MODELLINNG, CONTROL AND EXPERIMENTAL VALIDATION FOR MOTORISED WHEEL SPEED CONTROL

M.S.A. Razak[1], M.H. Che Hasan[2], and F. Ahmad[1]

[1]Fakulti Kejuruteraan Mekanikal,
Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.

[2]Fakulti Teknologi Kejuruteraan Elektrik dan Elektronik,
Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.

Corresponding Author's Email: [1]shukriazizi01@gmail.com

Article History: Received 02 May 2023; Revised 31 May 2023; Accepted 08 June 2023

ABSTRACT: *This paper presents the experimental validation of three-phase motorized wheel (MW) mathematical model. The research which ignited from the lack of validation of MW was started from the simulation that developed utilizing MATLAB/Simulink software. A speed control based Proportional-Integral (PI) controller was then implemented to the simulation to verify the effectiveness of the mathematical model. Several simulation tests namely step, sinewave and sawtooth function at 10, 20, and 30 km/h respectively have been conducted. In order to ensure the reliability of the simulation model, a series of validation tests were performed using the same tests method conducted in the simulation. Various parameters, such as speed, distance, current, torque, and voltage, were measured during the tests. The results indicated that the simulation results are able to mimic the trend of experimental data with an acceptable error rate of less than 5%.*

KEYWORDS: *Motorized Wheel (MW); PI-Controller; Quarter Car Traction Model; Simulation Model; HILS tests.*

1.0 INTRODUCTION

The enforcement of stringent safety standards has led to the need to ensure that electric vehicle propulsion systems are efficient [1]–[3]. This drive characteristic requires a fast response to act effectively, especially in critical situations. However, meeting this requirement with a single motor electric vehicle system is nearly impossible due to the complex mechanical linkage between a single motor and gearbox system which lead to the energy waste [4], as well as the system's bulky size, heavyweight, and delayed time response to transmit the power to the wheels [5]–[8]. Additionally, the power transmitted to the wheel varied depending on the gearing system and motor design [5], [9], [10].

Inspired by motorized wheel (MW) technology, this system has been used to overcome the drawback of a single-motor system. The MW technology transmits the power directly to the wheels [1], without mechanical linkage attached [11], [12], allowing for instant power transmission and no delay between the motor and wheels [4], [5], [13], [14]. Since the MW works independently on each side, it allows this system to be actively design by tuning the dynamic response of the MW based on the road surface. Consequently, the system can enhance the acceleration time and enable the integration of advanced control features [2], [5], [9], [15], such as adaptive cruise control (ACC), vehicle stability control (VSC), emergency braking (EB), and other advance features by actively design the MW behavior.

Most researchers today have successfully modeled and controlled the torque and speed of the MW through simulation [5], [16–19] with a variety of controllers being employed. This includes Space Vector Modulation Direct Torque Control (SVM-DTC) [5], [20], stator flux-oriented control (FOC) [20], [14], Predictive Torque Controller (PTC) [14], Neuro-Fuzzy Control (NFC) [21], Model Predictive Control (MPC) strategy [3], [13], Sliding Mode Control (SMC) [20], and V/f control [14]. However, majority of the research is focused on torque control and limited by the simulation model. It is worth mentioning that there is a lack of researchers who validate the simulation model constructed, leading a doubt regarding model developed and accuracy of the finding, rendering it impractical to be used.

Therefore, this study highlights the modelling and validation of MW model by utilizing real hardware. This research was further by developing a speed control of MW using Proportional-Integral (PI) controller, which underwent testing in both simulation model and experiment. In order to verify the credibility of the PI controller, various tests were conducted by using different patterns, which are step, sinewave and sawtooth, with amplitude of 10, 20, and 30 km/h, respectively.

This paper is structured to enhance comprehension and proceeds as follows: Section two expounds the simulation model of the motorized wheel (MW), while section three furnishes exhaustive details concerning the hardware and experimental setup. Section four delineates the speed control scheme of MW, and section five centers on the simulation and experimental findings.

2.0 SIMULATION MODEL OF MOTORIZED WHEEL

The MW used in this experiment is a permanent magnet synchronous motor (PMSM) type, that employs a three-phase voltage source inverter [1], [4], [19]. To mathematically characterize the MW system using mathematical equations, it is transformed to rotor reference dq and $\alpha\beta$ frame axis, as depicted in Figure 1.

