EVOLUTION IN ELECTRICAL AND ELECTRONIC ENGINEERING
e-ISSN: 2756-8458

EEEE

Vol. 5 No. 2 (2024) 262-269
https://publisher.uthm.edu.my/periodicals/index.php/eeee

Optimal Performance of Pole Number Combination in Permanent Magnet Motor

Muhammad Farid Shamsul Kahar[1], Roziah Aziz[1]*

[1] *Department of Electrical Engineering, Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, MALAYSIA*

*Corresponding Author: roziah@uthm.edu.my
DOI: https://doi.org/10.30880/eeee.2024.05.02.032

Article Info

Received: 30 June 2024
Accepted: 3 September 2024
Available online: 30 October 2024

Keywords

Permanent Magnet Synchronous Motor (PMSM), Motor performance, Pole number, Efficiency, 2D FEA, JMAG Designer

Abstract

Permanent magnet synchronous motors (PMSMs) demonstrate great efficiency, power density, and torque-to-weight ratio in the dynamic sector of electrical machines. On the other hand, the number of rotor poles in a permanent magnet motor significantly affects its performance, including torque, speed, efficiency, and power density. As a result, the purpose of this project is to improve the PMSM's performance by changing the arrangement of pole numbers. In this research, the JMAG programme is used to design the rotor, permanent magnet, stator, and armature coil as a 2D finite element using JMAG Designer. The development and evaluation of three designs with different pole numbers were observed and determined using effective design and coil test analysis, as well as testing for performance under no load and load situations. The operating principles of all three designs have been examined and the operating principle of each design with varied pole numbers was identified.

1. Introduction

Permanent magnet (PM) motors are renowned for their efficiency, power density, and torque-to-weight ratio in electrical machines. They are widely used in electric cars and robots due to their performance. The number of poles in the motor is a crucial design feature that releases their full power [1]. The complex connection between pole number and PM motor function is determined by various factors. Higher pole numbers produce stronger torque, which can manage bigger loads but limits their capacity to work at high revolutions per minute and requires more speed. Lower pole numbers support faster speeds but may struggle to provide enough torque for demanding applications [2]. The relationship between cogging torque and pole number is crucial in applications requiring quiet, smooth functioning. The stator's slot count also complicates the search for the ideal pole number selection, affecting variables like winding factor and torque density [1].

The number of rotor poles in a PM motor has a significant impact on its performance, including its torque, speed, efficiency, and power density. However, there is no one-size-fits-all solution, as the optimal number of poles will vary depending on the specific requirements of the application. It can be difficult to choose the optimal number of poles for a PM motor when there are constraints on size and weight. Researchers studied at how the number of poles affected the efficiency of Permanent Magnet Synchronous Motor (PMSM) which are utilized in electric cars. It is found that a PMSM with more poles had better torque, lower synchronous speed, and higher efficiency, according to the researchers' data. Researchers also studied the application of pole-changing permanent magnet motors in electric cars. Pole-changing PM motors have the ability to vary their pole number while operating. In comparison to conventional PMSMs, the researchers discovered that pole-changing PM motors can provide a variety of benefits, such as increased efficiency, less torque ripple, and decreased cogging torque.

Evolution in Electrical and Electronic Engineering Vol. 5 No. 2 (2024) p. 262-269

Thus, the goal of this project is to optimize the permanent magnet motor's performance by varying the combination of pole numbers.

2. Literature Review

2.1 Electrical Motor

Electric motors, responsible for 70% of electrical demand in the sector, generate force through magnetic fields and current-carrying conductors, used in power tools, blowers, pumps, and industrial fans [3]. Electric motors are divided into AC and DC types. AC motors use alternating current from wall outlets, while DC motors require direct current, like a battery. A rectifier converts AC current to DC current. DC motors, consisting of an armature and a rotor, are used for smooth acceleration across a wide speed range and high torque starting [4].

