Techniques for the Optimal Design of Permanent Magnet Synchronous Motor

R. S. Ambekar, R. M. Holmukhe, R. S. Desai, Jyoti Morbale, Sarita S. Shinde and Sujata R. Alone

***Abstract*—**This paper makes available the guidelines in the form of techniques for the design optimization of permanent magnet synchronous motor (PMSM). The design of permanent magnet synchronous motor used in propulsion, gearless elevator system, hybrid and fuel cell vehicles and high-performance applications required to be robust. The robust design techniques like genetic algorithm, bees algorithm. response surface methodology, taguchi optimization method, equivalent circuit and design of experiment are referred to optimize the design for improvement in starting torque, efficiency, reduction in eddy current loss and prevention of demagnetization. Stator and rotor copper losses, core losses, starting torque, maximum torque, torque ripple and efficiency are parameters that can be optimized.

***Index Terms*—** Bees algorithm, demagnetization, genetic algorithm, optimum design techniques, PMSM, rotor configuration, stator configuration.

How to cite this article: R. S. Ambekar R. M. Holmukhe R. S. Desai Jyoti Morbale Sarita S. Shinde and Sujata R. Alone. Techniques for the Optimal Design of Permanent Magnet Synchronous Motor. Int J Drug Deliv Technol. 2026;16(77s):1908-1914. DOI: 10.25258/ijddt.16.77s.221.

INTRODUCTION

THE permanent magnet synchronous motor has the features of high torque density, high power density and high efficiency. The permanent magnet used in the motor may demagnetize at high temperature causing the reduction in reliability of the system. The performance of the motor and reliability of the drive system can be maintained if the design is robust. The robust design can be achieved using different optimization techniques. In multistep optimum seeking technique the defined range of rotational speed is used to obtain the constant adaption coefficient, conductivity and average electromagnetic torque. The composite solid rotor is with the permanent magnets sandwiched in the axial slots of solid steel segments and surface of the brass cage. The composite solid rotor structure improves the starting torque and can run the motor under large load conditions [1]. The transient and steady state performance of the line start permanent magnet synchronous motor is studied by analyzing the impact of different parameters on machine performance up gradation. The performance gets affected with steady state and transient state characteristics as constraints [2]. The exceptional active performance for the motor drives makes model predictive control technique one of the best control techniques. The artificial neural network with genetic algorithm optimizes the selection of factors of model predictive control for permanent magnet synchronous motor drives [3]. The high efficiency and high power density makes the permanent magnet synchronous motor to use widely in propelling applications. The model of efficiency mapping can be used to determine the vehicles energy consumption [4]. Bees algorithm uses the mathematical procedure to decide or find the optimized design variables that reflect the machine geometry and machine specifications. The Optimization procedure using Bees Algorithm is encouraged by usual searching for food behavior of honey bees to discover the best possible solution for different aspect of design development. The optimized design with optimal variables obtained using Bees Algorithm reduces the size of the machines and optimizes the efficiency [5]. The performance of the IPMSM is improved by optimizing the rotor configuration. The optimized shape of the V-type magnets reduces the vibrations which are caused by torque ripples. The vibrations in motor are minimized by reducing the harmonics of the air gap flux density [6]. The control or variable parameters are selected based on the aim of the design of permanent magnet synchronous motor. In this paper, Taguchi optimization method is used for the analysis of cogging torque and back emf with five control parameters at five levels [7]. The ripple and cogging torques are reduced by using variety of shape of magnets and skewing of stator and rotor. Magnet shaping reduces the rare earth material used and cost of the machine too. The optimum design is achieved using Taguchi optimization method and Genetic algorithm [9]. The design of the permanent magnet linear synchronous motor is optimized using kriging interpolation and genetic algorithm [13]. The PMSM servo drive design is optimized using fuzzy techniques [14]. The cost effective permanent magnet synchronous motor

Prof. Rupalee Shrinivas Ambekar, Assistant Professor is with the Department of Electrical & Computer Engineering. Bharati Vidyapeeth (Deemed to be University) College of Engineering, Pune. (e-mail: rsambekar@bvucoep.edu.in).

Prof. Rajesh M. Holmukhe, Associate Professor is with the Department of Electrical & Computer Engineering. Bharati Vidyapeeth (Deemed to be University) College of Engineering, Pune. (e-mail: rmholmukhe@bvucoep.edu.in).

Prof. Rahul S. Desai, Assistant Professor is with the Department of Engineering Science And Allied Engineering, Bharati Vidyapeeth's College of Engineering For Women, Pune. (e-mail: rahul.desai@bharatividyapeeth.edu).

Prof. Jyoti Morbale, Assistant Professor is with the Department of Electronics & Communication Engineering. Bharati Vidyapeeth (Deemed to be University) College of Engineering, Pune. (e-mail: jsmorbale@bvucoep.edu.in).

Prof. Sarita S. Shinde, Assistant Professor is with Department of General Engineerin, Bharati Vidyapeeth College of Engineering, Kolhapur (sarita.shinde@bharatividyapeeth.edu)

Prof. Sujata R. Alone is with Electrical Engineering Department, Kavikulguru Institute of Technology and Science, Ramtek, Dist. Nagpur, India (*e-mail: rawalesujata@gmail.com*).

Mentions of supplemental materials and animal/human rights statements can be included here.