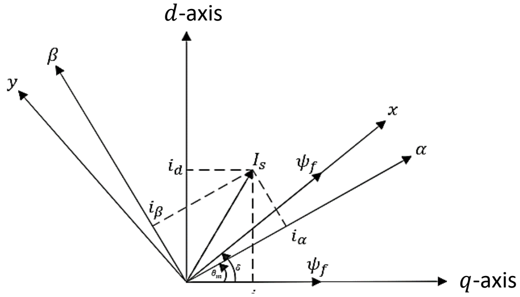


Figure 1: MW dq and $\alpha\beta$-axes

Assuming a sinusoidal electromotive force (EMF) is utilized and balanced stator windings, the stator equation on the dq-axis is expressed as follows:

$$V_{ds} = R_s i_{ds} + \frac{d\psi_{ds}}{dt} - P\omega_r \psi_{qs} \tag{1}$$

$$V_{qs} = R_s i_{qs} + \frac{d\psi_{qs}}{dt} - P\omega_r \psi_{ds} \tag{2}$$

Where the stator flux is represented as

$$\psi_{ds} = L_d i_{ds} + \psi_f \tag{3}$$

$$\psi_{qs} = L_q i_{qs} \tag{4}$$

Noted that the R_s is represented as stator resistance; i_{ds} and i_{qs} is defined as the stator current on dq-axis; P is the number of poles; ω_r is the rotor angular velocity; ψ_{ds} and ψ_{qs} is the stator flux on the dq-axis; L_d and L_q is the inductance on the dq-axis.

The electromagnetic torque equation is expressed as

$$T_e = \frac{3}{2} P(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}) \tag{5}$$

Thus, the dynamic equation of the MW is given as

$$J\frac{d\omega_r}{dt} = T_e - T_L - B\omega_r \tag{6}$$

Where J is the moment of inertia, T_L is the motor torque load, and B is the viscous friction coefficient. Table 1 shows the specification of MW modeled G-M045, which was obtained using the system identification (SI) method.

Table 1: Specification of MW

Definition	Symbol	Unit	Value
DC voltage source	V_{dc}	V	48
Number of poles pairs	P	-	22
d-axis inductance	L_d	H	0.0066
q-axis inductance	L_q	H	0.0058
Permanent magnet flux linkage	ψ_f	Wb	0.175
Moment inertia of the wheel	J	$Kg.m^2$	0.00176
Viscous damping	B	N.m.s	0.00038818

3.0 HARDWARE AND EXPERIMENTAL SETUP

Figure 2 illustrates the experimental setup of MW that has been configured and linked to MATLAB/Simulink software via computer. In order to obtain the MW responses data, various hardware and sensors have been employed, which are data acquisition system (DAQ), battery, speed sensor, current sensor, and voltage sensor. DAQ is used to capture data from transducers. It has been supplemented by a set of on-board peripherals used in digital control systems such as A/D and D/A converters. In addition, the MW driver is energized by a 48 V battery, consisting of gate driver circuits and a three-phase voltage source inverter (VSI) based on IGBTs. The VSI is recommended to function at a maximum switching frequency of 60 kHz and be capable of delivering up to 20A. The DC link voltage of 48V for the VSI is obtained by employing three-phase diode bridge rectifier modules. To avert a short-circuit malfunction, a dead time of 3.0μs is implemented for each switching transition in this VSI.

Moreover, the speed sensor used is based on hall sensor effect which using magnetic sensing method to detect the changes in the magnetic field induced by the rotation of the MW. The speed sensor operates by generating a voltage when the magnetic field is perpendicular to the current-carrying conductor when the MW is rotated. The resulting magnetic field changes are then applied for the analysis of MW speed, that transmitted through two signal wires designated as phase A and phase B and connected to a DAQ device. Other than that, a current and voltage sensor enables the analysis of the MW's current and voltage during dynamic. Even though the MW used a three-phase configuration, only a single phase of current is adequate to estimate the torque produced from the MW, where the i_{qs} is the peak current generated from the three-phase current [15], [20], thus it can be mathematically simulated based on the equation (5) by assuming $i_{ds} = 0$ due to the concept of vector control [14], [15].

