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Effect of Parameter Modification on Torque Ripple in Interior Permanent Magnet Synchronous Motor

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Abstract – *Electric motors are electromechanical machines commonly used in industry and automotive products. Interior Permanent Magnet Synchronous Motor (IPMSM) is a synchronous electric motor with a permanent magnet that is often used on electric vehicle engines. However, one of the characteristics of an electric motor with permanent magnet is the existence of torque ripples. The presence of torque ripples in electric motors can cause vibrations in the machine which affect efficiency, structural durability and operating speed. Therefore, it is necessary to make improvements or changes to the motor design to overcome this problem. This study was conducted to analyze the effect of a modification of the electric motor parameter on the torque value in the existing design. Modifications are applied to the existing design with an initial condition of torque ripples of 42.58%. This study modified the air gap, magnet angles, magnet thickness, and opening slot width. Modifications are carried out through a finite element method-based software simulation with the Taguchi method to reduce experimental configurations of design factors from 625 to 25 experiments. Through this research on parameter modification, the results of the analysis show that each modification of the design factor has an influence on the value of torque ripples. From the process of Analysis of Mean (ANOM), it can be seen that wider air gap and slot opening, the smaller torque ripples. Then, the greater magnet rib and thicker magnet cause the greater torque ripples.*

Kata Kunci – *Finite element method; IPMSM; modification; ripple torque; taguchi.*

I. INTRODUCTION

PROGRESS in the electricity sector is growing. It has a positive impact on society by fulfilling more equitable distribution of electricity needs in the industrial sector, small businesses, and household use. It is undeniable that the need for electrical energy continues to increase when compared to a few decades ago. Many industrial players electrify production systems to achieve production process efficiency. Among the efforts made is implementing the use of electric motors on production machines. This is done because electric motors are efficient tools and have long durability [1,2]. Based on these cases the demand for electric motors is now a staple in the industry. The projected need for electric motorbikes in the world is increasing every year in the Asia Pacific region with the largest sales figures. The data shows that electric motors play an important role in the acceleration and quality of production. Not only in the industrial sector, now electric motors are starting to replace the role of conventional engines (internal combustion engines / ICE) in vehicle engines. Now many manufacturers offer electric vehicles with their own specifications and advantages.

In electric vehicles (EV) electrical energy is converted into mechanical energy (rotation) which is channeled to the wheels through a transmission device [3], [4]. The type of electric motor used in electric vehicles is now experiencing significant progress. There are various electric vehicles on the market with various specifications and types of motors. These specifications differ depending on the function of each vehicle. It makes electric vehicle manufacturers design various variations of electric motors to suit consumer needs. Determination of the type of motor used must be done precisely because the quality of the design greatly affects the performance of the motor when applied. This makes more and more research in terms of the development of electric motors.

In a research process certainly involves several stages that require large costs. One of them occurs in the design process. The process of determining the design and parameters of an electric motor is a problem for every manufacturer. Because each design to be

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tested requires a lot of money, moreover the testing process is carried out directly by making prototypes. Design testing through prototyping is an expensive and time-consuming stage [5].

The high cost of prototypes and testing will have an impact on increasing production costs, so the selling price can be very expensive [6]. To overcome this problem, electric motor manufacturers can now carry out the design process with simulation software [7, 8]. By simulating the design model, we can predict how the system will work without having to build a prototype. Through simulation, manufacturers can now maximize the initial design, so that with a predictable model, failure during prototyping can be avoided [9].

Even though the above alternatives can be implemented, the process of designing an electric motor still requires the right design parameters so that the resulting design is in accordance with the requirements. To initiate this step, it is necessary to study the parameters that have been proven to produce an electric motor design with optimal performance. The parameters of an electric motor greatly affect the resulting performance [10]. This makes the process of optimizing a design important to maximize the performance of an electric motor. In addition, optimization can be done to reduce losses or deficiencies in electric motors.

One of the drawbacks of electric motor performance is the presence of torque ripple [11, 12]. When an electric motor is operating, large torque ripples can cause noise, vibrations that make the speed unstable, as well as interference with the controls [13]. This torque ripple must be minimized to maximize the efficiency and performance of the motor. Cogging torque is a common phenomenon in electric motors that use permanent magnets in their construction, such as permanent magnet synchronous motors (PMSM). The use of PMSM in electric cars is quite popular, such as in the Toyota Prius hybrid electric vehicle (HEV), where the function of the electric motor used is to provide power assist to the main engine (ICE) of the car [3]. The motor used in these vehicles is included in the interior permanent magnet synchronous motor (IPMSM) type with a V-type magnet configuration [14].

