli Bobin Adım Biçimi ile Performans ve Harmonik Analizi

Makale Bilgileri

Geliş: 18.04.2022
Kabul: 07.09.2022
Online Nisan 2023

DOI:10.53433/yyufbed.1105237

Anahtar Kelimeler
Asenkron motor,
Harmonik,
Sargı adımı,

Öz: Bu çalışmada üç-fazlı sincap kafesli bir asenkron motorun akım ve gerilim harmonikleri ile verim, çıkış gücü ve tork karakteristikleri sinüzoidal uyartım altında stator sargısında tam ve kesirli farklı sargı adımları kullanılarak sonlu elemanlar yöntemi ile incelenmiştir. Stator sargısı, Ansys/RMxprt ve Maxwell/2D yazılımı kullanılarak 100°, 120°, 140°, 160°, 180°, 200°, 220°, 240° ve 260° sargı adımları ile modellenmiş ve performans analizleri gerçekleştirilmiştir. Akım ve gerilim harmonik analizleri Maxwell/2D benzetim verilerinin Matlab ortamında işlenmesi ile elde edilmiştir. Maxwell/2D sonuçları maksimum verimin 200° yüksek adımlı konfigürasyonun tam sargı adımına göre %0.73 daha yüksek olduğunu göstermiştir. Maksimum çıkış gücü ve tork değerleri 240° yüksek adımlı konfigürasyon için tam sargı adımına göre sırasıyla

Sonlu elemanlar yöntemi, Stator sargısı

%7.96 ve %7.45 daha yüksek gerçekleşmiştir. Sonuçlar hem düşük hem de yüksek adımlı kesirli sargıların akım ve gerilim dalga şekillerindeki harmonik eliminasyonu için kullanılabileceğini göstermiştir. Ancak, yüksek adımlı sargılar faz akımı harmoniklerini bastırmada daha iyi sonuç vermiştir. Faz akımı ve endüklenen gerilim THD değerleri, 260° yüksek adımlı ve 120° düşük adımlı konfigürasyonlar için tam sargı adımına göre sırasıyla %52.39 ve %74.6 daha düşük elde edilmiştir. Yüksek adımlı sargılar, az farkla da olsa, düşük adımlı sargılara göre daha yüksek verim, çıkış gücü ve tork sunmaktadır. Tüm harmonik bileşenleri ortadan kaldırmak için tek bir sargı adımı konfigürasyonunun olmadığı anlaşılmıştır. Bu nedenle, spesifik bir harmonik bileşeni ortadan kaldırmak için özel bir sargı adımı uygulanmalıdır.

1. Introduction

Harmonic components of the air-gap flux density in an AC machine cause the stator voltage and current to be distorted and to have a non-sinusoidal shape. Several techniques have been developed to suppress these undesired harmonic components in the output voltages and currents of a machine. One of the well-known techniques is the use of fractional-pitch windings (Chapman, 2012).

In general, a distributed double-layer winding, where the coil sides belonging to the same phase occupy more than a single slot, is used in three-phase AC machines. The coil sides are distributed along the periphery in several slots. One coil side is placed at the bottom of a slot and the other coil side is placed at the top of another slot. The stator region corresponding to a phase over π electrical angle is known as the phase-belt. A pole-pitch, which is always π electrical degrees, is defined as the electrical angle between the corresponding points of successive poles. The electrical angle between the sides of a coil is called coil-pitch. If the coil-pitch is equal to the pole-pitch, it is a full-pitched coil. If the coil-pitch is less than π electrical degrees, it is an under-pitched coil, and if the coil-pitch is higher than π electrical degrees, it is an over-pitched coil (Fitzgerald et al., 2013).

The per-phase generated voltage can be calculated by (1) (Chapman, 2012; Fitzgerald et al., 2013), where k_w is the winding factor, N_{ph} is the number of series turns per-phase, $\emptyset$ is the flux, and f is the frequency.

$$E = \sqrt{2}\pi k_w f N_{ph} \emptyset \tag{1}$$

The winding factor (k_w), is the multiplication of the distribution factor (k_d) and the pitch (or chording) factor (k_p). Distribution and pitch factors are calculated as in (2) (Chapman, 2012; Fitzgerald et al., 2013), where n is the harmonic number, q is the number of slots per phase-belt, α is the slot angle, and λ is the coil-pitch.

$$\begin{gathered} k_d = \frac{\sin\left(qn\ \frac{\alpha}{2}\right)}{q \sin\left(n\ \frac{\alpha}{2}\right)} \\ k_p = \sin\left(\frac{n\lambda}{2}\right) \\ k_w = k_d\ k_p \end{gathered} \tag{2}$$

As seen from equations (1) and (2), harmonic components in the voltage can be eliminated by proper choice of coil-pitch, in other words, by using fractional-pitched windings.

