ISSN NO: 2770-4491
February 2025

Data-Driven Approach To Define Mathematical Model Of A Permanent-Magnet Synchronous Motor Used In Small Class Electric Vehicles.

Asanov Seyran,
Department of Mechanical and Aerospace Engineering, Turin Polytechnic University in Tashkent
seyran.asanov@polito.uz , https://orcid.org/0009-0002-2109-6294

Abstract. The development of cutting-edge motor technologies for electric vehicles (EVs) has been fueled by the global movement towards sustainable mobility. Because of its great efficiency, power density, and flexibility to operate at various speeds, Permanent-Magnet Synchronous Motors (PMSMs) have become the go-to option for small-class EVs. However, the accuracy and applicability of standard mathematical modeling techniques are limited because they frequently miss real-world nonlinearities and parameter fluctuations.
In this paper, a data-driven methodology for PMSM modeling that is tailored for small-class EV applications is presented. The suggested method improves the precision, flexibility, and computational efficiency of PMSM models by utilizing real-world operational data. The efficiency map and peak torque characteristics of the WULING MACARON EV's electric drive were defined using regression analysis, which produced low residual errors and high R-squared values of 0.9647 and 0.9789, respectively. The outcomes show that the model can optimize energy use, forecast performance under various circumstances, and assist real-time control applications.

Keywords: Permanent-Magnet Synchronous Motor (PMSM), Small-Class Electric Vehicles, Data-Driven Modeling, Motor Efficiency Map, Regression Analysis.

INTRODUCTION. The popularity of electric vehicles (EVs) has increased due to the global trend towards sustainable transportation, which calls for improvements in motor technologies that are economical, efficient, and small[1], [2]. Because of its great efficiency, power density, and exceptional performance in variable-speed operations, Permanent-Magnet Synchronous Motors (PMSMs) have become the motor type of choice for electric vehicle (EV) applications[3], [4], [5]. Because of these characteristics, PMSMs are especially well-suited for small-class electric vehicles, which need systems that are lightweight, effective, and compact in order to combine affordability and performance[6].
Traditionally, first-principles mathematical equations like Maxwell's equations and dq-reference frame transformations are used to study and model PMSMs[7]. Although these techniques offer a theoretical basis, they frequently fall short in capturing parameter fluctuations and real-world nonlinearities, such as manufacturing tolerances, temperature effects, and magnetic saturation[8]. When applied to real-world systems, this discrepancy may result in inaccurate simulations and less-than-ideal performance[9], [10].

LITERATURE REVIEW. New opportunities for motor modeling have been made possible by recent developments in data-driven methodologies[11]. Machine learning algorithms and optimization techniques can improve existing models or develop completely new ones by utilizing real-world data gathered from motor operation. These data-driven methods have the potential to increase precision, lessen reliance on laborious parameter estimation, and adjust to changing operating circumstances[12]. Such strategies can offer a substantial competitive advantage for small-class EVs, where efficiency and drivability are strongly impacted by motor control precision[13].
With an emphasis on their use in small-class electric vehicles, this work attempts to investigate the incorporation of data-driven approaches into the mathematical modeling of PMSMs. This study aims to overcome the shortcomings of current models and open the door for more reliable and flexible solutions that are suited to the requirements of tiny EVs by fusing conventional analytical frameworks with cutting-edge data-driven methodologies[14].

A modeling strategy that can close the gap between theoretical precision and real-world application is desperately needed. A potential remedy is provided by data-driven approaches, which use operational data to improve or reinterpret motor models. But nothing is known about how to incorporate them into PMSM modeling, especially for small-class EVs. In order to close this gap, this research suggests a data-driven framework that improves PMSM models' precision, flexibility, and computational efficiency while concentrating on satisfying the unique needs of small-class electric vehicles[4], [15].

This study's main goal is to create a mathematical model for a Permanent-Magnet Synchronous Motor (PMSM) that is specifically intended for small-class electric vehicles using a data-driven method. By using real-world operational data to capture nonlinearities and parameter fluctuations that standard models miss, this model seeks to[16]:

1. Improve accuracy by incorporating real-world operational data to capture nonlinearities and parameter variations that traditional models overlook.
2. Enhance adaptability by enabling the model to account for dynamic changes in operating conditions, such as temperature fluctuations and load variations.
3. Balance computational efficiency and precision to ensure the model is suitable for real-time control applications in small-class EVs.
4. Address the specific requirements of small-class EVs, including compact motor designs, high torque-to-weight ratios, and optimized energy utilization.