Color versions of one or more of the figures in this article are available online at http://ieeexplore.ieee.org is designed and optimized using gene handling genetic algorithm. The cost of the copper and magnet material is reduced and the design variables are also optimized using this technique [15]. The parameters inductance, resistance, counter emf and linear force constant are estimated from electromagnetic analysis. The dynamic equation and modeling is used with the switching scheme to estimate the dc link voltage [16]. The main design variables and effect on objective are determined by design of experiment. The optimum design variables are determined by response surface method and the losses, efficiency by equivalent circuit method [18]. The direct and quadrature axis inductances are determined here and the design of machines is optimized by response surface methodology [19]. The permanent magnet synchronous motor has the limitation of torque ripple which results in noise. The torque ripple is minimized by optimizing the rotor geometry and magnetic parameters [20]. Response surface methodology is used to design the interior permanent magnet synchronous motor and minimize the torque ripple and reduces the harmonics present in the line to line value of back emf [23]. Efficiency and main dimensions of interior Brushless DC motor is optimized using Taguchi and Genetic algorithm method [24]. The efficiency is optimized and the vibrations are reduced by changing the rotor and stator configurations of interior permanent magnet synchronous motor. The design parameters that are optimized are barrier distance, tooth width and yoke thickness, coil diameter, space factor. Flux barrier and V type permanent magnets are used for the sinusoidal flux wave. The yoke thickness needs to be adjusted as per the teeth width to have the same value of winding space factor as that of the reference basic model. The main causes which produce the vibrations are torque ripple and magnetic force which is perpendicular to the air gap flux (radial magnetic force). To reduce the vibrations by the motor, the torque ripple and radial magnetic force are reduced by the arc of the rotor [25]. The electrical machines are designed using three methods as analytical, numerical and empirical. Finite element method is used to analyze the design of induction motor, interior permanent magnet motor and line start permanent magnet synchronous motor. The empirical method (sizing equations) is also verified by finite element method. The rotor of line start permanent magnet synchronous motor is optimized using genetic algorithm. The rotor optimization improves the starting torque and efficiency of the motor [26]. Eddy current loss and irreversible demagnetization affects the optimum design of machines. A reduction in eddy current loss prevents the irreversible demagnetization. Optimum design for the minimum variations in eddy current loss is achieved with response surface methodology and design of experiments [27]. This paper presents the design optimization of single phase line start permanent magnet motor using equivalent circuit based on symmetric field theory, Latin hypercube sampling for sample selection and radial base function for approximation model. Genetic algorithm is used for optimizing the results. The optimized parameters are efficiency, stator and rotor copper losses, core losses, starting torque, maximum torque, and torque ripple. The validation of the proposed design is achieved by FE analysis and experimental results [28]. The IPMSM optimization is done with Taguchi method and optimization results in the reduced torque ripple, increased torque and efficiency. The Ansys Maxwell is used for analysis of the IPMSM with five parameters of the rotor structure. The parameters of the delta shaped rotor structure were permanent magnet layer position, pole arc angle of the two layers and angle of one of the permanent magnet layer [29]. The IPMSM has the limitation of demagnetization of permanent magnet at high temperature under operating conditions. Here, the demagnetization can be optimized by changing the magnet arrangement and angle between them. The magnet arrangement is changed from flat to spoke type. The variation in magnet thickness and magnet width also gives better demagnetization resistance. This improves the output torque and reduces the torque ripple [31]. The response surface method is used to optimize the design of rare earth free concentrated flux synchronous motor. The performance of the motor is optimized by considering three design factors that are opening width of stator slot, opening width of rotor slot and width of permanent magnet [32].

Hybrid magnet is one of the methods used for design optimization of PMSM. The same results of rare earth PMSM are possible when thick ferrite magnets and thin rare earth magnets are used [33].

II. DESIGN OPTIMIZATION TECHNIQUES

The performance of any rotating electrical machines is dependent on the choice of maximum flux density in the air gap, current density and losses. In addition to this the rotor structure, winding layout and main dimensions of the motor also affects the efficiency or performance of the motor. The parameters that need to be focused while enhancing the performance of the motor are output torque, flux, efficiency etc. The general process stages in any electrical machines are input energy, electromagnetic process, energy losses and output energy. The performance of the motor can be affected by stator or rotor geometrical parameters and trouble causing parameters as shown in figure 1.

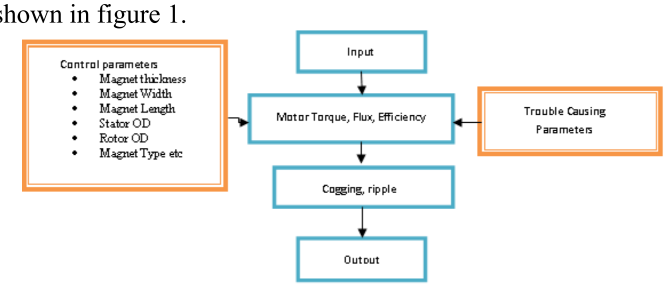

Fig. 1. Process stages of the motor.