2.2 Permanent Magnet Motor

Permanent magnet DC motors are widely used in the machine tool sector due to their superior operational stability, linearity, and efficiency. However, their applications require advanced design decisions to maintain high performance while optimizing unit design [1]. The choice of magnet material significantly impacts motor performance, size, and cost. This article examines the requirements for selecting permanent magnet material and highlights the advantages of using this type of motor over wound field DC motors [1],[2],[5]. Fig. 1 shows the example of electric motors which are permanent magnet motor and induction motor.

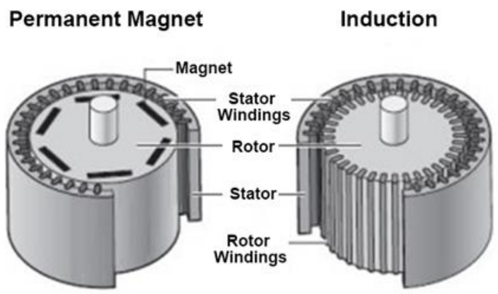


Fig. 1 *Two types of electric motors, permanent magnet motor and induction motor*

2.3 Surface Permanent Magnet Motor (SPM)

Permanent magnet synchronous motors (PMSMs) are popular for their efficiency and high torque in compact sizes. There are two main designs: surface-mounted permanent magnet (SPM) and interior permanent magnet (IPM). SPM motors have magnets fixed to the outer surface of the rotor, reducing the risk of magnet detaching due to centrifugal force at high speeds. They also allow for reluctance torque, a secondary torque produced by the motor's geometry [6]. However, SPM motors rely solely on the magnetic torque generated by the permanent magnets. They are widely used in electric vehicles (EVs) as traction motors due to their high power density and efficiency. In EVs, overall efficiency across the entire driving cycle is more crucial than peak efficiency at a single operating point [7],[8]. Fig. 2 shows the differences of SPM and IPM.

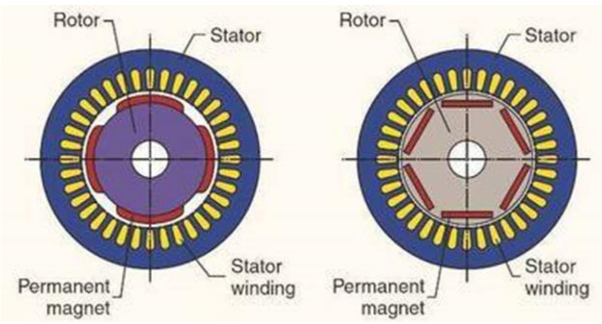


Fig. 2 *Differences of SPM and IPM*

2.4 Number of Poles in Motors

Three-way electromagnetic windings form the basis of a three-phase motor, forming an electromagnetic pole that runs north-south. This configuration creates two poles in the motor. The voltage phases increase and decrease when positioned 120 degrees apart, and the frequency of the voltage change determines the strength of each electromagnetic winding set. An average system operating at 50 Hz can reach a speed of 3000 rpm. Choosing the right pole number for a constant frequency source is straightforward, as the synchronous speed dictates the pole number required for the given application [9]. Adjusting the motor's frequency allows for the selection of any even number for pole numbers, giving control over the synchronous speed that produces the required values [10]. Pole numbers are proportional to frequency, and increasing frequency increases the iron loss of the motor. Two and four pole motors are the most viable options, unless low-speed applications are required. Materials like powdered iron or low loss steel with thinner laminations can help decrease iron losses [11].

3. Methodology

JMAG Designer, a specialized simulation programme, Finite Element Analysis (FEA) is used in the development and design of this permanent magnet synchronous motor. With simulation technologies, this programme combines heat, the structure of the emf core, a wide range of material characteristics, geometry, and other physical phenomena to enable precise analysis. The electromechanical design performance based on variable pole numbers and its impact on PMSM features is investigated in this study using the JMAG programme. This software goes beyond simply collecting data. It can accurately capture intricate physical processes happening within a machine and analyse them rapidly. This allows for a deeper understanding of how the machine functions and potential issues that might arise.