Motor harmonics reduction research has been widely adopted due to the harmful effects of harmonics. In (Karnavar & Jisha, 2020), a control technique is developed with the objective of reducing brushless DC motors current harmonics. An algorithm for minimizing the overall harmonic distortion of the air-gap MMF of single- and double-layer three-phase windings is presented in (Silva et al., 2018). The algorithm is based on choosing the optimal combination of turns per coil. In (Lu et al., 2015), harmonic compensation technique, which is based on harmonic voltage injection, has been proposed in order to achieve stable operation of permanent magnet synchronous motor without torque ripple caused by flux/current harmonics. Using the high-precision harmonic detection approach, (Liu et al., 2018) presented a selective current harmonic suppression strategy for high-speed permanent magnet synchronous motors.

One of the widely used methods for harmonics suppression of induction motors is using fractional-pitched windings. Low-order odd harmonic voltage component and efficiency at different loads for four different pitched pulse-width modulation (PWM) inverter-fed induction motors are experimentally tested at different loads in (R. Deshmukh et al., 2006b), and the total harmonic distortion (THD) due to 3rd, 5th, and 9th harmonics is found to be less with a coil-pitch of 160° and the efficiency is increased by 7.5% with a coil-pitch of 120°. However, the results for sinusoidal voltage supply have not been reported. Design criteria for stator winding coil-pitch decision in AC inverter-fed multi-phase motors are discussed in (Tessarolo, 2008). Moreover, the effects of coil-pitch on motor dimensioning, motor overload capability, commutation transients, and harmonic reactance are investigated analytically and Finite Element Analysis (FEA) has been performed to test the harmonic inductance calculated by the proposed analytical approach. Design and testing of the stator winding configuration of three-phase induction motors with various coil pitches (180°, 160°, 140°, and 120°) under sinusoidal and PWM supplies are investigated experimentally in (R. R. R. Deshmukh, 2006). However, investigation for over-pitched windings has not been reported. A 12-pole, three-phase, squirrel cage induction motor is designed with full-pitched and under-pitched coils and THD analysis for phase current has been performed by FEA in (Srinivasan et al., 2016). It has been found that the under-pitch configuration reduces the phase current THD by around 3.9%. However, the analysis contains only one under-pitched coil case and does not include over-pitched coils. The performance analysis of squirrel-cage induction motor for electric vehicle applications with different stator coil pitches is studied experimentally and by 2D FEA in (Gundogdu et al., 2020). The coil pitch is changed by changing the stator slot number, layers, and winding topology. However, this study keeps the stator and rotor slot number along with the number of poles unchanged and investigates the optimal coil pitch for minimum THD and maximum performance. In (Hua et al., 2018), harmonic analysis of the induced voltage has been performed on flux-reversal permanent magnet machines with different coil pitches using analytical expression and 2D FEA. It has been found that the optimal coil pitch can enhance the winding factor, which in turn enhances the fundamental induced voltage. In (Birbir & Nogay, 2007), harmonic analysis of the voltage and current has been performed for 1100W, 36-slot, three-phase, four-pole squirrel cage induction motors with full-pitch and different under-pitch configurations of the stator windings. The analysis has been carried out experimentally and the motors are supplied both using sinusoidal PWM inverter and sinusoidal voltage excitation. In (R. Deshmukh et al., 2006a), harmonic analysis of the voltage has been performed for three-phase, 746 W, four-pole squirrel cage induction motors with full-pitch and under-pitch stator windings configurations. The analysis has been carried out experimentally and the motors are supplied using sinusoidal PWM inverter and sinusoidal voltage excitation. A double layer short-pitched asymmetric winding arrangement with prefabricated coils is proposed by (Di et al., 2019) to mitigate the solid-rotor losses of induction machines. Effect of the distributed fractional-pitched winding (one-layer, two-layer and three-layer) on the electromagnetic performance of a three-phase HTS induction motor has been analyzed by (Arish & Yaghobi, 2021) via ANSYS-Maxwell software using FEM method. In (Deshmukh et al., 2020), the effect of under-pitching the stator windings on the efficiency of a PWM inverter fed three-phase induction motor is investigated with various switching frequencies, where it has been found out the under-pitched stator winding provided higher efficiency. In (Li et al., 2022), experimental and FEA have been carried out on four reluctance motors with the same slot and pole number but with different layers and coil pitches in order to verify the unity of the proposed vector model. However, in the studies mentioned above, the stator windings have not been configured as over-pitched.

In this work, we take a step further to existing literature examples in investigating motor efficiency, output power, torque, and current and voltage harmonics by configuring the stator coil pitch not just as full- and under-pitch, but also as over-pitch. Nine finite element models of 5.5 kW, three-phase, squirrel cage induction motor are carried out to perform FEA with sinusoidal excitation. The investigated coil pitches are; 100°, 120°, 140°, 160°, 180°, 200°, 220°, 240°, and 260°.

