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Brushless DC motor drive with optimal fractional-order sliding-mode control based on a genetic algorithm

Introduction. *Brushless DC (BLDC) motor is a type of permanent magnet synchronous motor that operates without brushes employed in many applications owing to its efficiency and control in electric cars. One of the main reasons BLDC motors are better than brushed DC motors is that they employ an electronic commutation circuit instead of a mechanical one. The fractional order sliding mode controller (FOSMC) was used, which is characterized by high durability and is not affected by the disturbances that the motor is exposed to during operation, as well as overcoming the chattering phenomenon present in the conventional sliding mode controller (CSMC).* ***The novelty*** *of the proposed work consists of to use FOSMC by genetic algorithm (GA) to mitigate the chattering phenomena in sliding mode control (SMC) for optimal response for speed control and regeneration braking control in BLDC motor by using single stage by voltage source inverter and decrease energy use during motor starting.* ***Purpose.*** *Improvement FOSMC techniques for the regulation of BLDC motor's driving control system.* ***Methods.*** *Employing the GA to optimize the parameters of FOSMC to mitigate the chattering phenomenon in SMC to regulate BLDC motor's driving control system.* ***Results.*** *A comparison was made between two types of sliding controllers to obtain the best performance of the control system in speed control operations and motor braking operations, the FOSMC, through parameter optimization via the GA, surpasses the CSMC in achieving optimal performance in driving the BLDC motor.* ***Practical value.*** *FOSMC exhibits superiority over the CSMC, as indicated by the reduced integral time absolute error in motor speed tracking and regenerative brake control, with values of (0.028, 0.046, and 0.075) for the FOSMC, in contrast to (2.72, 1.56, and 0.17) for the CSMC, the overshoot for FOSMC is (0, 0, and 11.4), but for CSMC it is (60.4, 43.7, and 11.2). During braking mode for FOSMC, the power recovery from the motor to the battery was (1.96, 9, and 17.76), but in CSMC, it was (0.99, 4.49, and 11.98). Moreover, the braking length was expedited, and the battery's initial power consumption diminished at the outset.* References 32, tables 5, figures 6.

Key words: **fractional order sliding mode control, brushless DC motor, genetic algorithm, sliding mode controller.**

Вступ. *Безщітковий двигун постійного струму (BLDC) – це тип синхронного двигуна з постійним магнітом, який працює без щіток і використовуються в багатьох сферах застосування завдяки своїй ефективності та контролю в електромобілях. Одна з головних причин, чому BLDC двигуни кращі за щіткові двигуни постійного струму, полягає в тому, що вони використовують електронну схему комутації замість механічної. Використовувався контролер режиму ковзання дробового порядку (FOSMC), який характеризується високою довговічністю та не залежить від збурень, яким піддається двигун під час роботи, а також подолав явище вібрації, присутнє у звичайному контролері режиму ковзання (CSMC).* ***Новизна*** *запропонованої роботи полягає у використанні FOSMC за допомогою генетичного алгоритму (GA) для пом'якшення явища вібрації в управлінні режимом ковзання (SMC) для оптимальної реакції для керування швидкістю та керування регенераційним гальмуванням у BLDC двигуні за допомогою одноступінчатого інвертора джерела напруги і зменшити споживання енергії під час запуску двигуна.* ***Призначення***. *Удосконалення методів FOSMC для регулювання системи керування приводом BLDC двигуна.* ***Методи***. *Використання GA для оптимізації параметрів FOSMC для пом'якшення явища вібрації в SMC для регулювання системи керування приводом BLDC двигуна.* ***Результати***. *Проведено порівняння між двома типами ковзних контролерів для отримання найкращої продуктивності системи керування в операціях регулювання швидкості та операцій гальмування двигуна. FOSMC, завдяки оптимізації параметрів через GA, перевершує CSMC у досягненні оптимальної продуктивності в керуванні BLDC двигуном.* ***Практична цінність***. *FOSMC демонструє перевагу над CSMC, на що вказує зменшена абсолютна похибка інтегрального часу у відстеженні швидкості двигуна та управлінні рекуперативним гальмом зі значеннями (0,028, 0,046 і 0,075) для FOSMC, на відміну від (2,72, 1,56 і 0,17) для CSMC, перевищення для FOSMC становить (0, 0 і 11.4), але для CSMC це (60.4, 43.7 і 11.2). Під час режиму гальмування для FOSMC відновлення потужності від двигуна до батареї було (1,96, 9 і 17,76), але в CSMC воно було (0,99, 4,49 і 11,98). Крім того, довжина гальмування була прискорена, а початкове енергоспоживання батареї зменшилося на початку.* Бібл. 32, табл. 5, рис. 6.