Basically, cogging torque cannot be eliminated, but can be reduced in various ways [15]. One of them is to modify the motor construction parts. Examples of some parts that can be modified are the width of the air gap, the shape of the magnet, the shape of the stator slots, and the stator coating [16]. In addition, many researchers conducted parameter sensitivity analysis to determine the effect of parameter modification on the overall performance of electric motors [17]. Based on the problems above, this research was conducted to analyze the effect of parameter changes on the torque ripple performance of existing electric motors. This research will make changes to the motor's existing parameters through FEM simulation, then use statistical methods to see the effect on the motor. The aim of this research is expected to be a method of modifying electric motor parameters for the resulting performance. So, this research will contribute in produce the best parameter modification method of the air gap width, magnet angle, magnet thickness and slot opening width to reduce the ripple torque in motor performance. This research is expected to be useful as a reference in developing research and modifying electric motor designs, especially through the simulation process.

II. RESEARCH METHODS

i. Torque on IPMSM

IPMSM generates torque from two different mechanisms. The first is the permanent magnet torque generated by the interaction of the flux between the rotor magnetic field and the stator electromagnetic field [18–20]. After that the IPMSM generates a second force known as the reluctance torque [21]. This study involved the process of measuring electromagnetic torque using equation 1. Where Te is the electromagnetic torque in Nm. P is the number of motor poles tested.

$$T_s = \frac{1}{2} P_{i_q} \left(L_d - L_q\right) i_d + \Psi_m \tag{1}$$

I_q and id are the q-axis currents and $d-$axis currents in the motor section in Ampere units. L_d and L_q are $d-$axis inductance, $q-$axis inductance (H). And Ψ_m is the magnitude of the flux linkage (Wb) that is formed. Equation 1 is used to calculate the motor electromagnetic torque value, which is the main source of electric motor torque. This equation is coupled to the Ansys simulation software, where it will calculate the amount of torque on the motor object that has been previously designed. Then, the software measures the torque while the motor is rotating. The resultant electromagnetic torque is calculated based on the variable values input previously in the design. Through comprehensive FEM simulation, the torque value per second can be determined. In addition to electromagnetic torque, there is also torque ripple. Torque ripple is defined as the percentage difference between peak torque (N.m) and minimum torque (N.m) with average torque. One of the main problems of IPMSM is the torque ripple that exists when the motor is operating [22]. In general, torque ripple can be known by analyzing the results of torque measurements in the performance of a motor. Torsional ripple can be calculated through the following equation [23]:

$$\tau_{\text{ripple}} = \left(\frac{\tau_{\max} - \tau_{\min}}{\tau_{\text{avg}}} \right) \times 100\% \qquad (2)$$

Where τ ripple is the torque ripple in %. $\tau_{\max}$ is the maximum torque measured when the motor is operated while $\tau_{\min}$ is the minimum torque (Nm). τ_{avg} is the average torque (Nm) which is calculated from the average torque generated in every single torsion sigma sinusoidal wave. Equation 2 is used to calculate torque ripple manually. This calculation is carried out to determine the magnitude of the torque ripple in the motor each rotation, and also for each parameter change that is made.

ii. *Finite element analysis*

The finite element method (FEM) is defined as a method used to analyze a part of a physical object through a simple arithmetic computation approach that represents complex differential calculations based on scientific formulas. The finite element method (FEM) is a popular method for numerically solving differential equations arising in engineering and mathematical modeling. Typical problem areas of interest include the traditional fields of structural analysis, heat transfer, fluid flow, mass transport, and electromagnetic potential. It is a numerical method used to perform a finite element analysis (FEA) of any given physical phenomenon to predict the behavior of a structure. The method was originally developed for engineering analysis to model and analyze complex systems in mechanical, electromechanical, civil, and aeronautical engineering.