2. Motor Specifications

Since this study aims to compare the performance of the motor with different stator coil pitches, a motor design was not performed from scratch, instead, the parameters of the designed motor in (Yetgin et al., 2019) were used for analysis. The general data of the motor under consideration are given in Table 1.

Table 1. Motor specifications

Output power (W)	5500
Rated voltage (V)	460
Frequency (Hz)	60
Synchronous speed (rpm)	1800
Operation speed (rpm)	1750
Winding connection	Y
Number of poles	4
Number of phases	3
Type of load	Constant power
Operating temperature (°C)	75
Number of turns per phase	192

By using the data in Table 1, q, α, λ, and other parameters can be calculated as given in (3).

$$\frac{slots}{pole} = \frac{36}{4} = 9 \text{ slots per-pole}$$
$$q = \frac{9}{3} = 3 \tag{3}$$
$$\alpha = \frac{180}{9} = 20^{\circ}$$

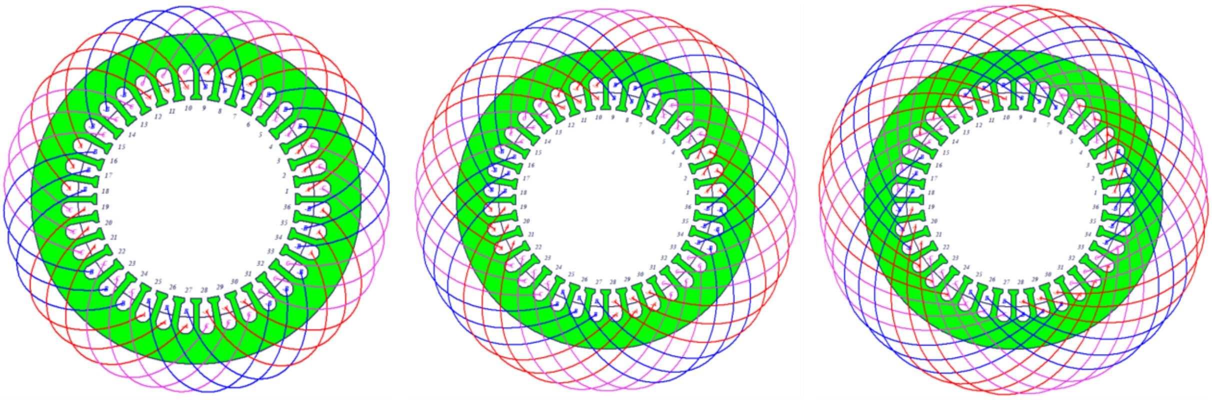
A coil pitch of 180° corresponds to full-pitched, 100°, 120°, 140°, 160° to under-pitched, and 200°, 220°, 240°, 260° to over-pitched windings, respectively.

3. Modeling for FEA

Several motors, each with a different coil pitch, have been modeled in Ansys/RMxprt software to observe efficiency, output power, and torque characteristics. Motor data for FEA are given in Table 2.

Table 2. Motor data for FEA

Number of stator slots	36
Stator outer diameter (mm)	180
Stator inner diameter (mm)	111.6
Stator core length (mm)	131.5
Stator stacking factor	0.92
Type of steel	M19_24G
Number of parallel branches	1
Number of conductors per slot	32
Winding layer	Double
Rotor type	Squirrel cage with cast aluminum bars
Number of rotor slots	28
Air-gap (mm)	0.175
Rotor inner diameter (mm)	35
Rotor length (mm)	131.5
Rotor stacking factor	0.92
Type of steel	M19_24G

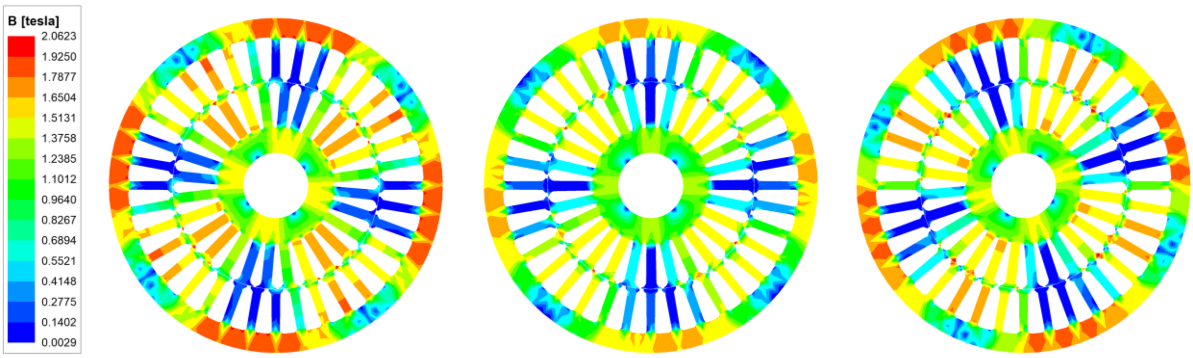


(a) (b) (c)

Figure 1. Slot and winding configurations for (a) 120°, (b) 180°, (c) 240° coil spans.