Ключові слова: **керування ковзним режимом дробового порядку, безщітковий двигун постійного струму, генетичний алгоритм, контролер ковзного режиму.**

Introduction. Brushless DC (BLDC) motor is widely used among the several permanent magnet synchronous motors (PMSMs) due to its enhanced efficiency and control in electric vehicles [1]. Recent trends indicate that BLDC motor technologies are utilized for variable-speed drives in global industrial applications and electric vehicles etc [2, 3]. PMSM characterized by a sinusoidal back electromagnetic force (EMF) waveform, is 15 % less efficient than a BLDC motor [4]. The flux distribution is the main differentiator between the PMSM and the BLDC motor. BLDC motor is a type of PMSM that is identified by a trapezoidal back-EMF waveform [5]. In contrast, BLDC motors have many benefits over brushed DC motors, including quiet operation, reduced size and weight, increased service life, reduced maintenance needs, a large torque capacity, reduced size and weight and improved dependability and efficiency [6]. The electronic commutation circuit, which takes the place of the mechanical commutated in brushed DC motors, is the source of BLDC motors' advantages. As a result, BLDC motors are currently the industry standard [7]. BLDC motor uses an electronic commutation technique instead of employing brushes [8]. Sliding mode control (SMC) has become known as a robust control technique that ensures superior tracking performance despite internal parameter fluctuations and external disruptions [9, 10]. Aside from that, SMC's notable attributes include its exceptional accuracy and straightforwardness. BLDC motors are only one example of the several machine kinds that have benefited from SMC's widespread use and effective implementation [11]. The use of SMC for BLDC motor speed control is the main topic of this paper.

The goal of the paper is to use FOSMC by genetic algorithm (GA) to mitigate the chattering phenomena in SMC for optimal response for speed control and regeneration braking control in BLDC motor by using single stage by voltage source inverter.

Review of the literature. Several speed control structures are suggested for regulating BLDC motors, encompassing PID controllers [12, 13], fuzzy logic controllers, sliding mode controllers, fractional order sliding mode controllers (FOSMC) and additional controller types [14]. Numerous researchers are engaged in this domain, employing metaheuristic algorithms to determine optimal values for these controllers. In [15] the researchers devised an adaptive integer sliding controller, which demonstrated superior performance to the conventional integer sliding controller regarding variations in reference speeds and motor load changes. Using a variable slope sliding mode observer (SMO), the study [16] presents a way to control the speed of a high-speed BLDC motor in a hand-stick Hoover cleaner. For irrational BLDC motor estimations, the SMO based on the signum function works wonders. The work [17] utilises the Dragonfly Algorithm (DA) to identify optimal configurations for the PI and SMC parameters. To optimise the controllers, simulation findings indicate that the DA-based SMC surpasses the optimised PI controller and SMC. The study [18] presents the design and use of the FOSMC to the quadrotor to demonstrate its fractional behaviour in response to disturbances. Additionally, to evaluate the FOSMC, the integer-order SMC (IOSMC) has been executed on the quadrotor for identical routes to regulate this unstable system. The experimental results indicate that the FOSMC exhibits reduced trajectory tracking error with minimal variations when following inclined circular and zigzag paths. In contrast, the IOSMC has more tracking errors and increased overshoot and undershoot. The work [19] compares the conventional PI controller and a sliding mode controller for closed-loop speed regulation of a BLDC motor. The results demonstrate that the SMC surpasses the PID controller. The study [20] examines the regenerative braking of a BLDC motor for electric vehicle applications using PI controller. The paper [21] a predictive senseless driving system based on SMO for a BLDC motor with regenerative capabilities in electric vehicle applications is given. The rotor speed and location calculation by SMO is highly precise and resilient under fluctuating solar insulation. This paper thoroughly analyses diverse control techniques aimed at reducing torque ripples in BLDC motors for electric vehicles, rigorously analyzed for their functionality and control methodologies, using the SMC controller employed for motor regulation [22].

Mathematical model of BLDC motor. BLDC motor regulates the currents flowing through the armature with the use of position sensors and an inverter (Fig. 1). Its streamlined size, high efficiency, dependability, quiet operation, and low maintenance requirements make it excellent for use in industrial applications. There are several configurations of BLDC motors; however, the three-phase variant is the most popular because to its fast speed and little torque ripple [23]. It is driven by a six-switch inverter, whereby two phases operate concurrently during each control step, while the third phase is deactivated. Pulses ($S_1, \ldots, S_6$) generated at 60 electrical degree intervals control these switches from the 120-degree-displaced Hall effect position sensor signals (H_r, H_s, H_t). Using a sequence of Hall effect sensors and transistors, the rotor's evolution may be switched between 0 and 360° in angular position, as detailed in Table 1 [24].