A. Composite Solid Rotor

The starting torque of the line start permanent magnet synchronous motor can be improved by composite solid steel rotor. The solid steel of the rotor develops high starting torque. The starting capability of the motor can also be improved by providing slots axially and cage bars on the rotor surface. The slotted rotor with short circuited cage bars and smooth rotor with solid steel are shown in figure 2. The flux path for both slotted and smooth rotor is shown in figure 2 (a). The flux penetrates deeply in slotted rotor as compared with smooth rotor. The slotted rotor with squirrel cage bars shows higher flux which results in high current density of the rotor. The current density of the composite solid rotor is higher and more than twice to that of the solid rotor. The distribution of current in slotted rotor and solid steel rotor is shown in figure 2 (b). The construction view of proposed composite solid rotor is shown in figure 3.

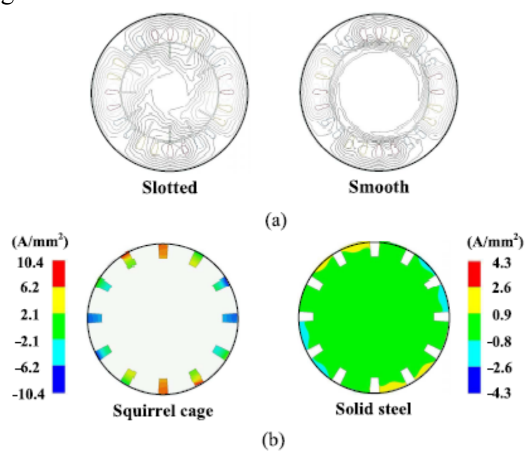

Fig. 2. Distribution of a) flux and b) eddy current [1].

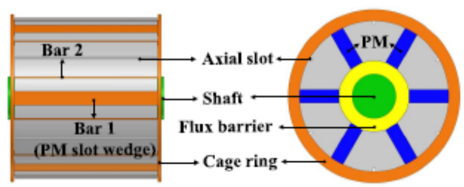

Fig. 3. Constructional view of composite solid rotor [1].

B. Bees Algorithm

The factor which affects the design optimization of rotating electrical machines is the particular application. The designer then needs to decide certain parameters. In case of propulsion or traction application the high torque density, high power density and high efficiency are the major considerations to evolve an optimum design.

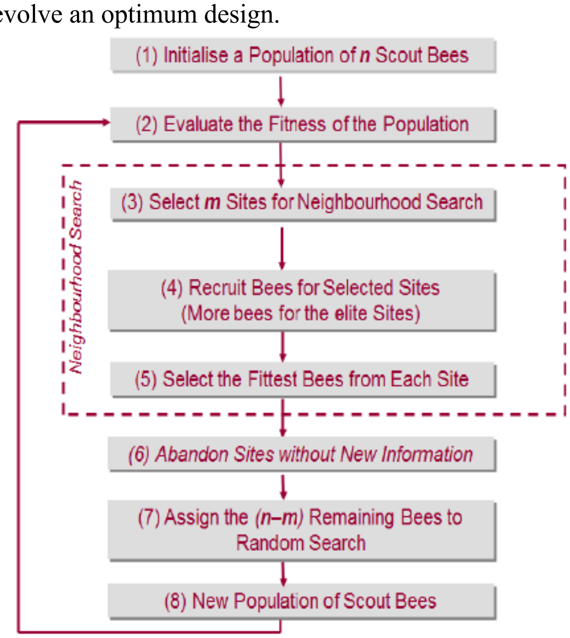

Fig. 4. Bees Algorithm optimal parameters selection criteria [5].

The Bees algorithm is the technique to search the parameters for design optimization. The flow chart of Bees Algorithm is described in figure 4. The first step is to initiate the number of design variables. The design variables are the geometrical parameters, electrical and magnetic specifications. For example the design variables like stator inside diameter, stator core length, rotor magnet width, length and thickness, power density, torque density, current density etc. The second step is to verify/estimate the design variables as per the application/requirement and then confirm the best selected variables in third step. The forth step is to decide the remaining variables for other analysis. The fifth step explains about the effect of each variable on other variables and parameters. After the analysis, the best parameters are confirmed and the results of the analysis are concluded in step 6. The step 7 and step 8 is to assign the suitable design variables for future analysis based on particular application [5].

C. Response Surface Methodology

The design of experiment theory and analytical model are the strategies for identification of electrical machines performance. The relationship between the response (Q) and input variables (P) along with the error (ϵ) to optimize the machine performance is

$$Q = f(P_k) + \epsilon \qquad (k = 1, 2, 3, \dots\dots.. n) \qquad (1)$$

In Response Surface Methodology, the experimentation (simulation) at the time of motor operation provides data as design variables. The design variables decided after analysis can be used as functions. The variation in results owing to a range of functions is the response. The simulation or actual carrying out tests provides the responses.

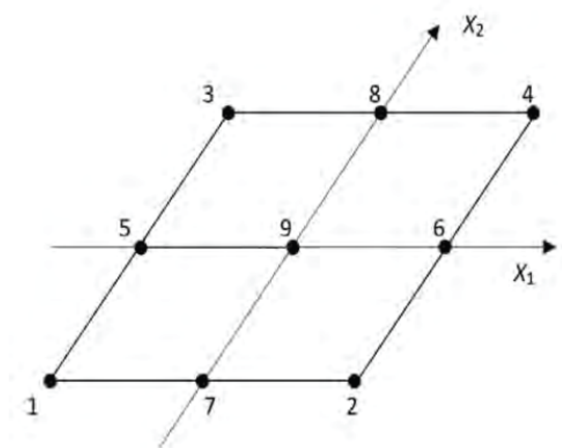

Fig. 5. Central Composite Design of experiment points [6].