Figure 1 shows slot and winding configurations for 120° (under-pitched), 180° (full-pitched), and 240° (over-pitched) coil spans. The same sinusoidal excitation has been applied for each configuration.

In the second phase of the analysis, a 2D finite element model of each configuration is generated in Ansys/Maxwell to obtain the induced voltage and current waveforms. The models are simulated using the transient solution with the laminated structure of the stator and rotor being neglected. The obtained waveform data are then exported and the graphs for harmonic analysis are plotted by FFT analysis in Matlab. Maxwell 2D model with the plot of magnetic flux distributions for 120° (under-pitched), 180° (full-pitched), and 240° (over-pitched) coil spans are given in Figure 2. It can be recognized that there is no significant variation between the three configurations, however, the 240° over-pitched one provided slightly higher values of stator and rotor flux densities.



(a) (b) (c)

Figure 2. Magnetic flux distributions for (a) 120°, (b) 180°, (c) 240° coil spans.

4. Results and Discussion

The variation of efficiency, output power, and torque with rotational speed obtained by RMxprt analysis for each coil pitch configuration are shown in Figure 3. Comparison between the latter performance parameters obtained using RMxprt and Maxwell/2D is shown in Figure 4. The error between the two solutions is found to be negligible, especially in the power and torque results.

Simulation results show that the highest efficiency rate is reached for full-pitched and 160° under-pitched coils and the lowest efficiency rate is reached for 100° under-pitched coil. The output power and hence the torque is observed to be the highest for the 100° under-pitched coil and to be the lowest for the full-pitched coil. In general, in terms of efficiency, power, and torque the motor performed better with under-pitched coils than with over-pitched coils at the same coil span.