In order to provide a reliable and scalable solution for next-generation small-class electric vehicles, this study aims to close the gap between theoretical modeling and actual motor performance[17].

METHODOLOGY. In the field of electrical machines, it is common practice to use a multi-parameter machine characterisation, describing the iso-contours of efficiency as a function of torque and rotor speed. This type of characterisation is called multi-parameter characterisation of an electric motor. Quite often, the efficiency map of an electric drive also takes into account the inverter efficiency and gives the generalised efficiency of the drive and inverter respectively. An example of multi-parameter characteristic of electric drive is shown in Figure 1[18].

This characterisation describes the electric drive characteristic of the WULING MACARON EV, which is the subject of this study. This characterisation can be extended to take into account the fact that in the process of studying the longitudinal dynamics of the vehicle in this study, not only the traction characteristics of the electric drive are considered, but also its ability to operate in generator mode when the rotor is rotating, i.e. the operation of the vehicle is defined in the first and fourth quadrants[19], [20], [21]. Taking the above into account, the corrected characteristic of the electric drive is given in Figure 1.

ISSN NO: 2770-4491
February 2025

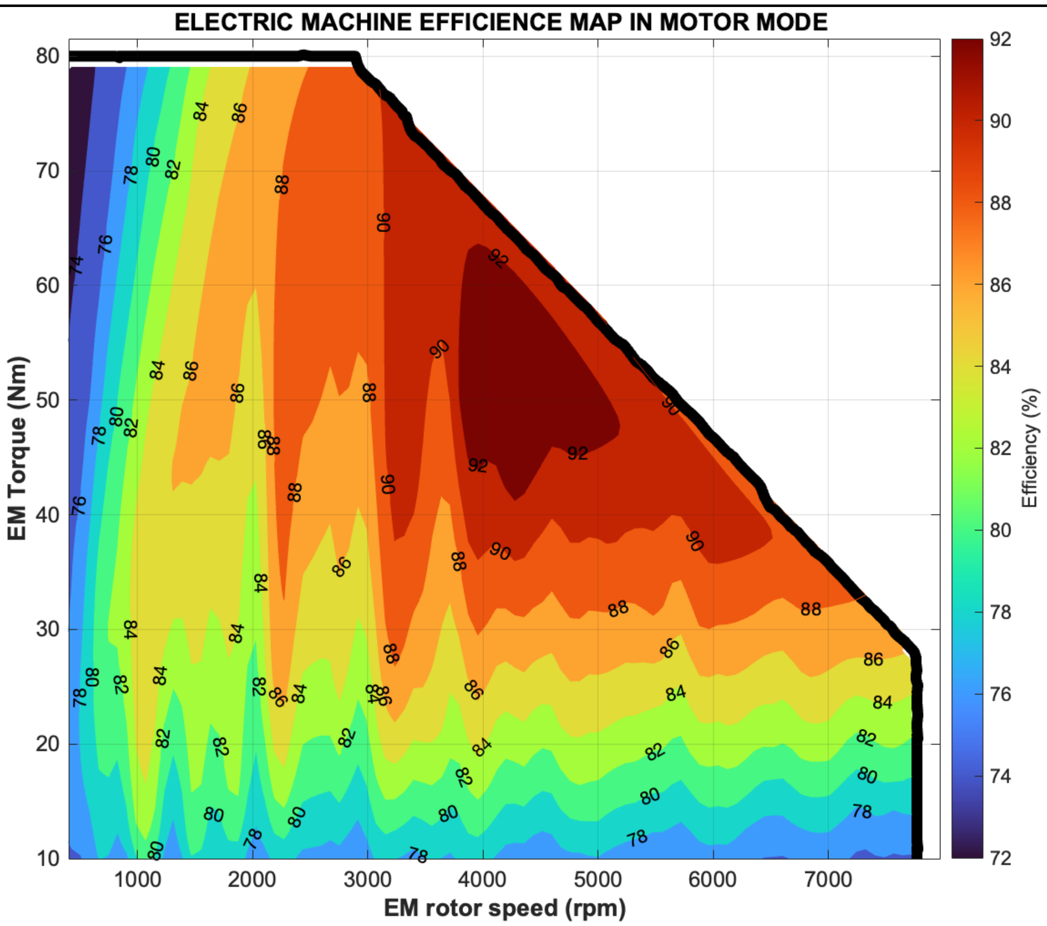

Figure 1 Electric machine efficiency map in motor mode

This characteristic of an electric machine takes into account several input quantities, such as the required torque and rotor speed, and also allows the calculation of the power value of the electric machine, which is the output quantity of the characteristic[22].

The relationship between the input and output quantities is realised through the efficiency of the electric machine in traction mode and in generator mode, respectively. This relationship is represented as a function of two variables:

$$\begin{cases} \eta_{mot} = f(T_{mot}, \omega_{mot}), \\ \eta_{gen} = f(T_{gen}, \omega_{gen}) \end{cases}$$

ISSN NO: 2770-4491
February 2025

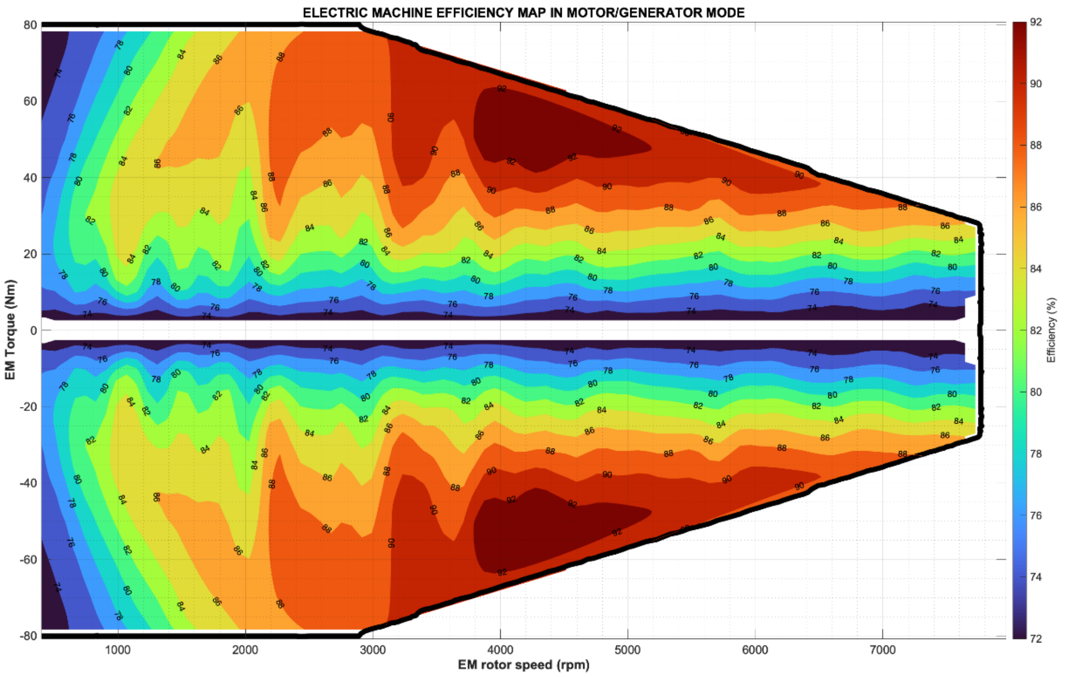

Figure 2 Electric machine efficiency map in motor/generator mode

With the help of the electric machine characteristic shown in Figure 2, it is possible to calculate the required power in the modes of traction P_{mot} and generator P_{gen}, respectively, taking into account the efficiency in the desired mode of operation:

$$\begin{cases} P_{mot} = \dfrac{T_{mot}\omega_{mot}}{\eta_{mot}}, \\ P_{gen} = \eta_{gen}\mathrm{T}_{gen}\omega_{gen} \end{cases}$$