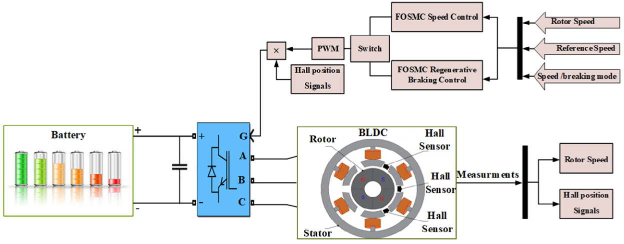

Fig. 1. The control drive for BLDC motor

Table 1

The sequence of switching utilizing Hall effect outcomes

Angle, deg.	Cycle	Hall sensors (H_a, H_b, H_c)	Phase current (i_a, i_b, i_c)	Switch active
0–60	1	(1, 0, 1)	(+DC, –DC, off)	T_1–T_4
60–120	2	(1, 0, 0)	(+DC, off, –DC)	T_1–T_6
120–180	3	(1, 1, 0)	(off, +DC, –DC)	T_3–T_6
180–240	4	(0, 1, 0)	(–DC, +DC, off)	T_3–T_2
240–300	5	(0, 1, 1)	(–DC, off, +DC)	T_5–T_2
300–360	6	(0, 0, 1)	(off, –DC, +DC)	T_5–T_4

The model of the BLDC motor is [24]:

$$\begin{bmatrix} \mathrm{d}i_a/\mathrm{d}t \\ \mathrm{d}i_b/\mathrm{d}t \\ \mathrm{d}\omega_m/\mathrm{d}t \\ \mathrm{d}\theta_m/\mathrm{d}t \end{bmatrix} = \begin{bmatrix} -R/L & 0 & 0 & 0 \\ 0 & -R/L & 0 & 0 \\ 0 & 0 & -k_f/J & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ \omega_m \\ \theta_m \end{bmatrix} +$$

$$+ \begin{bmatrix} 2/3L & 1/3L & 0 \\ -1/3L & 1/3L & 0 \\ 0 & 0 & 1/J \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v_{ab} - e_{ab} \\ v_{bc} - e_{bc} \\ T_e - T_l \end{bmatrix}; \qquad (1)$$

$$i_c = -(i_a + i_b),$$

where $e_{ab} = e_a - e_b$; $e_{bc} = e_b - e_c$; e_a, e_b, e_c are the motor back-EMFs; i_a, i_b, i_c are the stator phase currents; v_a, v_b, v_c are the stator phase voltages; v_{ab}, v_{bc}, v_{ca} are the stator phase to phase voltages; R, L are the resistance and inductance of a stator phase; ω_m is the rotor speed; θ_m is the mechanic angle; k_f is the friction constant; J is the rotor inertia; T_e, T_l are the electromagnetic and load torque.

Improvements to BLDC drive control via sliding mode controllers. SMC is an effectively recognized control technique in the domain of electric drives. It is a variable structure nonlinear discontinuous control method distinguished by precision, resilience, and straightforward implementation [25, 26]. The mathematical equation for SMC is:

$$s(t) = e(t) + \Delta e(t), \qquad (2)$$

where $s(t)$ is the sliding surface for SMC; $e(t)$ is the difference between the reference speed and the actual speed of the motor; $\Delta e(t)$ is the rate of variation of the error signal.

The current theory views chattering problems in SMC as the main challenge to SMC's recognition as a significant theoretical advancement. Researchers have suggested different methods for dealing with this issue (Fig. 2).

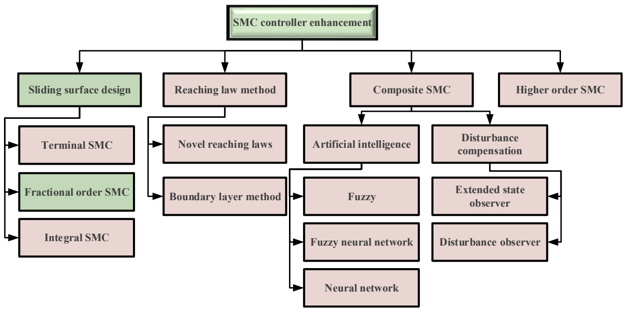

Fig. 2. Techniques to mitigate the chattering phenomenon in CSMC [26]

Figure 2 shows that the FOSMC surface is used as a nonlinear sliding surface design method in this study to reduce chattering problems [27]. GA was employed to improve the functionality of FOSMC by identifying the most effective components for regulating motor speed and breaking in all scenarios [28]. For speed mode the FOSMC is:

$$s_1(t)=k_1\cdot\left|e(t)\right|^{v_1}\cdot\mathrm{sign}(e(t))+\mathrm{d}e(t)/\mathrm{d}t\,, \tag{3}$$

braking mode the FOSMC is:

$$s_2(t)=k_2\cdot\left|e(t)\right|^{v_2}\cdot\mathrm{sign}(e(t))+\mathrm{d}e(t)/\mathrm{d}t\,, \tag{4}$$

where k_1, v_1, k_2, v_2 are the parameter of FOSMC tuning by GA.