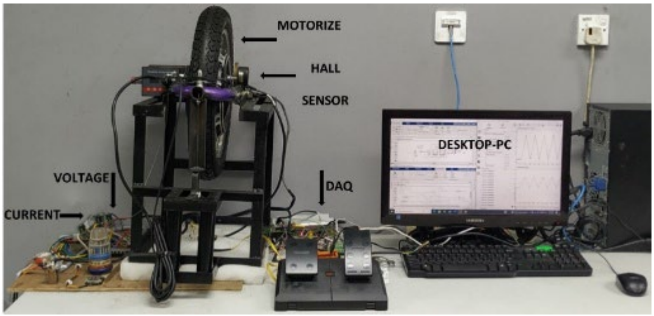


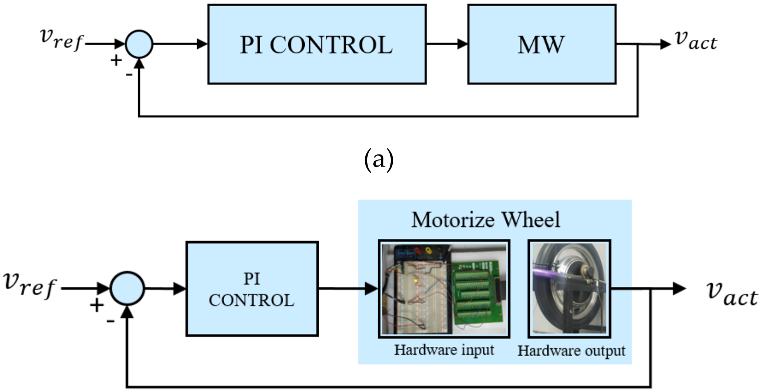
Figure 2: Experimental setup of MW via MATLAB/ Simulink software

4.0 SPEED CONTROL SCHEME OF MW

Drawing on prior research [4], [14], it was found that a MW has been utilize PI control. Therefore, a close-loop PI control scheme has been devised, where the input is the reference speed, while the output is the actual speed, which can be seen in Figure 3 (a). The controller has been tuned using the sensitivity analysis method, yielding values of 13 and 7 for P and I, respectively. The mathematical equation of the PI control scheme is expressed as follows:

$$PI = K_p + K_i \int_0^t e(t)\, dt \tag{7}$$

To enhance the trustworthiness of the developed speed control, Figure 3 (b) illustrates the integration of the PI controller with the MW hardware. From the figure, the output of the PI control is connected to the hardware input, while the hardware output (hall sensor) is used to track the MW speed and utilized as feedback and output for this control system. The MW experimental tests have been compared with the MW simulation design to analyze the deviation between simulation results and experimental data regarding speed. Both experiment and simulation are tested using three different input modes, which are step, sine wave, and sawtooth, at the speed of 10, 20, and 30 km/h. This ensures that the PI control can adapt to different input modes and speeds, which have variations in amplitude.



(a)

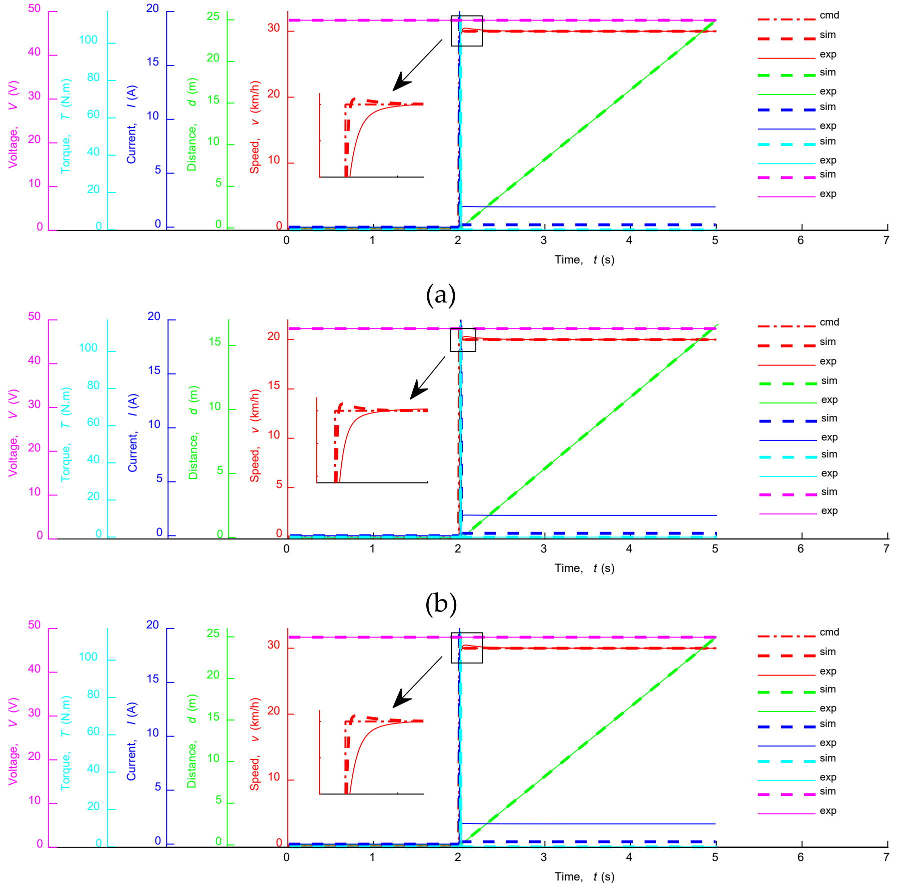
(b)