Isolines of electric machine efficiencies are described by a polynomial from two variables:

$$\eta_{mot} = p_{00} + p_{10}\omega_{em} + p_{01}T_{em} + p_{20}\omega_{em}^2 + p_{11}\omega_{em}\mathrm{T}_{em} + p_{02}T_{em}^2 + p_{30}\omega_{em}^3 + p_{21}\omega_{em}^2\mathrm{T}_{em} + p_{12}\omega_{em}\mathrm{T}_{em}^2 + p_{03}\mathrm{T}_{em}^3 + p_{40}\omega_{em}^4 + p_{31}\omega_{em}^3\mathrm{T}_{em} + p_{22}\omega_{em}^2\mathrm{T}_{em}^2 + p_{04}\mathrm{T}_{em}^4 + p_{50}\omega_{em}^5 + p_{41}\omega_{em}^4\mathrm{T}_{em} + p_{32}\omega_{em}^3\mathrm{T}_{em}^2 + p_{23}\omega_{em}^2\mathrm{T}_{em}^3 + p_{14}\omega_{em}^1\mathrm{T}_{em}^4 + p_{05}\mathrm{T}_{em}^5$$

RESULTS AND DISCUSSIONS. The coefficients p_{ij} were determined using regression analysis from two variables, according to which the following main results were obtained, summarised in Table 1. The approximation coefficients p_{ij} have the following values:

$$p_{00} = 71.14;\ p_{10} = 10.9;\ p_{01} = -1.564; p_{20} = -144.5; p_{11} = 1087;\ \ p_{02} = 46.26;\ p_{30} = 393.7;\ p_{21} = -2848; p_{12} = -1946;\ p_{03} = -273.9;\ p_{40} = -375.4;\ p_{31} = 2195;\ p_{22} = 5055;\ p_{13} = 813; p_{04} = 460.4; p_{50} = 114.4;\ p_{41} = -456.4; p_{32} = -2517; p_{23} = -1972; p_{14} = 88.34; p_{05} = -234.1.$$

Table 1. Regression analysis results for finding the coefficients of the efficiency polynomial as a function of normalised torque and normalised angular velocity

Regression analysis criterion	**Value**
R-square	0.9647
Sum of regression residuals	2.03
RMS error	1.4254

The maximum torque value of an electric machine is the curve limiting the area of operation. This curve is described by the function of the angular speed of the EM:

$$T_{mot.max} = -2932\omega_{em}^6 + 7317\omega_{em}^5 - 6378\omega_{em}^4 + 2251\omega_{em}^3 - 344.6\omega_{em}^2 + 21.16\omega_{em} + 79.67$$

The coefficients of the sixth-degree polynomial were obtained using regression analysis from one variable, according to which the following main results were obtained as shown in Table 2.

Table 2. Results of regression analysis to find the dependence of peak torque on normalised angular velocity

Regression analysis criterion	**Value**
R-square	0.9789
Sum of regression residuals	12.034
RMS error	4.066

The regression analysis applied to the efficiency map of the WULING MACARON EV yielded significant results, demonstrating the efficacy of the proposed data-driven methodology. The coefficients p_{ij}, calculated for the polynomial function representing efficiency as a function of normalized torque and angular velocity, show a high degree of accuracy, with an R-squared value of 0.9647. This indicates a strong correlation between the modeled and actual efficiency data, while the sum of regression residuals (2.03) and RMS error (1.4254) confirm the robustness of the polynomial approximation.

Similarly, the maximum torque function obtained an R-squared value of 0.9789. It was defined as a sixth-degree polynomial that depends on normalized angular velocity. This highlights even more how well the model predicts the electric machine's operating boundaries. The model's accuracy in describing peak torque behavior under various circumstances is further supported by the comparatively low residual sum (12.034) and RMS error (4.066). The outcomes also demonstrate how well the suggested framework can adjust to changing operational circumstances. The model successfully captures nonlinearities and parameter fluctuations, such as those brought on by temperature effects and magnetic saturation, by utilizing data-driven methodologies. Even in situations where conventional analytical models are unable to produce accurate forecasts, this flexibility guarantees excellent accuracy. The torque boundary function and resulting efficiency map allow for accurate power need estimation in both traction and generator modes in real-world applications. Because small-class electric vehicles are naturally limited by their modest energy storage capacities, this is essential for optimizing their energy consumption. The model's applicability to actual driving situations is further demonstrated by its capacity to take into consideration both traction and regenerative braking actions, as represented by the first and fourth quadrants of operation. All things considered, the suggested method increases computational efficiency and PMSM modeling quality, which qualifies it for real-time control applications. The unique requirements of small-class EVs are met by this precision and efficiency combination, opening the door for additional developments in environmentally friendly transportation technology.