3.1 Flowchart of project implementation

The JMAG-designer software is being utilized in this project to model the motor structural design. Fig. 3 below displays the process's general workflow. This implementation consists of two parts: the PMSM motor's design and a performance study of its thermal and electromagnetic characteristics. The software's Geometry Editor is used to create all component of the motor, which includes the stator, armature coil, permanent magnets, and rotor. However, before creating the simulation, JMAG-designer is utilised to set the materials and conditions for the motor components as well as their state.

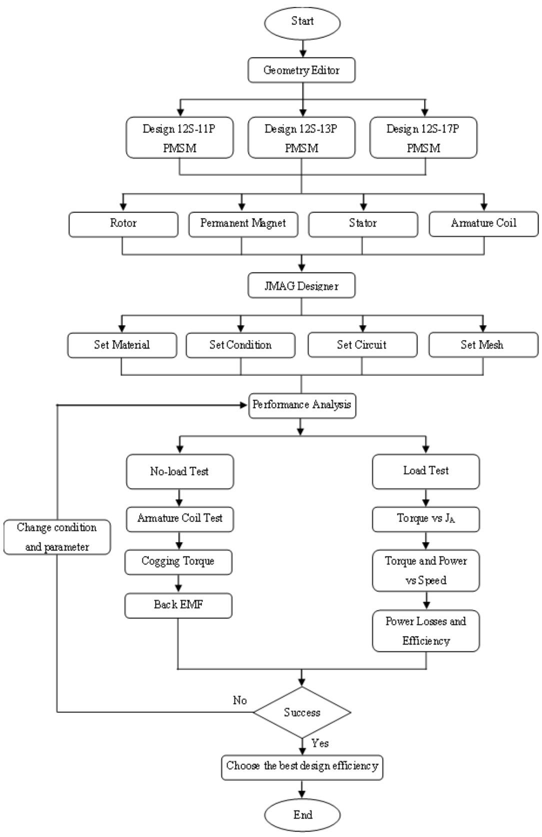


Fig. 3 *General flowchart of project implementation*

3.2 Design restrictions and specifications

The relationships between parameters of the motor design are used to study the pole number effect on electromagnetic characteristic of the permanent magnet synchronous motors. These motors have their designs modified to have their electromagnetic characteristics with the design constraints as in Table 1 and Table 2.

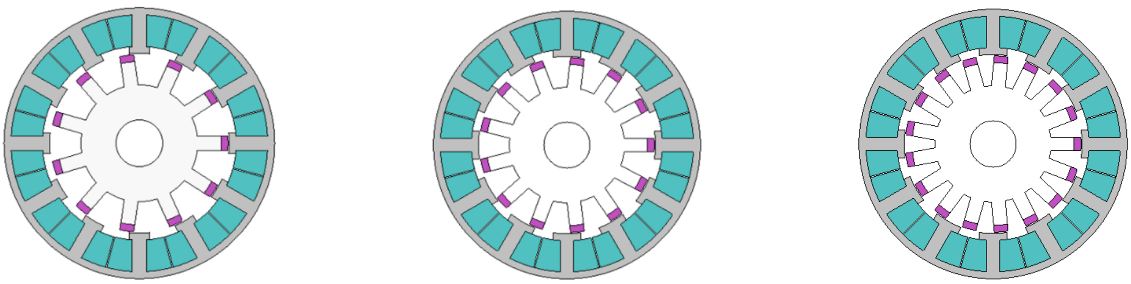
Table 1 *Specifications of the motor*

Parameters	Dimensions
Rated speed, rpm	1500
Stator outer radius, mm	58
Stator inner radius, mm	38.5
Rotor outer radius, mm	35
Rotor inner radius, mm	25
Pole width, mm	6
Stator slot width, mm	8.2
Shaft radius, mm	10
Number of turns	81

Table 2 *Materials and conditions*

Parts	Materials	Conditions
Rotor	Nippon Steel 35H210	Motion: rotation Torque: nodal force
Stator	Nippon Steel 35H210	-
Armature Coil	Conductor Copper	FEM Coil
Permanent Magnet	Neomax-35AH (irreversible) (Magnetization pattern: radial direction)	Motion: rotation Torque: nodal force

The three-phase PMSM motors that were designed are 12S-11P, 12S-13P, and the 12S-17P respectively. They have the same stator pole number with the stated dimension specifications while number of poles is varied from one and the other. The cross-sections of the motors are shown in Fig. 4. JMAG Designer version 18 was used to carry out this study. Data analysis in the form of 2D-FEA are the results obtained in this study.