Figure 3: Testing of MW via: (a) Simulation model; (b) Experimentation

5.0 PERFORMANCE VALIDATION OF SPEED TRACKING CONTROLLER FOR MW

Figure 4 to 6 demonstrated the validation results of proposed mathematical model for MW. There are five parameters that were observed for each test: speed, distance, current, torque, and voltage, where the solid line represents the experimental data, while the dashed line represents the simulation results. According to [20], the comparison must be conducted under two identical conditions. Therefore, both experimental and simulation tests were performed by using real MW parameter and similar control period. Noted that the tests were done without external load applied to obtain reliable results for the validation of the mathematical model. This will eliminate the effect of external factors on the performance of the system, allowing for a more precise comparison between experimental data and simulation results.

Figure 4 illustrates the step input tests were conducted at a speed of 10, 20 and 30 km/h. It can be seen that the controller structure shows a promising ability to track the desired trajectory for different peak speeds. However, there exists a discrepancy in the reaction time, with the experimental results exhibiting a minor delay of 0.02 s compared to the simulation. Meanwhile, the simulation results indicated that the percentage overshot for 10, 20, and 30 km/h peak speed in the simulation are 5 %, whereas the experimental response, are 1.57 %, 1.59 %, and 2.1%, respectively. Besides, the settling time for speeds of 10, 20, and 30 km/h in simulation is 2.01 s, 2.03 s, and 2.06 s, while for the experiment, are 2.02 s, 2.04 s, and 2.07 s, respectively. Ahmad et al. [23] mention that the maximum allowable error between simulation and experiment should be less than 5% to consider the model simulation realistic.



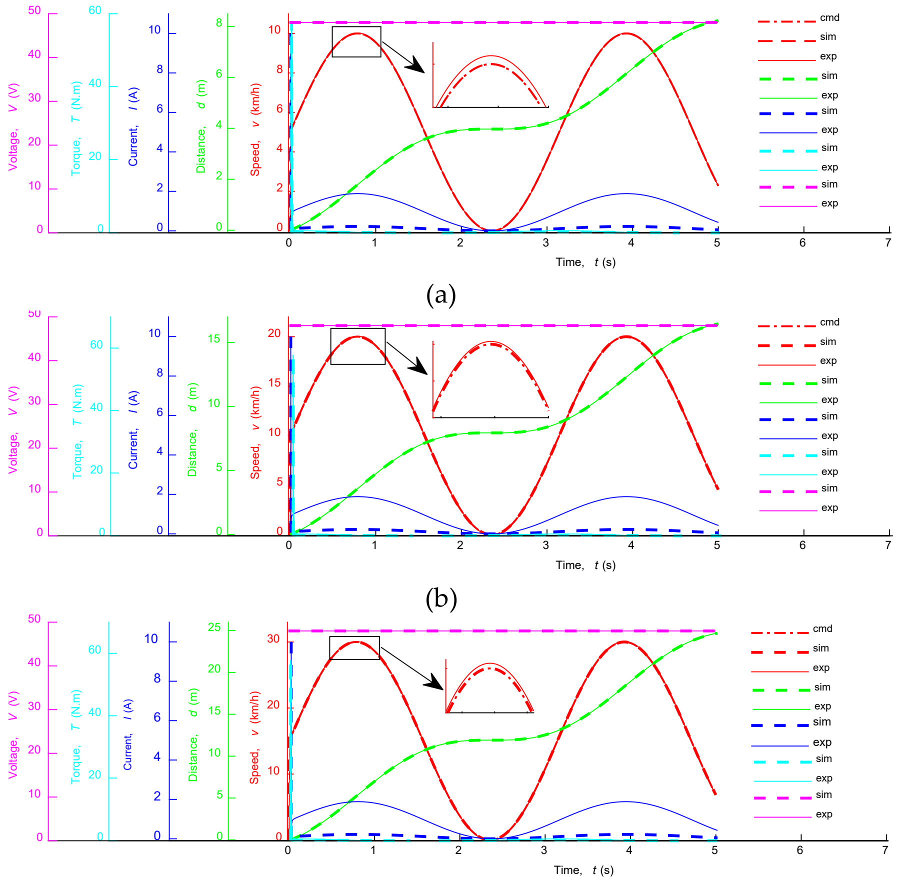
(a)