iii. *Taguchi method*

Taguchi is one of the statistical methods used to assist the design modification process to produce a more optimal design of a problem. Taguchi optimization basically uses a simple statistical method that can reduce the number of trials of the total combinations that are generally carried out. This method has the advantage of reducing the number of trials, thereby reducing optimization time [13]. The Taguchi method is a problem-solving technique that helps improve process performance, increase efficiency and productivity. It involves reducing the variation in a process through robust design of experiments [24]. The overall objective of the method is to produce high-quality products at low cost to the manufacturer. The method was developed by Dr. Genichi Taguchi of Japan, who maintained that variation should be minimized to achieve quality. Taguchi developed a method for designing experiments to investigate how different parameters affect the mean and variance of a process performance characteristic that defines how well the process is functioning.

iv. *Analysis of mean*

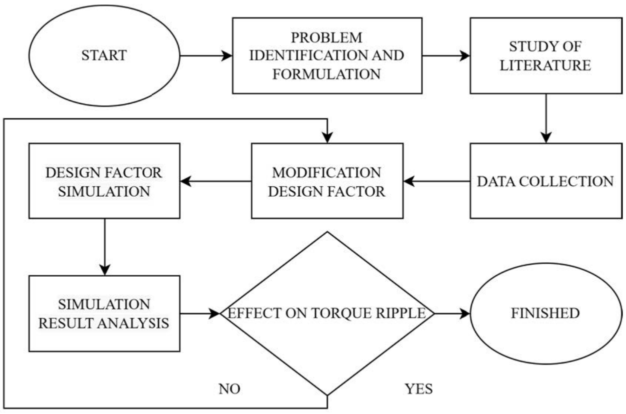
Analysis of means is a graphical alternative to ANOVA that tests the equality of population means. The graph displays each factor level mean, the overall mean, and the decision limits. If a point falls outside the decision limits, then evidence exists that the factor level mean represented by that point is significantly different from the overall mean. It is active mostly in quality control. To analyze the influence of the parameters on the resulting motor performance, optimization of the taguchi method uses statistical means made from orthogonal arrays based on the results of the finite element method (FEM) analysis. The mean value is calculated as follows [25]:

$$M = \frac{1}{n} \sum_{i=1}^{n} \qquad (3)$$

Where M is the average value (mean), n is the amount of data generated and i is the identity of the i-th data. Through equation 3, the average value of each simulation result for each design factor will be found. The average value obtained will be analyzed as a response to motor performance to the parameter changes that have been made. Analysis of the resulting data can represent the effect of parameter modifications on the magnitude of the motor's torque ripple when operating, so that this data can be used as a reference for carrying out projects to improve the performance of the electric motor.

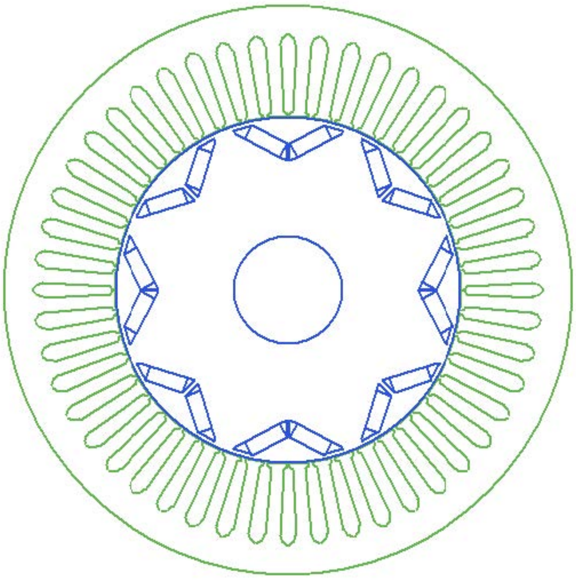
v. *Research flow*

This research is composed of several stages of work which have been presented in the form of the flowchart in figure 1.



Gambar 1: Flowchart

The data needed in this study is the existing initial design of the IPMSM Toyota Prius 2010, where the parameter data was obtained from an evaluation report by the Oak Ridge Laboratory entitled ”Evaluation of the 2010 Toyota Prius Hybrid Synergy Drive System”.