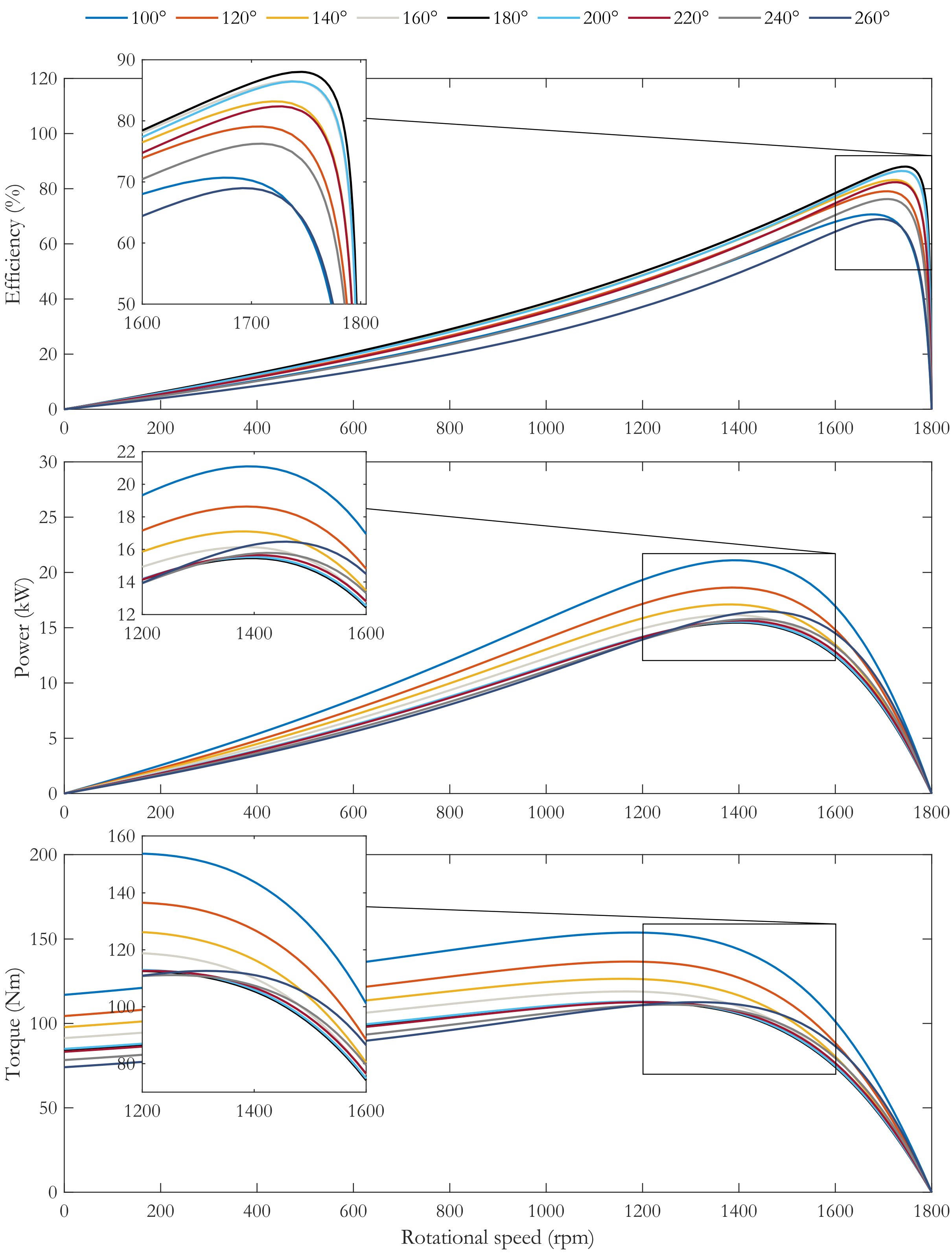


Figure 3. Efficiency, output power, and torque variation with motor rotational speed.

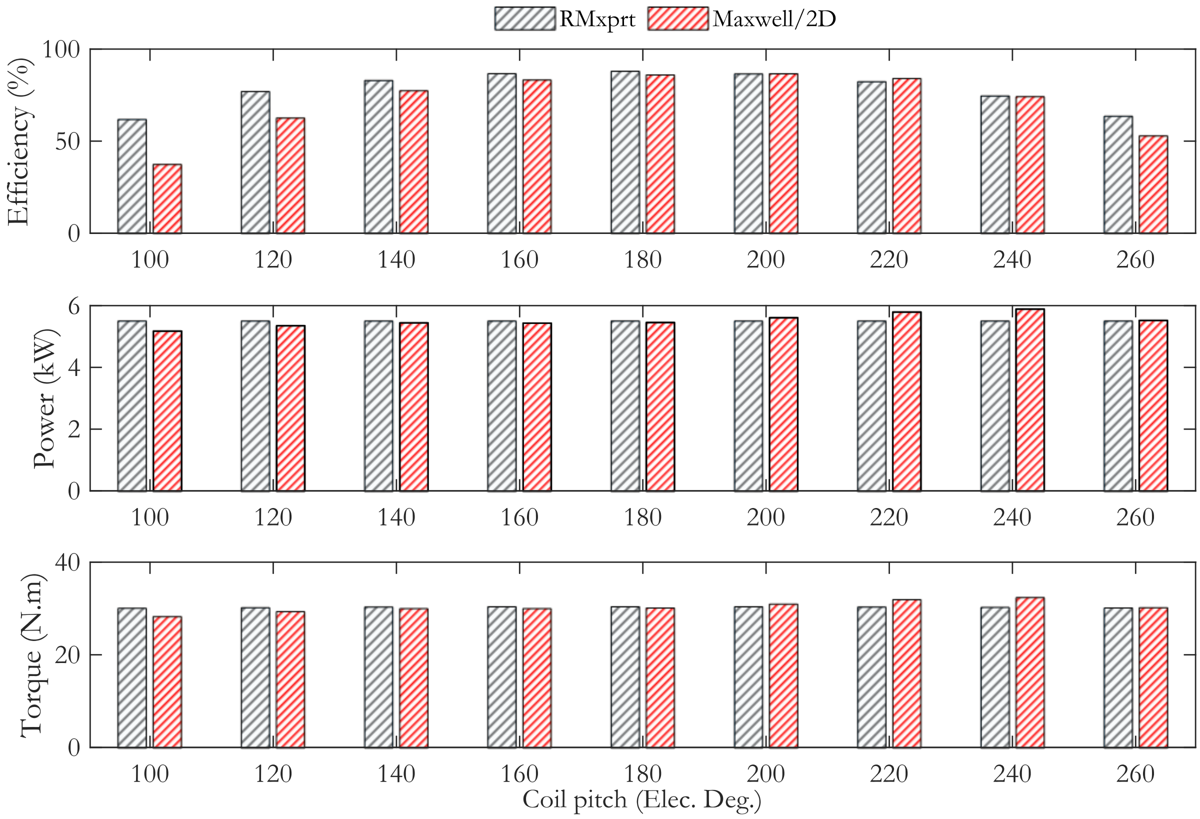


Figure 4. Efficiency, output power, and torque results obtained using RMxprt and Maxwell/2D.

The phase current and induced voltage waveforms for all pitch configurations are shown in Figure 5. Harmonic components in these waveforms are investigated and current and voltage results are shown in Figures 6 and 7, respectively.