(a) (b) (c)

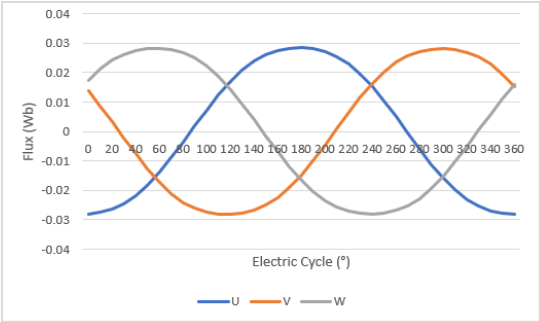
Fig. 4 *Final design of PMSP motors (a) 12S-11P (b) 12S-13P (c) 12S-17P*

4. Result and Discussion

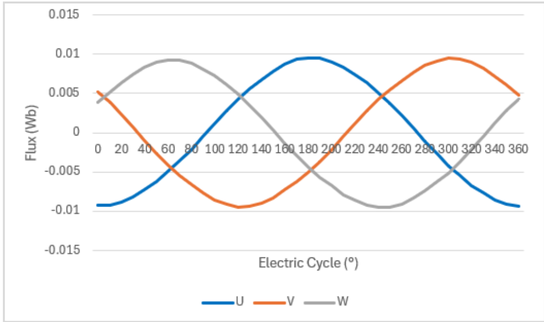
Once the entire design has been completed, motor performance analysis begins. 12S-11P, 12S-13P, 12S-17P PMSM were created with the JMAG-Designer. The performance of all designs is examined in no-load and load tests.

4.1 Armature Coil Test

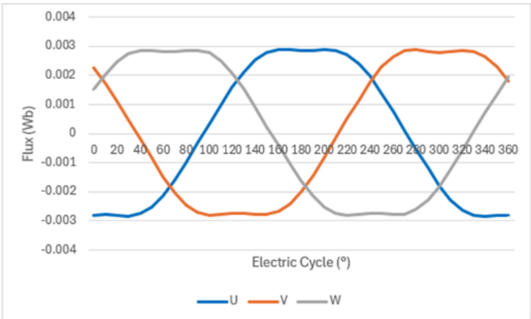
This test, performed without the motor running (no load), checks if the armature coils are wired and positioned correctly. Before running the test, it's crucial to ensure the UVW coil phases are aligned with the rotor at a specific point. Essentially, the motor needs to be rotated so the magnetic field (called U-phase flux) is perpendicular (90°) to a designated axis (x-axis) and also creates zero flux at another point (270°). This process is repeated for the V-phase and W-phase coils, each offset by 120 degrees, as expected in a balanced three-phase system. Fig. 5 shows the graph flux linkage for 12S-11P, 12S-13P and 12S-17P types.



(a)



(b)



(c)

Fig. 5 *Graph Flux linkage (a) 12S-11P (b) 12S-13P (c) 12S-17P*

4.2 Back-Electromotive Force (EMF)

Back electromotive force is caused by the relative motion of the magnetic field and the coil. It is produced when the coil rotates within the magnetic field. The back EMF is aimed at setting the motor's speed at a given voltage and should be similar to or lower than the applied voltage, which in this case is 415V. This guarantees that the motor functions safely and without causing harm to the coils. Fig. 6 illustrates the back-emf graph for the 12S-11P, 12S-13P, and 12S-17P configurations while the motors rotate at 1500 rpm. The amplitude of the 12S-11P is 54.36 V, with a better sinusoidal waveform, but the peak value of the 12S-13P is 19.55 V, with degraded harmonics. Meanwhile, the 12S-17P obtained a back-emf value of 9.96 V.