(b)

(c)

Figure 4: Performance validation of MW using step input at (a) 10km/h; (b) 20km/h; (c) 30km/h

The seconds test is performed using sinewave input, where Figure 5 (a) exhibits the sinewave input tests at a speed of 10 km/h. It can be seen that the input speed starts at 5.23 km/h, where both the simulation model, as well as the experimental response is able to track the sinewave input speed, which resulted in a distance of 8.22 m. The dynamic of MW uses a current of 10 A at an initial sudden speed and produces a torque of 60 Nm, powered by a 48 V battery voltage. Besides that, the speed track has been tested with various speeds of 20 and 30 km/h, as illustrated in Figure 5 (b) and (c). Despite the present of nonlinearities exist in the experimental response, the comparison between simulation results and experimental response shows good agreement with minimum error.



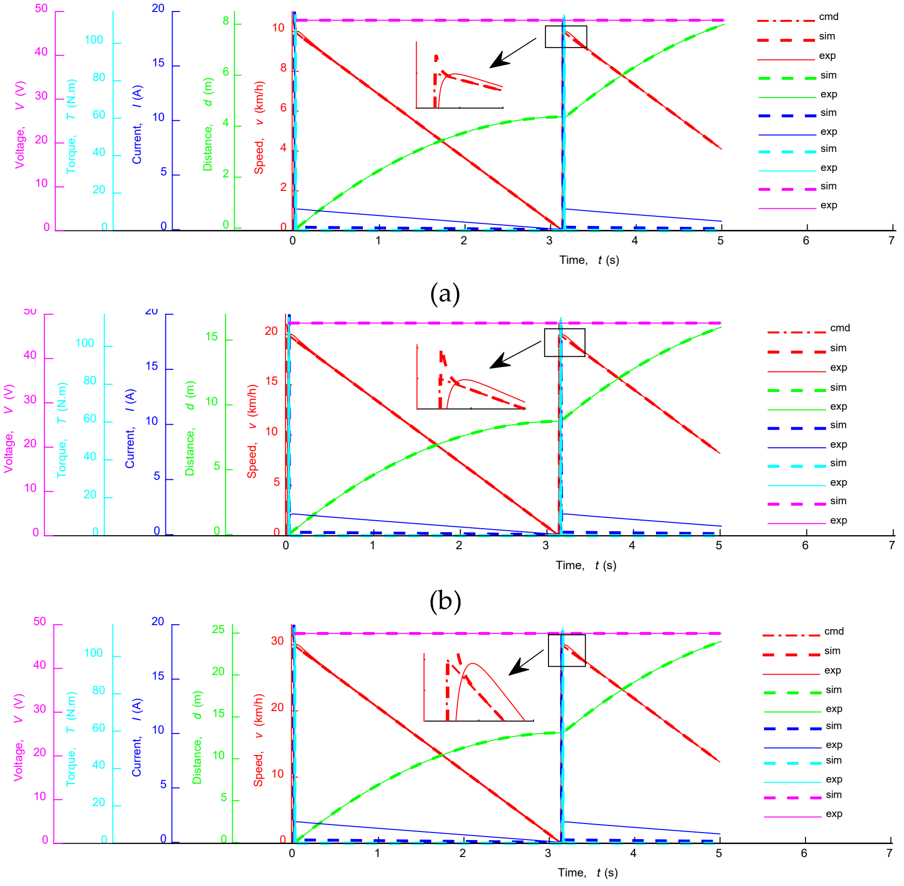
(a)