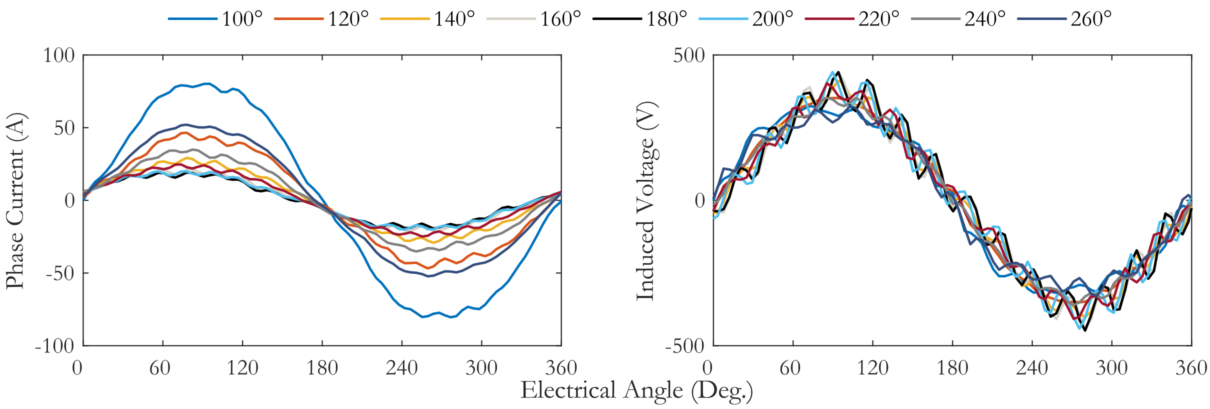


Figure 5. Motor Phase-A current and induced voltage waveforms.

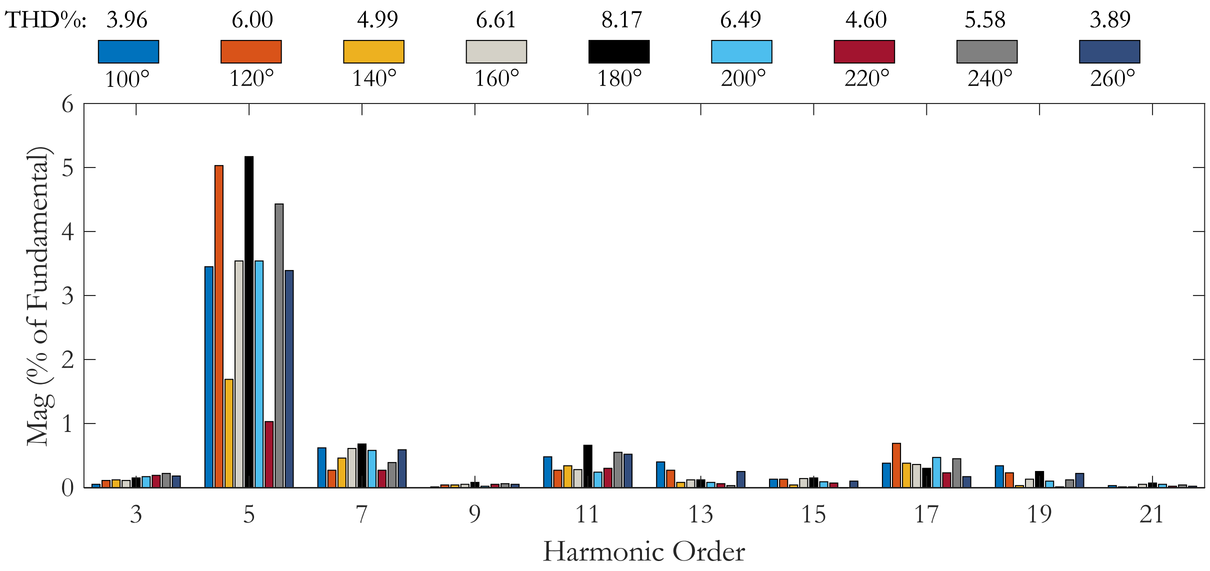


Figure 6. Phase current harmonic components.