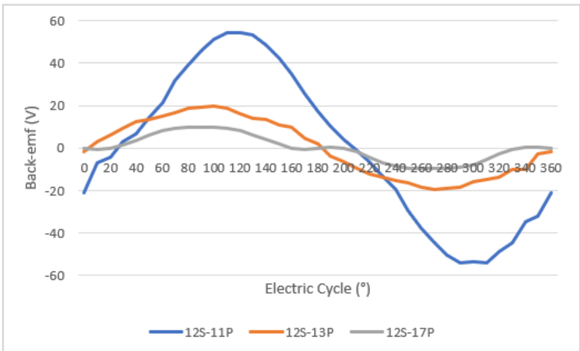


Fig. 6 *Comparison of back EMF graphs for all three motors*

4.3 Torque vs Armature Current Density J_A

To analyse torque behaviour, the FEM coil is injected with currents ranging from JA 5 A/mm^2 to JA 30 A/mm^2. Fig. 7 shows the simulated results for the 12S-11P, 12S-13P, and 12S-17P PMSMs. The simulation results showed a clear trend, as increased the current, the torque produced by all three motors also steadily increased. The 12S-11P motor achieved the highest torque, reaching 7.57 Nm at the maximum current. The other two motors produced lower torques, 2.82 Nm and 0.77 Nm for 12S-13P and 12S-17P respectively even though they were simulated with the same high current. This suggests that the number of poles in a PMSM design significantly impacts its torque output.

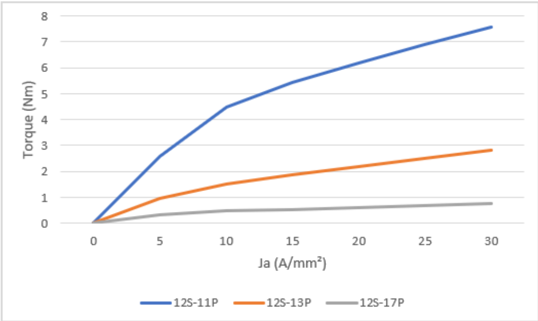
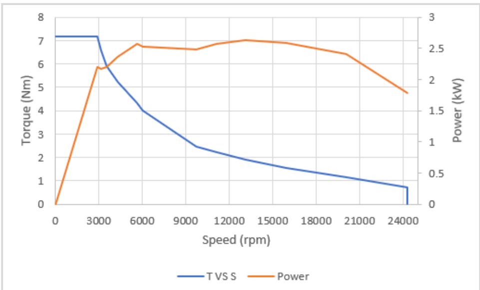


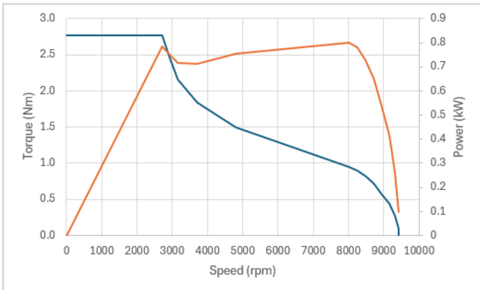
Fig. 7 *Torque vs various J_A for all three motors*

4.4 Torque and Power vs Speed at various Armature Current Density J_A

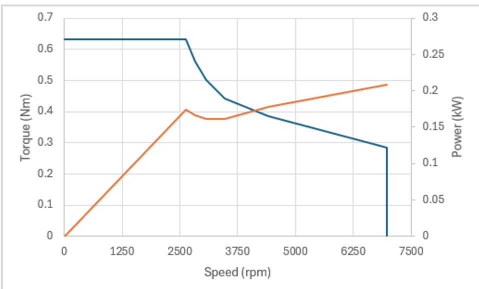
Fig. 8 shows the torque and power vs speed characteristics of the designed motors. Fig. 8(a) shows that 12S-11P motor exhibits the strongest performance, generating the highest torque (7.13 Nm) and power (2.63 kW) at a base speed of around 2920 rpm. However, its power output drops by 32% as the speed increases to its maximum of roughly 24270 rpm. As demonstrated in Fig. 8(b), the 12S-13P motor achieves a maximum torque of 2.76 Nm at a base speed of 2708 rpm, but this value significantly decreases at higher speeds due to increased iron loss. Similarly, its power output drops from 2.76 kW to a mere 0.1 kW (almost 97% reduction) as the speed reaches its maximum of 9416 rpm. As the motor accelerates, the back electromotive force (EMF) rises, countering the supply voltage and diminishing the armature current. Simultaneously, the magnetic field produced by the armature current can interfere with the permanent magnets' field, a phenomenon known as armature reaction. Both effects can lead to a reduction in the motor's power output at higher speeds, as they adversely affect the current flow and magnetic field distribution necessary for optimal motor performance.