Conclusion. In order to define the mathematical model of a Permanent-Magnet Synchronous Motor (PMSM) specifically for small-class electric vehicles, this study offered a data-driven approach. The shortcomings of conventional analytical techniques were addressed by incorporating real-world operational data into the modeling process, which allowed for increased precision, flexibility, and computational efficiency. The efficacy of the suggested method was shown by the regression analysis findings, which showed minimal residuals, RMS errors, and high R-squared values (0.9647 for the efficiency polynomial and 0.9789 for the peak torque function). These results confirm that the model can accurately and reliably forecast performance by capturing nonlinearities, parameter fluctuations, and dynamic operating conditions.

The outcomes also demonstrated the model's usefulness for real-time control in small-class EVs, which have limited energy storage capacities and compact designs. The framework's usefulness for maximizing energy efficiency and drivability in practical situations is further increased by its capacity to describe both traction and regenerative braking actions.

Bibliography.

[1] M. Islameka, B. A. Budiman, F. B. Juangsa, and M. Aziz, "Energy management systems for battery electric vehicles," in *Emerging Trends in Energy Storage Systems and Industrial Applications*, Elsevier, 2023, pp. 113–150. doi: 10.1016/B978-0-323-90521-3.00006-5.

[2] Z. Hongyan and Z. Tianjun, "Improving Vehicle Stability Using Electro-hydraulic Braking System," in *2009 International Conference on Information Technology and Computer Science*, IEEE, Jul. 2009, pp. 593–596. doi: 10.1109/ITCS.2009.129.

[3] M.Ehsani, *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles, Third Edition*. CRC Press, 2018. doi: 10.1201/9780429504884.

[4] J. G. Hayes and G. A. Goodarzi, *Electric Powertrain*. Wiley, 2017. doi: 10.1002/9781119063681.

[5] S. Heydari, P. Fajri, I. Husain, and J.-W. Shin, "Regenerative Braking Performance of Different Electric Vehicle Configurations Considering Dynamic Low Speed Cutoff Point," in *2018 IEEE Energy Conversion Congress and Exposition (ECCE)*, IEEE, Sep. 2018, pp. 4805–4809. doi: 10.1109/ECCE.2018.8558324.

[6] E. Pipitone and G. Vitale, "A regenerative braking system for internal combustion engine vehicles using supercapacitors as energy storage elements - Part 2: Simulation results," *J Power Sources*, vol. 448, p. 227258, Feb. 2020, doi: 10.1016/j.jpowsour.2019.227258.

[7] Ali Emadi, *Advanced Electric Drive Vehicles*. CRC Press, 2014.

[8] G. A. Goodarzi and J. G. Hayes, "Electric Powertrain: Energy Systems, Power Electronics and Drives for Hybrid, Electric and Fuel Cell Vehicles," 2018.

[9] F. U. S. A. Jamshid Inoyatkhodjaev, "METHOD FOR SIZING AN ELECTRIC DRIVE FOR SMALL CLASS ELECTRIC VEHICLES," *UNIVERSUM:ТЕХНИЧЕСКИЕ НАУКИ*, vol. 109, no. 4, Apr. 2023, doi: 10.32743/UniTech.2023.109.4.15230.