(b)

(c)

Figure 5: Performance validation of MW using sinewave input at (a) 10km/h; (b) 20km/h; (c) 30km/h

The validation test of speed tracking control is continued by using a sawtooth function with various speeds, as shown in Figure 6. Figure 6 (a-c) shows the results of speed control tests at a speed of 10, 20, and 30 km/h, respectively. It can be seen that the speed tracking system is quite good at an acceleration and deceleration, although there is an error occurring, especially at the peak. In addition, it also can be observed that there is no jerking when MW tracks the desired trajectories speed due to its dynamic characteristics of robust torque, accurate and fast response. Besides, the electrical dynamic of MW exhibits an excellent correlation between the current response of both simulation and experimental results during the acceleration. However, the current response is poor during deceleration due to parasitic loss experienced in the experiment, while the simulation simulates the behavior based on the parameter used.



(a)

(b)

(c)

Figure 6: Performance validation of MW using sawtooth input at (a) 10 km/h; (b) 20km/h; (c) 30km/h

6.0 CONCLUSION

In this study, the speed control of MW has been designed using mathematical equations. The simulation model was configured to match the characteristics of the actual hardware by using the same properties, and measured parameters from the motor manufacturer. The parametric model of MW was identified to represent the dynamic behavior of the proposed MW, where the predicted response of the MW model was compared with the measured response using the MW test rig. Several parameters are observed from the simulation model and experimental hardware: speed, distance, current, torque, and voltage. The results showed a good agreement between the simulation model and experimental response. Using the validated MW model, the speed control-based PI controller has been developed. The tests were conducted using step, sinewave, and sawtooth inputs and speed variations of 10, 20, and 30 km/h, respectively. The proposed MW model and its control structure demonstrated good performance and closely followed the desired speed patterns. The simulation behavior was found to be agreeable with the experiment's data due to the ability of the developed mathematical model to describe the behavior of MW and its control adequately. Therefore, the speed control scheme is suitable to be utilized in the MW system.

ACKNOWLEDGMENTS

This work is a part of a research project entitled "Reliability Test of Electronic Wedge Brake (EWB) As Advance Emergency Braking System in Semi-Autonomous In-Wheeled Motor Based Electric Vehicle", funded by PJP grant no. (PJP/2022/ FTKEE/S01879) lead by Ts. Dr. Mohd Hanif Che Hasan and continuation from the previous research project entitled "Characterization of Brake Force and Wedge Properties of IBS Based Electronic Wedge Brake for Autonomous Braking System", grant no. (PJP/2020/FKM/PP/S01783) lead by Ir. Ts. Dr. Fauzi Ahmad. The authors would like to acknowledge support from Universiti Teknikal Malaysia Melaka for providing the research facilities.

REFERENCES

[1] Y. Li, H. Deng, X. Xu, and W. Wang, "Modelling and testing of in-wheel motor drive intelligent electric vehicles based on co-simulation with Carsim/Simulink", *IET Intelligent Transport Systems*, vol. 13, pp. 115–123, 2019.

[2] C. Chi, Y. Xu, G. Xu, B. Cheng, and J. Shen, "Modular design and analysis of the x-by-wire center point steering independent suspension for in-wheel electric vehicle", *Advances in Mechanical Engineering*, vol. 10, pp. 1–12, 2018.

[3] J. Guo, Y. Luo, K. Li, and Y. Dai, "Coordinated path-following and direct yaw-moment control of autonomous electric vehicles with sideslip angle estimation", *Mech Syst Signal Process*, vol. 105, pp. 183–199, 2018.

[4] Q. He, Y. Yang, C. Luo, J. Zhai, R. Luo, and C. Fu, "Energy recovery strategy optimization of dual-motor drive electric vehicle based on braking safety and efficient recovery", *Energy*, vol. 248, pp. 1–15, 2022.

[5] Y. Li, O. P. Adeleke, and X. Xu, "Methods and applications of energy saving control of in-wheel motor drive system in electric vehicles: A comprehensive review", *Journal of Renewable and Sustainable Energy*, vol. 11, pp. 1–22, 2019.

[6] J. Wu, B. Wang, and X. Hong, "Driving Torque Control of Dual-Motor Powertrain for Electric Vehicles", *Actuators*, vol. 11, pp. 1–21, 2022.