(a)



(b)



(c)

Fig. 8: *Graph Torque and Power vs Speed (a) 12S-11P (b) 12S-13P (c) 12S-17P*

Finally, the 12S-17P motor has the lowest overall performance as seen in Fig. 8(c). It produces a peak torque of only 0.63 Nm at a base speed of 2638 rpm, with a maximum power output of 0.17 kW. Interestingly, its power output shows a slight increase (3.4%) as the speed reaches its maximum of 6978 rpm.

The 12S-11P motor achieves a higher maximum RPM compared to the 12S-13P and 12S-17P motors due to its lower pole pair count, which decreases the required electrical frequency for high speeds, its potentially more trapezoidal back EMF waveform suitable for easier high-speed commutation, and its design focus on high-speed operation rather than low-speed torque, resulting in reduced iron losses and potentially lower rotor inertia.

4.5 Power Losses and Efficiency

A computer aided technique called 2-D Finite Element Analysis (FEA) to estimate the various power losses within the motor. These losses included those arising from the iron core (iron loss) and the heat generated in the armature windings due to current flow (copper loss). The results are visualized in Fig. 9, which plots torque versus motor speed for a specific motor design (12S-11P). The numbered points (1-15) highlight specific operating conditions, including points of maximum torque, high speed operation, and situations where the motor experiences light load.

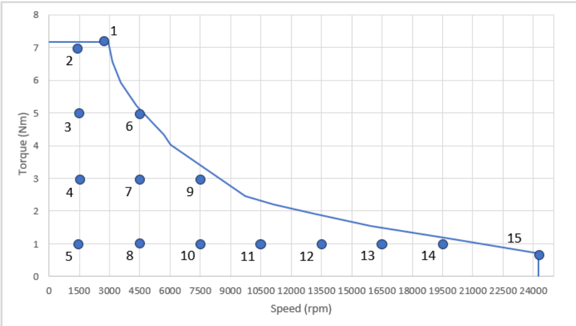


Fig. 9: *Torque vs Speed graph for 12S-11P PMSM*

Tables 3 and Fig. 9 show a detailed loss analysis of the 12S-11P PMSM at each of the listed points. When comparing the designs, it is clear that the 12S-11P motor has the largest average iron and copper losses. At maximum torque, point 1, the 12S-11P produced an iron loss of 471.49W and a copper loss of 3078.18W. At point 15, which represents maximum speed, the iron loss of the 12S-11P was 3779.98W, while the copper loss was 85.50W.

Table 3 *Percentage of power at operating points and overall efficiency of 12S-11P*

Point	P_{out} (W)	P_c (W)	P_i (W)	Efficiency, %
1	20951	3078.18	471.49	85.51
2	10500	2312.05	231.19	80.50
3	7500	534.41	174.26	91.37
4	4500	123.13	93.03	95.42
5	1500	13.68	36.36	96.77
6	22500	534.41	390.75	96.05
7	13500	123.13	351.31	96.60
8	4500	13.68	267.21	94.12
9	22500	123.13	399.50	97.73
10	7500	13.68	516.10	93.40
11	10500	13.68	915.99	91.87
12	13500	13.68	1468.07	90.11
13	16500	13.68	2144.95	88.43
14	19500	13.68	2974.50	86.71
15	16972	85.50	3779.98	81.45
Average	12828.2	458.2	947.646	91.07

According to the results of the investigation, when all three motors are compared, there is a significant difference in power loss and motor efficiency. It appears that, although having higher average iron and copper losses, the 12S-11P PMSM has more advantages over the other designs in terms of torque output. This confirms the effect of pole numbers on the properties of permanent magnet synchronous motors.