[10] S. ASANOV and F. UMEROV, "DYNAMIC MULTICRITERIA ANALYSIS DEVELOPMENT OF THE ELECTRIC VEHICLE MARKET AND THEIR INFRASTRUCTURE IN UZBEKISTAN," *Acta of Turin Polytechnic University in Tashkent*, vol. 13, no. 3, pp. 51–55, Nov. 2023, [Online]. Available: https://acta.polito.uz/index.php/journal/article/view/231

[11] F. Umerov, "The PROSPECTS FOR THE DEVELOPMENT OF ELECTRIC VEHICLES IN UZBEKISTAN," *Acta of Turin Polytechnic University in Tashkent*, vol. 12, no. 2, Nov. 2022, [Online]. Available: https://acta.polito.uz/index.php/journal/article/view/172

[12] S. ASANOV, "A data-driven approach to define a mathematical model of the traction battery used in small class electric vehicles.," *Acta of Turin Polytechnic University in Tashkent*, vol. 14, no. 2, pp. 52–56, Dec. 2024, [Online]. Available: https://acta.polito.uz/index.php/journal/article/view/298

[13] F. Umerov, "The JUSTIFICATION OF PERFORMANCE INDICATORS OF SMALL-CLASS ELECTRIC VEHICLES AND THEIR TRACTION BATTERIES," *Acta of Turin Polytechnic University in Tashkent*, vol. 12, no. 3, Apr. 2023, [Online]. Available: https://acta.polito.uz/index.php/journal/article/view/197

[14] Iqbal Husain, *Electric and Hybrid Vehicles*. CRC Press, 2021.

[15] J. Chen, C. Xu, C. Wu, and W. Xu, "Adaptive Fuzzy Logic Control of Fuel-Cell-Battery Hybrid Systems for Electric Vehicles," *IEEE Trans Industr Inform*, vol. 14, no. 1, pp. 292–300, Jan. 2018, doi: 10.1109/TII.2016.2618886.

[16] K. Mathew K, D. M. Abraham, and A. Harish, "Speed regulation of PMSM drive in electric vehicle applications with sliding mode controller based on harris Hawks optimization," *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, vol. 9, p. 100643, Sep. 2024, doi: 10.1016/j.prime.2024.100643.

[17] Asanov Seyran Enverovich, "CLASSIFICATION OF PARALLEL HYBRID ELECTRIC VEHICLES BASED ON THE POSITION OF THE ELECTRIC POWERTRAIN," Research and Education, Apr. 2022, pp. 95–99. Accessed: Jan. 16, 2025. [Online]. Available: https://researchedu.org/index.php/re/article/view/688

[18] F. Umerov, "ANALYSIS OF THE RECOVERY SYSTEM BRAKING ELECTRIC VEHICLES," *Acta of Turin Polytechnic University in Tashkent*, vol. 13, no. 3, pp. 43–46, Nov. 2023, [Online]. Available: https://acta.polito.uz/index.php/journal/article/view/235

ISSN NO: 2770-4491
February 2025

[19] K. POPIOŁEK, “Analysis of Regenerative Braking Strategies,” *PRZEGLĄD ELEKTROTECHNICZNY*, vol. 1, no. 6, pp. 119–125, Jun. 2019, doi: 10.15199/48.2019.06.21.
[20] L. Zhang and X. Cai, “Control strategy of regenerative braking system in electric vehicles,” *Energy Procedia*, vol. 152, pp. 496–501, Oct. 2018, doi: 10.1016/j.egypro.2018.09.200.
[21] W. Melis and O. Chishty, “Fully Regenerative braking and Improved Acceleration for Electrical Vehicles,” *International Journal of Sustainable Energy Development*, vol. 2, pp. 75–80, Sep. 2013, doi: 10.20533/ijsed.2046.3707.2013.0011.
[22] Z. Zhang, R. Ma, L. Wang, and J. Zhang, “Novel PMSM Control for Anti-Lock Braking Considering Transmission Properties of the Electric Vehicle,” *IEEE Trans Veh Technol*, vol. 67, no. 11, pp. 10378–10386, Nov. 2018, doi: 10.1109/TVT.2018.2866828.

BIOGRAPHY.

Asanov Seyran currently works as a Senior Lecturer at the Department of Mechanical and Aerospace Engineering at Turin Polytechnic University in Tashkent, Uzbekistan. He obtained his degree in Mechanical Engineering at Turin Polytechnic University in Tashkent in 2016. He obtained his Master’s degree in Mechanical Engineering at Politecnico di Torino (Italy). Currently he pursues his PhD degree in Automotive Engineering in the field of Electrified Transport.