The response surfaces are created by following the procedure of Central Composite Design. The experimental points for the response surfaces are shown in figure 5. The simulation or conducting tests provides the interaction between design variables as functions and response surfaces. The design variables can be selected based upon the particular response. The stator, rotor geometrical configuration and magnet dimensions make available the design variables. The confirmation of the design variables and response surfaces optimizes the design [6].

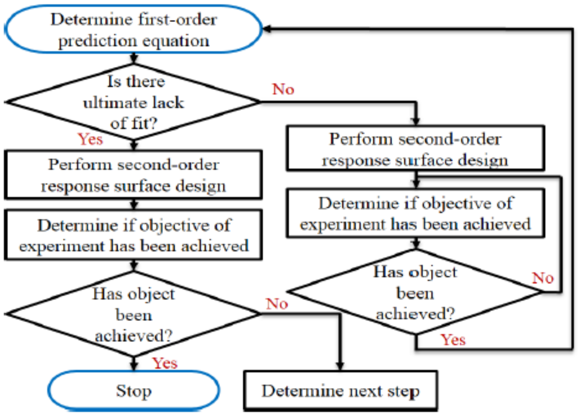

Fig. 6. Flow chart of Response Surface Methodology [23].

D. Taguchi Optimization Method

The lengthy electrical machine design optimization methods for 100 to 1000 numbers of tests may have the conflict in the choice of best possible combination of design variables. The design optimization with Taguchi Optimization method for a specified number of tests is the quick and result oriented technique.

In this technique, the design variables as per the application/objective are to be selected with their levels. The best possible combination of parameters is then confirmed after simulating the motor. The table I shows the design parameters which are also control parameters with their levels. The four parameters: Temperature, magnet thickness, magnet duct and type of magnet are considered and 256 tests have to be performed during full experimentation/simulation. This will be time-consuming process but using Taguchi optimization method only 16 tests are performed [7].

TABLE I

DESIGN VARIABLE PARAMETERS AND THEIR LEVEL [7]

Variable parameters	**Unit**	**Level of Variable Parameters**			
		1	2	3	4
Temperature	°C	20	40	70	80
Magnet Thickness	mm	4	4.5	5.5	6
Magnet Duct dimension	mm	1.5	2.4	3	5
Type of Magnet	--	Ferrite	Alnico	SmCo	NdFe35

E. Genetic Algorithm

The design optimization of machines is not an easy task. To make the optimization process quick and reliable, one of the techniques is genetic algorithm. The researcher or designer as per experience and knowledge of constraints in machine design can search for the optimum design variables/parameters. In genetic algorithm the following steps are helpful for searching the design parameters [9].

a) Decide the objective/application of machine design
b) Choose the design parameters with values and levels
c) Decide the limiting parameters
d) Estimation of the parameters satisfying the particular objective/condition
e) Check the fulfillment of the conditions (Balance)
f) Confirmation of the design parameters

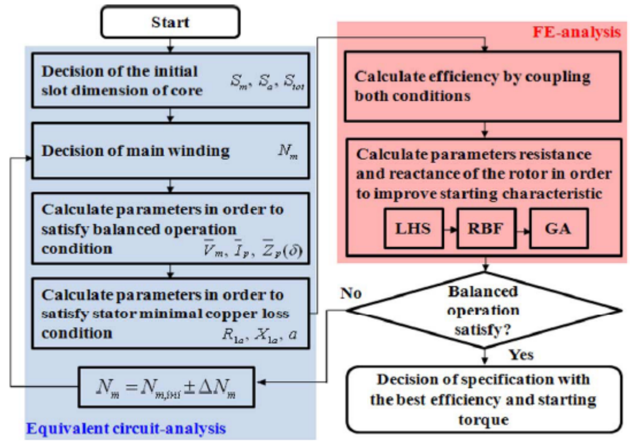

Fig. 7. Optimum Design Algorithm [28]

Design optimization of rotating machines is presented in figure 7. The Latin Hypercube Sampling (LHS) and Radial Basis Function as mentioned in optimum design algorithm are used for selection of sampling & creation of approximate model respectively. Finally the genetic algorithm is used to achieve the optimum design results [28].

III. DESIGN OPTIMIZATION OF IPMSM

The Interior Permanent Magnet Synchronous Motor (IPMSM) is analyzed using RMxprt tool of Ansys. The analysis is initially done for a variety of factors. It was very time consuming process to simulate the IPMSM for number of tests with different design variables. The design optimization techniques: Bees Algorithm, Taguchi Method and Genetic Algorithm help to decide the number and type of design variable. The 6 to 10 geometrical and electrical design variables have been initiated and the verified/estimated design variables are temperature, magnet thickness, magnet duct dimensions and magnet type. The effect of these variables on efficiency, armature current and torque angle is studied and estimated the value of these as objective variables. The best design variables are then confirmed. These are the common steps to be followed while referring the design optimization techniques. The Taguchi optimization method is used to decide the number of tests. The table I give details about the level of design variables. The optimum results of the design variables temperature, magnet thickness, magnet duct dimensions and type of magnet are used to check the optimum performance of the motor. Figure 8 shows the effect of type of magnet on the efficiency and rated torque. The performance of the motor is optimized with the magnetic material SmCo24 and NdFe30. It would be interesting to check the performance of the motor with combined magnetic material. The combination of rare earth and non rare earth magnetic material would be better as said by the literature reviewed.