5. Conclusion

This research examined how the number of poles in a permanent magnet synchronous motor (PMSM) affects its electromagnetic properties. Three specific designs were built and tested, which are 12S-11P, 12S-13P, and 12S-17P. This research used a combination of design analysis, coil testing, and performance testing under various loads to understand how each pole number configuration functioned.

The study revealed that the number of poles significantly impacts a motor's efficiency and reliability. Factors like cogging torque (resistance to rotation), starting torque, achievable speed, power output, and internal losses (iron and copper) were all measured for each design. The results showed that each configuration offered unique performance characteristics. Notably, the 12S-11P motor outperformed the others in terms of torque, speed, and overall output. Additionally, it exhibited the lowest average power loss, suggesting minimal internal heating. Based on these findings, it can conclude that the 12S-11P configuration offered the optimal balance between torque, speed, and efficiency for this application.

Acknowledgement

The authors would also like to thank the Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia for its support.

References

[1] Gieras, J.F., & Shen, J.-X. (2022). Modern Permanent Magnet Electric Machines: Theory and Control (1st ed.). CRC Press.
[2] Gieras, J.F. (2009). Permanent Magnet Motor Technology: Design and Applications, Third Edition (3rd ed.). CRC Pres.
[3] M. A. Fakhfakh, M. H. Kasem, S. Tounsi, and R. Neji, "Thermal analysis of a permanent magnet synchronous motor for electric vehicles," J. Asian Electr. vol. 6, no. 2, pp. 1145-1151, 2008.
[4] M. Z. Ahmad, E. Sulaiman, G. M. Romalan, M. Jenal and T. Kosaka, "Three-phase variable flux outer-rotor switched flux permanent magnet machine, 2016 XXII International Conference on Electrical Machines (ICEM), Lausanne, 2016, pp. 2563-2569.
[5] M. A. Rahman, "IPM motor drives for hybrid electric vehicles," 2007 International Aegean Conference on Electrical Machines and Power Electronics, Bodrum, Turkey, 2007, pp. 109-115, doi: 10.1109/ACEMP.2007.4510492.
[6] L. Qi, F. Tao, W. Xuhui, T. Xiang, L. Ye, and Z. Guangzhen, "Modeling of the Efficiency MAP of Surface Permanent Magnet Machine for Electrical Vehicles," pp. 1222-1225, 2013.
[7] D. Borg-Bartolo, D. Gerada, C. Micallef, A. Mebarki, N. L. Brown and C. Gerada, "Thermal modelling and selection of a high speed permanent magnet surface mount electrical machine," 6th IET International Conference on Power Electronics, Machines and Drives (PEMD 2012), Bristol, 2012, pp. 1-6, doi: 10.1049/cp.2012.0289.
[8] D. Misu and M. Matsushita, "Consideration of Optimal Number of Poles and Frequency for High-efficiency Permanent Magnet Motor," pp. 3012-3017, 2014.
[9] Tianyu Wang, Fengxiang Wang, Haoran Bai, & Junqiang Xing. (2007). Optimization design of rotor structure for high speed permanent magnet machines. 2007 International Conference on Electrical Machines and Systems (ICEMS).
[10] B. Tian, Q. An, L. Sun, D. Sun, and J. Duan, "Initial position estimation strategy for a surface permanent magnet synchronous motor used in hybrid electric vehicles," Front. Inf. Technol. Electron. Eng., vol. 17, no. 8, pp. 803-813, 2016.
[11] Klein, F., & Kenyon, M. (1984). Permanent Magnet DC Motors Design Criteria and Operation Advantages. IEEE Transactions on Industry Applications, IA-20, 1525-1531.