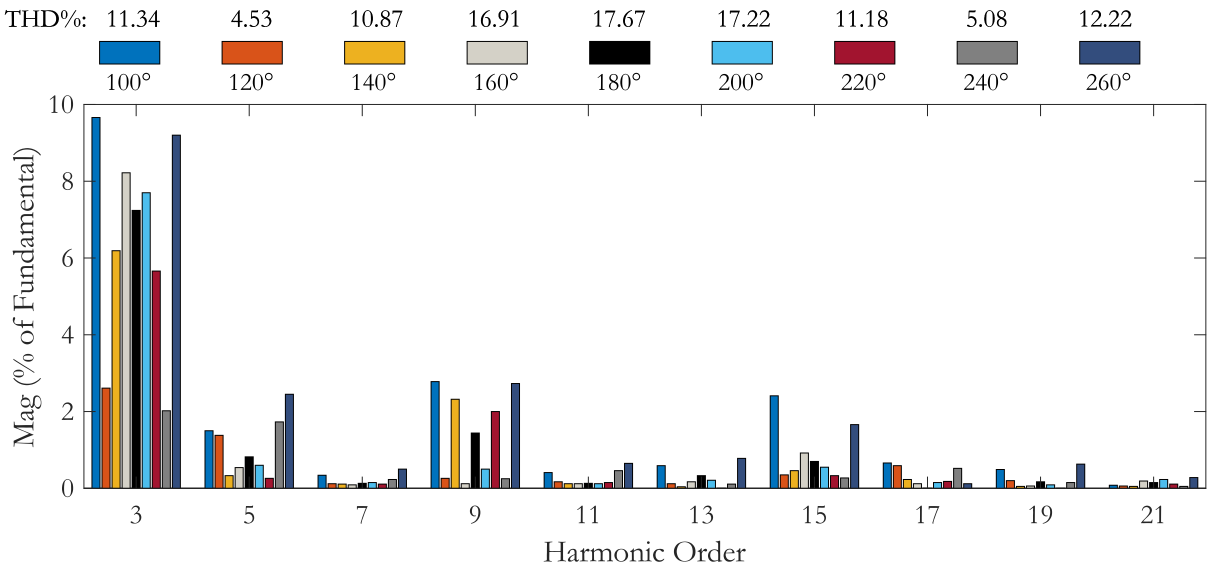


Figure 7. Induced phase voltage harmonic components.

Odd harmonics up to 21st have been considered for the FFT analysis. The triplen harmonics for all winding configurations were found to be very small. The most significant harmonic component in the current waveform is observed to be the 5th harmonic. For all under and over-pitched coils 5th harmonic reduction was achieved, where the reduction for 220° was the most significant. Over-pitched coils performed better in reducing both 5th and 7th harmonic. In the current waveform, 220° over-pitched coil seemed to be the best configuration for reducing almost all the harmonic components. Reduction rate in 5th harmonic was much higher than the others for all coil-pitch configurations. Only 220° and 260° over-pitched coils performed a decrease in 17th harmonic.

Same odd harmonics as in the current waveform have been considered for the induced voltage FFT analysis. The triplen harmonics, except 21st, were found to be high for all coil-pitch configurations, with the 3rd harmonic being the most significant. For 140° and 120° under-pitched, and 220° and 240° over-pitched coils, 3rd harmonic reduction was achieved. Over-pitched coils performed better than the under-pitched ones in terms of 3rd harmonic reduction. Although there exists a significant reduction in the 3rd harmonic with 120° under-pitched and 240° over-pitched coils, it is not zero as theoretically expected. Reduction in the 5th harmonic has been satisfied for 160° and 140° under-pitched, and 200° and 220° over-pitched coils, with the 220° pitched coil resulting in the highest reduction. The 7th harmonic was reduced with the 160°, 140°, and 120° under-pitched, and 220° over-pitched coils. When it came to 7th harmonic reduction, under-pitched coils performed better than the over-pitched coils. The most significant decrease in 9th harmonic was caused by 160° under-pitched coil. Neither under-pitched nor over-pitched coils caused a notable reduction in the 11th harmonic. The 13th and 19th harmonic reduction is achieved by almost all the under-pitched and over-pitched coils (excluding 100° and 260°). For 140° and 120° under-pitched, and 200°, 220°, and 240° over-pitched coils, 15th harmonic component is reduced. All under and over-pitched coils cause 17th harmonic to increase. Whilst 100°, 120°, and 140° under-pitched, and 200° and 220° over-pitched coils reduced the 21st harmonic.

5. Conclusion

The harmonic reduction in the current and voltage waveforms of induction motors is mostly achieved and reported by applying under-pitched fractional coils in the literature. Results of this study reveal that both under-pitched and over-pitched coils are capable of harmonic reduction under sinusoidal excitation. However, it should be taken into account that this is valid to some extent. According to the Maxwell/2D results, the maximum efficiency is achieved at 200° over-pitched configuration, which is 0.73% higher than the efficiency when the motor is full-pitched. The maximum output power and torque are achieved at 240° over-pitched configuration. Power and torque values are 7.96% and 7.45% higher than the values when the motor is full-pitched. The minimum THD of the phase current and induced voltage is achieved at 260° over-pitched and 120° under-pitched configurations, respectively. Phase current and induced voltage THD values are 52.39% and 74.36% lower than the THD values when the motor is full-pitched. It is found that there is no unique coil pitch configuration to eliminate all harmonic components. Therefore, in order to eliminate a specific harmonic component, a specific coil-pitch must be applied. The results reported in this work were obtained by simulations and only for full-load condition and sinusoidal voltage excitation. Therefore, comparing the results with the experimental ones and performing the analyses for different loading conditions with both sinusoidal and PWM excitation may be subject of future work.