Gambar 2: IPMSM Toyota Prius on Ansys simulation

Tabel 1: 2010 Toyota Prius IPMSM Parameter

No.	Parameter	Value	Unit
1.	Slot	48	-
2.	Pole	8	-
3.	Stator (OD/ID)	264/161.9	mm
4.	Rotor (OD/ID)	160.4/50.165	mm
5.	Stack length	50.8	mm
6.	Air gap	1.5	mm
7.	Slot opening	1.88	mm
8.	Magnet thickness	7.16	mm
9.	Magnet rib	10	mm

Table 1 is the parameter data for the IPMSM Toyota Prius 2010, it was the initial design that already exists. After obtaining the data, design computations and simulations were carried out using Ansys Electronics Desktop to form the initial design. Then, the results of this design are verified and validated against the data source by comparing several motor performance parameters from the simulation results with the original data. After simulating each design factor, the next step is to perform interim performance data collection, then proceed with design factor analysis. The analysis process is carried out with the help of statistical calculations involving a method, namely the analysis of the mean.

This study used four design variables (design factors) consisting of air gap, magnetic rib angle, magnet thickness and slot opening width. Where each variable is combined with five different levels. After obtaining the combination for the simulation of each design factor, the next step is to determine the modified value of each design factor by five levels in terms of the value in the initial design. The variable values for each design factor to be used are presented in table 2 with a range of modifications for each design factor made up of five levels. Through a simple calculation, the total number of combinations formed is 625, but using the Taguchi method, the number of trials can be reduced to 25.

Tabel 2: Design Factor Variable

No	Design factor	Level					Initial design
		1	2	3	4	5	
1	Air gap (mm) [A]	0.9	1.2	1.5	1.8	2.1	1.5
2	Magnet rib (mm) [B]	9	9.5	10	10.5	11	10
3	Magnet thickness (mm) [C]	6.6	6.8	7.16	7.2	7.4	7.16
4	Slot opening (mm) [D]	1.4	1.6	1.88	2	2.2	1.88

After simulating each design factor, the next step is to retrieve temporary performance data results, then proceed with an analysis of the influence of design factors. The analysis process is carried out with the help of statistical calculations involving the analysis of the mean method. This method is used to determine the effect of modifying design factors on temporary performance results. The result of the modification process is a combination of each design factor which will become a new parameter. Design and simulation can be re-done using new parameters to analyze the performance generated in the optimization process for further research.

III. RESULTS AND DISCUSSION

i. Design factor simulation results

The design factor simulation is carried out by modifying the motor design using a combination of variables according to the rules of the taguchi table. If done manually, 625 modifications will be formed that must be simulated. By using the taguchi orthogonal array, the number of modifications can be reduced to 25. The configuration is simulated to obtain measurements of nominal torque, then basic calculation using equation 2 is conducted to provide the ripple torque. In this design factor simulation is carried out at a speed rating of 6500 rpm to determine the amount of ripple at low speed. The following is the result of the design factor simulation which shows that each design configuration of the orthogonal array taguchi has an influence on the motor torque ripple. These results become the basis for the calculation process at a later stage.

The results in table 3 show that each Taguchi orthogonal array design configuration has an influence

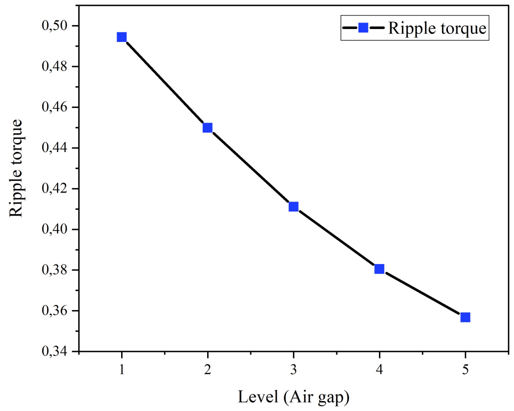
Tabel 3: Design Factor Simulation Result

Simulation-n	Ripple torque (%)
Original	39.5
1	50.1
2	49.2
3	47.4
4	48.3
5	51.9
6	42.9
7	43.1
8	42.3
9	49.5
10	46.9
11	38.7
12	41.7
13	42.9
14	40.8
15	41.2
16	37.4
17	37.6
18	36.6
19	37.2
20	41.3
21	34.4
22	33.8
23	35.9
24	36.5
25	37.5