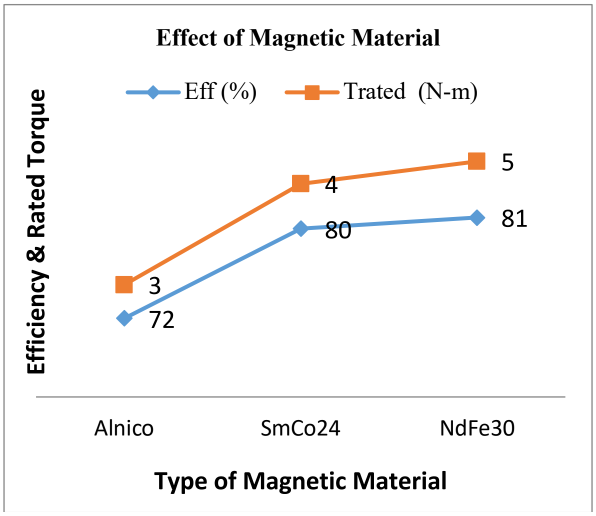

Fig. 8. Effect of magnetic material on Efficiency and rated torque

The performance of the motor is also analyzed with different stator and rotor configurations. The design variable stator outside diameter is varied within the range of 300 mm to 500 mm, stator inside diameter is varied within the range of 217 mm to 410 mm and rotor inside diameter is also varied within the range of 145 mm to 350 mm. These variations cause the changes in the dimensions of stator and rotor tooth and results in the increment of flux. The inductance at the direct and quadrature axis increases with the increment in flux. This effect is shown in figure 9.

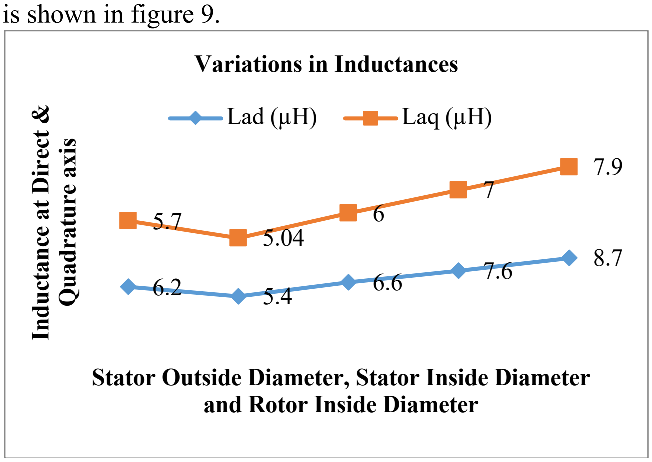

Fig. 9. Effect of variations in stator & rotor diameter on direct and quadrature axis inductance

Taguchi optimization technique and Surface response methodology are used to decide the design variables and their level, confirmation of the best suitable combination of design variables, to decide objective functions as per requirements. The optimization techniques are also used to decide the number and type of variable for future work.

IV. Conclusion

The design optimization techniques studied in this paper are used to identify the design variables, objective functions and the level of the variables. The taguchi optimization technique, response surface methodology and genetic algorithms are used for design optimization of IPMSM. This study is the base to analyze the same IPMSM with different rare earth and non rare earth magnetic materials with modifications in geometrical parameters. The efficiency obtained with the NdFe30 is 81 % and the rated torque is 5 N-m. The performance of the IPMSM is enhanced with the rare earth magnetic materials as compared with the non rare earth magnetic materials. This study can be extended to analyze the motor with the combination of rare and non rare earth magnetic materials.

References

[1] B. Yan, X. Wang and Y. Yang, "Starting Performance Improvement of Line-Start Permanent-Magnet Synchronous Motor Using Composite Solid Rotor," in IEEE Transactions on Magnetics, vol. 54, no. 3, pp. 1-4, March 2018, Art no. 7400504, doi: 10.1109/TMAG.2017.2753238.

[2] M. F. Palangar, W. L. Soong, N. Bianchi and R. -J. Wang, "Design and Optimization Techniques in Performance Improvement of Line-Start Permanent Magnet Synchronous Motors: A Review," in IEEE Transactions on Magnetics, vol. 57, no. 9, pp. 1-14, Sept. 2021, Art no. 900214, doi: 10.1109/TMAG.2021.3098392.

[3] C. Yao, Z. Sun, S. Xu, H. Zhang, G. Ren and G. Ma, "Optimal Parameters Design for Model Predictive Control using an Artificial Neural Network Optimized by Genetic Algorithm," 2021 13th International Symposium on Linear Drives for Industry Applications (LDIA), Wuhan, China, 2021, pp. 1-6, doi: 10.1109/LDIA49489.2021.9505956.

[4] N. Ben Halima, N. Ben Hadj, M. Krichen and R. Neji, "Permanent magnet synchronous motor performance study dedicated to parallel hybrid electric vehicle," 2022 IEEE 21st international Conference on Sciences and Techniques of Automatic Control and Computer Engineering (STA), Sousse, Tunisia, 2022, pp. 629-634, doi: 10.1109/STA56120.2022.10019211.