[7] M. S. Elrefaey *et al.*, "A Proposed Three-Phase Induction Motor Drive System Suitable for Golf Cars", *Energies (Basel)*, vol. 15, pp. 1–22, 2022.

[8] Z. Liang *et al.*, "Powertrain Design and Energy Management Strategy Optimization for a Fuel Cell Electric Intercity Coach in an Extremely Cold Mountain Area", *Sustainability (Switzerland)*, vol. 14, pp. 1–16, 2022.

[9] D. Meng *et al.*, "Design and modeling of an in-wheel two-speed AMT for electric vehicles", *Mech Mach Theory*, vol. 163, 2021.

[10] S. Gudhe, S. Singh, M. Rezkallah, and A. Chandra, "Dynamic Control of Traction Motor for EV Fed via Dual Source Inverter with a Two Battery System", *Energies (Basel)*, vol. 16, pp. 1–18, 2023.

[11] W. Chanpeng and P. Hachanont, "Design of efficient in-wheel motor for electric vehicles", in *Energy Procedia*, Elsevier Ltd, 2014, pp. 525–531.

[12] J. Wideberg, C. Bordons, P. Luque, D. A. Mántaras, D. Marcos, and H. Kanchwala, "Development and Experimental Validation of a Dynamic Model for Electric Vehicle within Hub Motors", *Procedia Soc Behav Sci*, vol. 160, pp. 84–91, 2014.

[13] A. Mora, A. Orellana, J. Juliet, and R. Cardenas, "Model Predictive Torque Control for Torque Ripple Compensation in Variable-Speed PMSMs", *IEEE Transactions on Industrial Electronics*, vol. 63, pp. 4584–4592, 2016.

[14] B. Prasad Ganthia, S. Mohanty, S. Aparajita Pattanaik, and P. Kumar Rana, "Study of Speed and Torque Characteristics of MATLAB-Simulink Designed PMSM: A Review", *International Research Journal of Engineering and Technology*, vol. 03, pp. 731–734, 2016.

[15] X. Zhao, Q. Yu, M. Yu, and Z. Tang, "Research on an equal power allocation electronic differential system for electric vehicle with dual-wheeled-motor front drive based on a wavelet controller", *Advances in Mechanical Engineering*, vol. 10, pp. 1–24, 2018.

[16] L. Gang, H. Yuan, J. Shi, N. Li, and Z. C. Zhou, "Developing simulation model for four in-wheel motor electric vehicle based on Simulink", in *Advanced Materials Research*, pp. 22–25, 2014.

[17] H. Ding, X. Gong, and Y. Gong, "Estimation of Rotor Temperature of Permanent Magnet Synchronous Motor Based on Model Reference Fuzzy Adaptive Control", *Math Probl Eng*, vol. 2020, pp. 1–11, 2020.

[18] D. V. Samokhvalov, M. V. Schemelev, P. A. Shpakov, V. A. Skurikhin, and N. A. Ulissky, "Characteristics of a permanent magnet synchronous motor in field weakening mode," in *Proceedings of the 2016 IEEE Northwest Russia Section Young Researchers in Electrical and Electronic Engineering Conference, EIConRusNW 2016*, Institute of Electrical and Electronics Engineers Inc, 2016, pp. 668–670.

[19] M. Essaaidi, S. El Hani, "Direct Torque Control of Permanent Magnet Synchronous Motors in MATLAB/Simulink", in *2nd International Conference on Electrical and Information Technologies,* Institute of Electrical and Electronics Engineers, Morocco, 2016, pp. 978–984.

[20] Q. Song, Y. Li, and C. Jia, "A novel direct torque control method based on asymmetric boundary layer sliding mode control for PMSM", *Energies (Basel)*, vol. 11, pp. 1–15, 2018.

[21] J. Zhang *et al.*, "Longitudinal–vertical comprehensive control for four-wheel drive pure electric vehicle considering energy recovery and ride comfort", *Energy*, vol. 236, pp. 1–18, 2021.

[22] D. K. Kang and M. S. Kim, "Hardware-In-The-Loop Simulation to Evaluate the Drive Performance of The Electric Two-Wheelers on A Motor Dynamometer", *International Journal of Automotive Technology*, vol. 16, pp. 1031–1040, 2015.

[23] F. Ahmad *et al.*, "Modelling and control of a fixed calliper-based electronic wedge brake", *Strojniski Vestnik/Journal of Mechanical Engineering*, vol. 63, pp. 181–190, 2017.