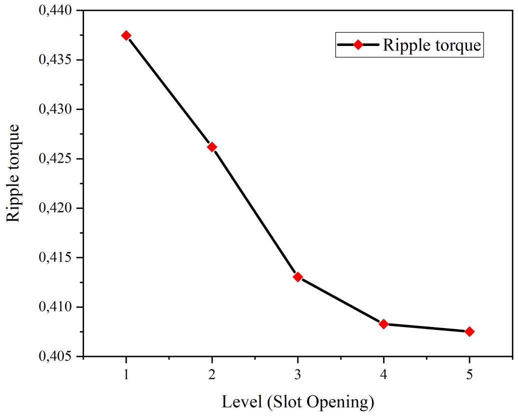
on the torque ripple. In the next stage, the simulation results from the previous variable configuration will be sorted based on the Taguchi orthogonal array. Then analyzed using a simple average equation, by grouping the data according to the variables. This process uses the ANOM table based on the Taguchi method. By arranging the average measurement results in the ANOM table, we can get a graphic representation that illustrates the effect of parameter changes at each variable value on the performance output we want to know.

ii. Analysis of means

At this stage the simulation results of the variable configuration based on the orthogonal array taguchi are analyzed using a simple average equation, by grouping the data according to the variable. From Figure 2 below it can be seen that the magnitude of the torque ripple measured when the motor is operating can be influenced by modifications of the four parameters. As we can see in Figure 3, the torque ripple is inversely proportional to the air gap distance. The greater the gap between the rotor and stator, the smaller the torque ripple will be.



Gambar 3: Air gap modification effect



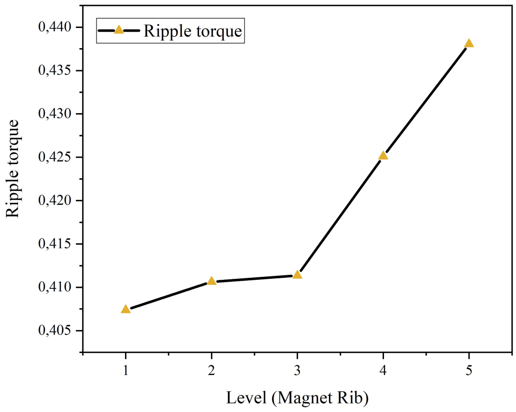
Gambar 4: Slot opening modification effect

Likewise with the slot opening distance, the greater the distance, the lower the torque ripple will be compared to the initial design. Then, the next two parameters have different effects from the previous one, namely modification of the thickness and angle of the magnet.

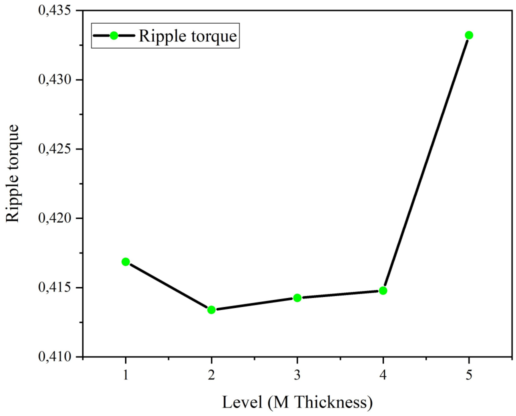
In this modification, the thickness of the magnet is directly proportional to the magnitude of the torque ripple. Just like thickness, a larger magnetic angle will have an impact on increasing torque ripple. Based on the simulation results, two pairs of parameters have been obtained that are contradictory to the magnitude of the torque ripple if the parameter values are changed.

iii. Discussion

It can be seen from the figure that the torque ripple value is inversely proportional to the size of the air gap and the slot opening. Then directly proportional to the magnetic rib and the thickness of the magnet. When



Gambar 5: Magnet rib modification effect



Gambar 6: Magnet thickness modification effect

the air gap and slot opening increase, these two parameters will produce a larger gap in each structure. This means that there is an increase in the air gap and width of the slot opening in the motor structure. Changing the gap value will change the reluctance torque value that occurs in the motor. Because, if we talk about the working principle of permanent magnet synchronous motors, the total torque created is influenced by the presence of reluctance torque which is a torque component in electric motors due to the interaction of magnetic forces with empty space in the motor structure. Changes in the reluctance torque have an influence on the total torque, so that when these two parameters are modified, it also affects the torque ripple.