[5] N. Y. Braiwish, F. J. Anayi, A. A. Fahmy and E. E. Eldukhri, "Design optimization of Permanent Magnet Synchronous Motor for electric vehicles traction using the Bees Algorithm," 2014 49th International Universities Power Engineering Conference (UPEC), Cluj-Napoca, Romania, 2014, pp. 1-5, doi: 10.1109/UPEC.2014.6934742.

[6] A. Semon, L. Melcescu, O. Craiu and A. Crăciunescu, "Design Optimization of the Rotor of a V-type Interior Permanent Magnet Synchronous Motor using Response Surface Methodology," 2019 11th International Symposium on Advanced Topics in Electrical Engineering (ATEE), Bucharest, Romania, 2019, pp. 1-4, doi: 10.1109/ATEE.2019.8724856.

[7] S. Mirnikjoo, S. Milad Kazemi Sangdehi and S. Ehsan Abdollahi, "Multi-objective Optimization of a Permanent Magnet Synchronous Motor for Gearless Elevator," 2021 12th Power Electronics, Drive Systems, and Technologies Conference (PEDSTC), Tabriz, Iran, 2021, pp. 1-6, doi: 10.1109/PEDSTC52094.2021.9405830.

[8] B. P. Ruddy, A. J. Taberner and J. Boyce-Bacon, "Optimization of linear permanent magnet synchronous motors for needle-free jet injection," 2015 Intl Aegean Conference on Electrical Machines & Power Electronics (ACEMP), 2015 Intl Conference on Optimization of Electrical & Electronic Equipment (OPTIM) & 2015 Intl Symposium on Advanced Electromechanical Motion Systems (ELECTROMOTION), Side, Turkey, 2015, pp. 375-381, doi: 10.1109/OPTIM.2015.7427029.

[9] M. Chowdhury, M. Islam, A. Gebregergis and T. Sebastian, "Robust design optimization of permanent magnet synchronous machine utilizing genetic and Taguchi's algorithm," 2013 IEEE