References

Arish, N., & Yaghobi, H. (2021). *Effect of winding arrangement on the electromagnetic performance of HTS squirrel cage induction motor*. 2021 29th Iranian Conference on Electrical Engineering (ICEE), Theran, Iran. doi:10.1109/ICEE52715.2021.9544360

Birbir, Y., & Nogay, H. S. (2007). Voltage and current harmonic variations in three-phase induction motors with different stator coil pitches. *International Journal of Energy*, 1(4).

Chapman, S. J. (2012). Electric machinery fundamentals (5th Ed.). New York, USA: Mcgraw-Hill.

Deshmukh, R., Moses, A. J., & Anayi, F. (2006a). Behavior of three-phase induction motors with variable stator coil winding pitch. *Journal of Applied Physics*, 99(8), 08R310. doi:10.1063/1.2170062

Deshmukh, R., Moses, A. J., & Anayi, F. (2006b). Voltage harmonic variation in three-phase induction motors with different coil pitches. *Journal of Magnetism and Magnetic Materials*, 304(2), e810–e812. doi:10.1016/j.jmmm.2006.03.005

Deshmukh, R. R. R. (2006). *Voltage Harmonics Analysis and Efficiency of Three-phase Induction Motor with Change in Coil Pitch of the Stator Winding*. UK: Cardiff University.

Deshmukh, R., Kumar, K. S., Joshi, P., & Subrahmanyam, K. (2020). Effect of chording on the efficiency of induction motor supplied by PWM inverter. *IOP Conference Series: Materials Science and Engineering*, 981(4), 42058. doi:10.1088/1757-899X/981/4/042058

Di, C., Petrov, I., & Pyrhönen, J. J. (2019). Design of a high-speed solid-rotor induction machine with an asymmetric winding and suppression of the current unbalance by special coil arrangements. *IEEE Access*, 7, 83175-83186. doi:10.1109/ACCESS.2019.2925131

Fitzgerald, A. E., Kingsley, C., & Umans, S. D. (2013). Electric machinery (6th Ed.). New York, USA: Mcgraw-Hill.

Gundogdu, T., Zhu, Z., & Mipo, J. (2020). Analysis of coil pitch in induction machines for electric vehicle applications. *IET Electric Power Applications*, 14(12), 2525–2536. doi:10.1049/iet-epa.2019.0980

Hua, W., Zhu, X., & Wu, Z. (2018). Influence of coil pitch and stator-slot/rotor-pole combination on back EMF harmonics in flux-reversal permanent magnet machines. *IEEE Transactions on Energy Conversion*, 33(3), 1330–1341. doi:10.1109/TEC.2018.2795000

Karnavar, P. H., & Jisha, V. R. (2020). *Harmonic reduction and performance improvement of BLDC motor using a selective harmonic elimination PWM based controller*. 2020 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), Jaipur, India. doi:10.1109/PEDES49360.2020.9379727

Li, A., Jiang, D., Sun, J., Liu, Z., & Lee, C. H. T. (2022). Unified vector torque control for reluctance motor with different coil pitch. *IEEE Transactions on Industrial Electronics*, 70(6), 5527-5536. doi:10.1109/TIE.2022.3192600

Liu, G., Chen, B., Wang, K., & Song, X. (2018). Selective current harmonic suppression for high-speed PMSM based on high-precision harmonic detection method. *IEEE Transactions on Industrial Informatics*, 15(6), 3457–3468. doi:10.1109/TII.2018.2873652

Lu, J., Yang, J., & Ma, Y. (2015). *Research on harmonic compensation for flux and current of permanent magnet synchronous motor*. 2015 IEEE International Conference on Advanced Intelligent Mechatronics (AIM), Busan, Korea (South). doi:10.1109/AIM.2015.7222600

Silva, A. M., Ferreira, F. J. T. E., Falcão, G., & Rodrigues, M. (2018). *Novel method to minimize the air-gap MMF spatial harmonic content in three-phase windings*. 2018 XIII International Conference on Electrical Machines (ICEM), Alexandroupoli, Greece. doi:10.1109/ICELMACH.2018.8507206

Srinivasan, J., Selvaraj, K., Chitrarasu, J., & Resmi, R. (2016). *Design and analysis of squirrel cage induction motor in short pitch and full pitch winding configurations using FEA*. 2016 International Conference on Emerging Technological Trends (ICETT), Kollam, India. doi:10.1109/ICETT.2016.7873759

Tessarolo, A. (2008). *Design criteria for stator winding coil pitch choice in AC inverter-fed multi-phase motors.* 4th IET International Conference on Power Electronics, Machines and Drives (PEMD 2008), York. doi:10.1049/cp:20080610

Yetgin, A. G., Turan, M., Cevher, B., Çanakoğlu, A. İ., & Ayhan, G. Ü. N. (2019). Squirrel cage induction motor design and the effect of specific magnetic and electrical loading coefficient. *International Journal of Applied Mathematics Electronics and Computers*, 7(1), 1-8. doi:10.18100/ijamec.461795