Then, when the size of the magnet and the V-angle (magnet rib) in the rotor structure are increased, it will affect the strength of the magnetic field generated from the permanent magnet and increase the magnetic flux distribution at the induction area. The strength of the magnetic field can affect the amount of electromagnetic torque and reluctance torque in the total torque. This means that changes in magnetic parameters also affect the magnitude of the torque ripple. Based on the analysis of mean, the variable combinations that can produce the smallest percentage of torque ripple are A5, B1, C1 and D5. However, the results of this parameter selection are not sufficient to be used as a torque ripple improvement design. This is because the data results are still in the analysis stage, so there are still several further steps to determine the final parameters because of improvements.

The data results at this stage must be carried out in an optimization process as the next step to consider other performance parameters so that they do not tend to decrease or become worse. In the next stage, several ways to optimize can be carried out, including the statistical analysis of variance method which is also assisted by a software simulation process.

IV. CONCLUSION

From this study it can be concluded that each design factor modification has an influence on the torsional ripple value. It can be seen from the analysis of mean process that the wider air gap and slot opening, the smaller the torque ripple. And the bigger magnet rib and magnet thick, the bigger the torque ripple. From this research it can also be concluded that the existence of torque ripples is greatly influenced by the components that make up total torque, electromagnetic torque, and reluctance torque, where each type of torque has its own influence due to modification of design parameters. This research has succeeded in knowing the effect of modifying the IPMSM parameters so that it can later be used as a reference for conducting research in similar fields such as optimizing or improving torque ripple in electric motors. Apart from that, the method in this research can also be used as a reference for improving electric motor designs for other purposes such as improving efficiency, cogging torque, output power, etc.

DAFTAR PUSTAKA

[1] H. A. Toliyat and G. B. Kliman, *Handbook of electric motors*. CRC press, 2018, vol. 120.

[2] A. Hughes and B. Drury, *Electric motors and drives: fundamentals, types and applications*. Newnes, 2019.

[3] I. Husain, *Electric and hybrid vehicles: design fundamentals*. CRC press, 2010.

[4] P. Ramesh and N. C. Lenin, "High power density electrical machines for electric vehicles—comprehensive review based on material technology," *IEEE Trans Magn*, vol. 55, no. 11, pp. 1–21, Nov 2019. [Online]. Available: https://doi.org/10.1109/TMAG.2019.2929145

[5] M. Aishwarya and R. M. Brisilla, "Design of energy-efficient induction motor using ansys software," *Results*

in Engineering, vol. 16, Dec 2022. [Online]. Available: https://doi.org/10.1016/j.rineng.2022.100616

[6] H.-J. Park and M.-S. Lim, "Design of high power density and high efficiency wound-field synchronous motor for electric vehicle traction," *IEEE Access*, vol. 7, pp. 46 677–46 685, 2019. [Online]. Available: https://doi.org/10.1109/ACCESS.2019.2907800

[7] L. Li and Y. Liu, "Design and simulation of permanent magnet synchronous motor control system," in *AIP Conference Proceedings*. AIP Publishing LLC, 2018.

[8] P. Lumyong and P. Sarikprueck, "A study on induction motor efficiency improvement for implementing in electric vehicle," in *2018 21st International Conference on Electrical Machines and Systems (ICEMS)*. IEEE, Oct 2018, pp. 616–619. [Online]. Available: https://doi.org/10.23919/ICEMS.2018.8549478

[9] M. Felderer and G. H. Travassos, *Contemporary empirical methods in software engineering*. Springer, 2020.

[10] A. DALCALI, "Optimal design of high performance interior pm motor for electric vehicle," *The International Journal of Energy and Engineering Sciences*, vol. 3, no. 2, pp. 46–54, 2018.