Energy Conversion Congress and Exposition, Denver, CO, USA, 2013, pp. 5006-5012, doi: 10.1109/ECCE.2013.6647376.
[10] Ming-Tsan Lin and Ching-Guo Chen, "Design and implementation of a direct torque controlled interior permanent magnet synchronous motor drive based on a novel flux model," 2011 IEEE Ninth International Conference on Power Electronics and Drive Systems, Singapore, 2011, pp. 394-398, doi: 10.1109/PEDS.2011.6147278.
[11] T. Mohanarajah, J. Rizk, M. Nagrial and A. Hellany, "Comparative analysis of synchronous reluctance machines with and without permanent magnets," 2016 IEEE International Conference on Power System Technology (POWERCON), Wollongong, NSW, Australia, 2016, pp. 1-6, doi: 10.1109/POWERCON.2016.7754013.
[12] G. Y. Sizov, P. Zhang, D. M. Ionel, N. A. O. Demerdash and M. Rosu, "Automated Multi-Objective Design Optimization of PM AC Machines Using Computationally Efficient FEA and Differential Evolution," in IEEE Transactions on Industry Applications, vol. 49, no. 5, pp. 2086-2096, Sept.-Oct. 2013, doi: 10.1109/TIA.2013.2261791.
[13] Y. Zhang, Jingguo Yuan, D. Xie, In Sung Hwang and C. S. Koh, "Shape optimization of a PMLSM using Kriging and genetic algorithm," 2010 5th IEEE Conference on Industrial Electronics and Applications, Taichung, 2010, pp. 1496-1499, doi: 10.1109/ICIEA.2010.5514796.
[14] Kuang-Yao Cheng and Ying-Yu Tzou, "Fuzzy optimization techniques applied to the design of a digital PMSM servo drive," in IEEE Transactions on Power Electronics, vol. 19, no. 4, pp. 1085-1099, July 2004, doi: 10.1109/TPEL.2004.830036.
[15] J. Gao, J. Liu, S. Huang and K. Huang, "Optimum Design of Permanent Magnet Synchronous Motor Based on Gene Handling Genetic Algorithms," 2010 International Conference on Electrical and Control Engineering, Wuhan, China, 2010, pp. 1449-1452, doi: 10.1109/iCECE.2010.358.
[16] S. -M. Jang, J. -H. Choi, J. -H. Park, K. -J. Ko and D. -J. You, "Optimum DC Link Voltage Extraction Based on Dynamic Performance Analysis and Design Parameters of Slotless Double-Sided Permanent Magnet Linear Synchronous Motor," in IEEE Transactions on Magnetics, vol. 46, no. 6, pp. 2286-2289, June 2010, doi: 10.1109/TMAG.2010.2040468.
[17] Yong Li, Jibin Zou and Yongping Lu, "Optimum design of magnet shape in permanent-magnet synchronous motors," in IEEE Transactions on Magnetics, vol. 39, no. 6, pp. 3523-3526, Nov. 2003, doi: 10.1109/TMAG.2003.819462.
[18] L. Fang, J. -w. Jung, J. -P. Hong and J. -H. Lee, "Study on High-Efficiency Performance in Interior Permanent-Magnet Synchronous Motor With Double-Layer PM Design," in IEEE Transactions on Magnetics, vol. 44, no. 11, pp. 4393-4396, Nov. 2008, doi: 10.1109/TMAG.2008.2002001.
[19] J. H. Lee, Tae Won Yun and Ah Ram Jeon, "Characteristic analysis & optimum design of Permanent Magnet Assisted Synchronous Reluctance Motor for premium efficiency performance," Digests of the 2010 14th Biennial IEEE Conference on Electromagnetic Field Computation, Chicago, IL, USA, 2010, pp. 1-1, doi: 10.1109/CEFC.2010.5480556.
[20] M. Chaieb, S. Tounsi, R. Neji and F. Sellami, "Optimum geometry for torque ripple minimization of permanent magnet motor by the finite element method," MELECON 2008 - The 14th IEEE Mediterranean Electro technical Conference, Ajaccio, France, 2008, pp. 459-464, doi: 10.1109/MELCON.2008.4618478.
[21] V. Ghorbanian and D. A. Lowther, "Magnetic and Electrical Design Challenges of Inverter-Fed Permanent Magnet Synchronous Motors," in IEEE Transactions on Magnetics, vol. 53, no. 6, pp. 1-4, June 2017, Art no. 8103804, doi: 10.1109/TMAG.2017.2662013.
[22] M. U. Sardar, D. Manfeng, U. Saleem, S. Siddique and Tanzeela, "Design and Numerical Optimization for High-Performance IPM Synchronous Motor Using PSO Search Algorithm," 2023 IEEE International Conference on Emerging Trends in Engineering, Sciences and Technology (ICES&T), Bahawalpur, Pakistan, 2023, pp. 1-5, doi: 10.1109/ICEST56843.2023.10138874.
[23] J. -H. Sim, B. -H. Lee, Y. -H. Jung and J. -P. Hong, "Optimum design of IPMSM for in-wheel direct-drive by response surface methodology and FEA," 2013 World Electric Vehicle Symposium and Exhibition (EVS27), Barcelona, Spain, 2013, pp. 1-5, doi: 10.1109/EVS.2013.6914729.
[24] Kwang-Ho Lee, Kyung-Ho Kim and Yun-Hyun Cho, "Optimal design of interior type permanent magnet synchronous motors based on magnetic equivalent circuit network method," 2002 IEEE International Magnetics Conference (INTERMAG), Amsterdam, The Netherlands, 2002, pp. DT13-, doi: 10.1109/INTMAG.2002.1001097.
[25] G. -D. Lee, G. -T. Kim, H. -K. Shin and C. -J. Kim, "The optimum design of interior permanent magnet synchronous motor for the vibration reduction," 2015 18th International Conference on Electrical Machines and Systems (ICEMS), Pattaya, Thailand, 2015, pp. 227-231, doi: 10.1109/ICEMS.2015.7385032.
[26] M. F. Palangar, A. Mahmoudi, S. Kahourzade and W. L. Soong, "Optimum Design of Line-Start Permanent-Magnet Synchronous Motor Using Mathematical Method," 2020 IEEE Energy Conversion Congress and Exposition (ECCE), Detroit, MI, USA, 2020, pp. 2064-2071, doi: 10.1109/ECCE44975.2020.9236205.
[27] Jae-Woo Jung, Sang-Ho Lee, Jung-Pyo Hong, Ki-Nam Kim, Hyoung-Jun Cho and Sang-Hoon Moon, "Optimum design for eddy current reduction in permanent magnet to prevent irreversible demagnetization," 2007 International Conference on Electrical Machines and Systems (ICEMS), Seoul, Korea (South), 2007, pp. 949-954, doi: 10.1109/ICEMS12746.2007.4412226.
[28] S. -w. Baek, B. -t. Kim and B. -i. Kwon, "Practical Optimum Design Based on Magnetic Balance and Copper Loss Minimization for a Single-Phase Line Start PM Motor," in IEEE Transactions on Magnetics, vol. 47, no. 10, pp. 3008-3011, Oct. 2011, doi: 10.1109/TMAG.2011.2158077.
[29] J. Xu, L. Gao, L. Zeng and R. Pei, "Optimum Design of Interior Permanent Magnet Synchronous Motor Using Taguchi Method," 2019 IEEE Transportation Electrification Conference and Expo (ITEC), Detroit, MI, USA, 2019, pp. 1-4, doi: 10.1109/ITEC.2019.8790592.
[30] V. Ghorbanian and D. A. Lowther, "A Statistical Solution to Efficiently Optimize the Design of an Inverter-Fed Permanent-Magnet Motor," in IEEE Transactions on Industry Applications, vol. 53, no. 6, pp. 5315-5326, Nov.-Dec. 2017, doi: 10.1109/TIA.2017.2726968.

[31] N. Nishiyama, H. Uemura and Y. Honda, "The optimum design of the magnetic orientation of permanent magnets for IPMSM under hot environments," 2017 IEEE 12th International Conference on Power Electronics and Drive Systems (PEDS), Honolulu, HI, USA, 2017, pp. 380-385, doi: 10.1109/PEDS.2017.8289239.