[11] A. Dianov and A. Anuchin, "Adaptive maximum torque per ampere control for ipmsm drives with load varying over mechanical revolution," *IEEE J Emerg Sel Top Power Electron*, vol. 10, no. 3, pp. 3409–3417, Jun 2022. [Online]. Available: https://doi.org/10.1109/JESTPE.2020.3029647

[12] M. Caruso, A. O. D. Tommaso, R. Miceli, and F. Viola, "A cogging torque minimization procedure for interior permanent magnet synchronous motors based on a progressive modification of the rotor lamination geometry," *Energies (Basel)*, vol. 15, no. 14, p. 4956, Jul 2022. [Online]. Available: https://doi.org/10.3390/en15144956

[13] J. Hao, S. Suo, Y. Yang, Y. Wang, W. Wang, and X. Chen, "Optimization of torque ripples in an interior permanent magnet synchronous motor based on the orthogonal experimental method and miga and rbf neural networks," *IEEE Access*, vol. 8, pp. 27 202–27 209, 2020. [Online]. Available: https://doi.org/10.1109/ACCESS.2020.2971473

[14] A. Hughes and B. Drury, "Synchronous, permanent magnet and reluctance motors and drives," in *Electric Motors and Drives*. Elsevier, 2019, pp. 307–373. [Online]. Available: https://doi.org/10.1016/B978-0-08-102615-1.00009-X

[15] M. Arehpanahi and H. Kashefi, "Cogging torque reduction of interior permanent magnet synchronous motor (ipmsm)," *Scientia Iranica*, vol. 0, no. 0, pp. 0–0, Aug 2017. [Online]. Available: https://doi.org/10.24200/sci.2017.4365

[16] M. I. S. Batisah and R. Aziz, "Cogging torque reduction of ipmsm by adjusting the stator opening width," *Evolution in Electrical and Electronic Engineering*, vol. 3, no. 2, pp. 343–350, 2022.

[17] H. Chen and C. H. T. Lee, "Parametric sensitivity analysis and design optimization of an interior permanent magnet synchronous motor," *IEEE Access*, vol. 7, pp. 159 918–159 929, 2019. [Online]. Available: https://doi.org/10.1109/ACCESS.2019.2950773

[18] J. Zhao, J. Wang, L. Zhou, W. Huang, Y. Ma, and Z. Zhang, "Cogging torque reduction by stepped slot-opening shift for interior permanent magnet motors," in *2019 22nd International Conference on Electrical Machines and Systems (ICEMS)*. IEEE, Aug 2019, pp. 1–4. [Online]. Available: https://doi.org/10.1109/ICEMS.2019.8921448

[19] J. Liang, A. Parsapour, Z. Yang, C. Caicedo-Narvaez, M. Moallem, and B. Fahimi, "Optimization of air-gap profile in interior permanent-magnet synchronous motors for torque ripple mitigation," *IEEE Transactions on Transportation Electrification*, vol. 5, no. 1, pp. 118–125, Mar 2019. [Online]. Available: https://doi.org/10.1109/TTE.2019.2893734

[20] J.-W. Jung, B.-H. Lee, K.-S. Kim, and S.-I. Kim, "Interior permanent magnet synchronous motor design for eddy current loss reduction in permanent magnets to prevent irreversible demagnetization," *Energies (Basel)*, vol. 13, no. 19, p. 5082, Sep 2020. [Online]. Available: https://doi.org/10.3390/en13195082

[21] T. A. Huynh and M.-F. Hsieh, "Comparative study of pm-assisted synrm and ipmsm on constant power speed range for ev applications," *IEEE Trans Magn*, vol. 53, no. 11, pp. 1–6, Nov 2017. [Online]. Available: https://doi.org/10.1109/TMAG.2017.2707125

[22] T. Gundogdu and G. Komurgoz, "The impact of the selection of permanent magnets on the design of permanent magnet machines–a case study: permanent magnet synchronous machine design with high efficiency," *Przeglad Elektrotechniczny*, vol. 89, no. 3a, pp. 103–108, 2013.

[23] E. T. KARTAL and F. K. ARABUL, "Elektrikli araclar için aynı stator gövdesine sahip asenkron motor ile gömülü sürekli mıknatıslı senkron motorun karsılastırılması ve performans analizi," *European Journal of Science and Technology*, Jun 2022. [Online]. Available: https://doi.org/10.31590/ejosat.1108129

[24] J. M. Cimbala, "Taguchi orthogonal arrays," 2014.

[25] J. Song, F. Dong, J. Zhao, S. Lu, S. Dou, and H. Wang, "Optimal design of permanent magnet linear synchronous motors based on taguchi method," *IET Electr Power Appl*, vol. 11, no. 1, pp. 41–48, Jan 2017. [Online]. Available: https://doi.org/10.1049/iet-epa.2016.0164