[32] D. -M. Kim, K. -S. Cha, M. -S. Lim and J. -P. Hong, "Rare-Earth-Free Electric Motor Design for EV Traction Comparing Overall Vehicle Efficiency Considering Driving Cycle," 2016 IEEE 84th Vehicular Technology Conference (VTC-Fall), Montreal, QC, Canada, 2016, pp. 1-5, doi: 10.1109/VTCFall.2016.7881188.

[33] D. Yu, X. Huang, Y. Fang and X. Zhang, "Design Optimization with Outer Rotor Interior Permanent Magnet Synchronous Motor with Hybird Permanent Magnet," 2018 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices (ASEMD), Tianjin, China, 2018, pp. 1-2, doi: 10.1109/ASEMD.2018.8559015.

[34] L. Gao, H. Zhang, L. Zeng and R. Pei, "Rotor Topology Optimization of Interior Permanent Magnet Synchronous Motor With High-Strength Silicon Steel Application," in IEEE Transactions on Magnetics, vol. 57, no. 2, pp. 1-6, Feb. 2021, Art no. 8202806, doi: 10.1109/TMAG.2020.3027893.

[35] A. Fatemi et al., "Design Optimization of an Electric Machine for a 48-V Hybrid Vehicle With Comparison of Rotor Technologies and Pole-Slot Combinations," in IEEE Transactions on Industry Applications, vol. 56, no. 5, pp. 4609-4622, Sept.-Oct. 2020, doi: 10.1109/TIA.2020.3007132.

[36] A. Srivastava, D. K. Das, A. Rai and R. Raj, "Parameter Estimation of a Permanent Magnet Synchronous Motor using Whale Optimization Algorithm," 2018 Recent Advances on Engineering, Technology and Computational Sciences (RAETCS), Allahabad, India, 2018, pp. 1-6, doi: 10.1109/RAETCS.2018.8443839

[37] S. Pastellides, S. Gerber and R. -J. Wang, "Design Strategy and Comparison of Four PM Motor Topologies for a 2kW Traction Application," 2019 Southern African Universities Power Engineering Conference/Robotics and Mechatronics/Pattern Recognition Association of South Africa (SAUPEC/RobMech/PRASA), Bloemfontein, South Africa, 2019, pp. 358-363, doi: 10.1109/RoboMech.2019.8704829.

[38] C. -H. Wi and D. -K. Lim, "Tornado Optimization With Pattern Search Method for Optimal Design of IPMSM," in IEEE Transactions on Magnetics, vol. 58, no. 2, pp. 1-4, Feb. 2022, Art no. 8201404, doi: 10.1109/TMAG.2021.3086797

[39] G. Y. Sizov, P. Zhang, D. M. Ionel, N. A. O. Demerdash and M. Rosu, "Automated Multi-Objective Design Optimization of PM AC Machines Using Computationally Efficient FEA and Differential Evolution," in IEEE Transactions on Industry Applications, vol. 49, no. 5, pp. 2086-2096, Sept.-Oct. 2013, doi: 10.1109/TIA.2013.2261791.

[40] J. F. Cardoso, C. Chillet, L. Gerbaud and L. A. Belhaj, "Electrical Machine Design by optimization for E-motor Application: a Drive Cycle Approach," 2020 International Conference on Electrical Machines (ICEM), Gothenburg, Sweden, 2020, pp. 2514-2519, doi: 10.1109/ICEM49940.2020.9270888.

[41] A. J. Sorgdrager, R. -J. Wang and A. J. Grobler, "Retrofit design of a line-start PMSM using the Taguchi method," 2015 IEEE International Electric Machines & Drives Conference (IEMDC), Coeur d'Alene, ID, USA, 2015, pp. 489-495, doi: 10.1109/IEMDC.2015.7409103.

[42] S. -G. Lee, S. Kim, J. -C. Park, M. -R. Park, T. H. Lee and M. -S. Lim, "Robust Design Optimization of SPMSM for Robotic Actuator Considering Assembly Imperfection of Segmented Stator Core," in IEEE Transactions on Energy Conversion, vol. 35, no. 4, pp. 2076-2085, Dec. 2020, doi: 10.1109/TEC.2020.2999127.

[43] D. Fodorean and L. Idoumghar, "Improved Performances of a PMSM with Reduced Torque Ripples, Optimized Based on Hybrid Algorithm, Dedicated for Light EV," 2015 IEEE Vehicle Power and Propulsion Conference (VPPC), Montreal, QC, Canada, 2015, pp. 1-6, doi: 10.1109/VPPC.2015.7352965.

Rupalee S. Ambekar (Member, IEEE) was born in 1978. She received the Bachelor's Degree in Electrical, Electronics and Power Engineering, the Master's Degree in Electric Power Systems from the Dr. Babasaheb Ambedkar Marathwada University of Aurangabad, India, in 2002, 2010 respectively.

She is currently pursuing the Ph.D. degree with the Bharati Vidyapeeth (Deemed to be University) College of Engineering, Pune, India. She has gained 22 years of teaching experience in engineering colleges. Currently, she is doing research work with the Department of Electrical and Computer Engineering, Bharati Vidyapeeth (Deemed to be University) College of Engineering, Pune, India. Her research interests include electric vehicle, electrical machines, Electrical Machine Design, Special Machines.

Dr. Rajesh M. Holmukhe, photograph and biography not available at the time of publication.

Rahul S. Desai, photograph and biography not available at the time of publication.

Omkar Patil, photograph and biography not available at the time of publication.