Genetic algorithm (GA). The evolutionary algorithm known as a GA is based on the ideas of natural selection and how the strongest individuals reproduce [29]. GA has earned a stellar reputation as an optimization method among its many real-world uses. GA generates the optimal solution for several generations by randomly populating the candidate solutions. GA uses a set of genetic operators during its search procedure, including mutation, selection and crossover [30]. GA was used in this work to find the best elements for FOSMC in BLDC motor speed control and braking operations. Table 2 explains the parameters of GA algorithm.

Table 2

Selection of the settings for the GA

Parameters	Values
Crossover function	Arithmetic
Selection function	Tournament size 4
Scaling function	Rank
Mutation rate	0.1
Population size and iteration number	20 (double vector) and 20
Range of FOSMC tuning parameters k, v	$0 \le k \le 400$, $0 \le v \le 5$

The training process of the GA to find the best parameters for a FOSMC is shown in Fig. 3.

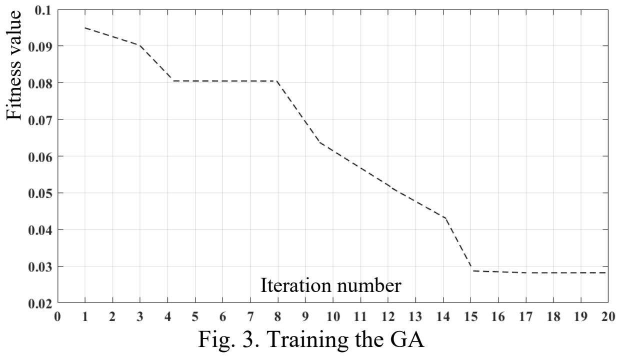

Fig. 3. Training the GA

Simulation and results. This section shows the simulation method for driving BLDC motor with parameters from Table 3.

Table 3

Parameters of the BLDC motor

Parameters	Value
Rated power P, kW	0.4712
Voltage V, V	400
Frequency f, Hz	50
Angular speed ω_r, rpm	1500
Stator resistance R_s, Ω	0.0485
Stator self-inductance L_s, mH	3.045
Magnetizing inductance L_m, H	0.1194
Inertia J, kg·m^2	0.0027
Friction factor F, N·m·s	0.0004924
Number of pole pairs p	4

It implements an SMC with the proposed FOSMC surface types, this is due to the chattering phenomena in SMC. The proposed type was used to control the motor speed (speed mode) and the braking motor (braking mode) using the regeneration braking technique, when the machine is under regenerative braking (RB), the motor inverter transfers power from the DC-link side to the low-voltage source known as back-EMF, much like a boost converter. Whenever the top diodes of the voltage source converter are operational, energy is returned to the battery pack [31]. GA was used in both models to find the best values for the FOSMC at a different reference speed during the motor's full load.

The power reinstated to the battery pack may be calculated by assessing the DC bus voltage $v_{DC\text{-}link}$ and current i_{brake}. The average power restored during the RB operation is calculated as

$$P_r=\frac{1}{T_b}\int_0^{T_b} v_{DC-link}(t)\cdot i_{brake}(t)\mathrm{d}t\,. \tag{5}$$

Equation (5) is used to determine the average power output generated by the drive when it is in RB mode [32].

The performance Integral Time Absolute Error (ITAE) index was used:

$$ITAE=\int_0^t t\left|e(t)\right|\mathrm{d}t\,. \tag{6}$$

Table 4 explains the parameters of all modes of FOSMC by tuning GA.

Table 4

Tuning the FOSMC controller using GA

n, rpm	k_1	v_1	k_2	v_2	$ITAE$
500	382.23	1.016	338.35	3.254	0.028
1000	296.019	1.155	69.475	4.431	0.046
1500	299.625	2.480	158.192	3.073	0.075

Table 5 compares between FOSMC and CSMC the time response of the BLDC motor.

Table 5

Comparison of FOSMC and SMC controllers at different reference speeds in terms of the time characteristics of the speed response

SMC controller type	Speed reference, rpm	Overshoot speed, %	Settling time T_s, ms	Error steady state, %	Braking time T_b, ms	Power recovery P_r, W
FOSMC	500	0	28	0	27	1.96
	1000	0	15	0	39.4	9
	1500	11.4	20	0	58.5	17.76
SMC	500	60.4	6	0.4	38	0.99
	1000	43.7	45	0.2	65.5	4.49
	1500	11.2	21	0.2	88.33	11.98

Figures 4–6 show the time response of the motor in the case of speed control mode and braking mode for each figure using 2 types of sliding controllers. The results show the superiority of the FOSMC in the speed control process, in addition to the fast braking process and less energy consumption from the battery when starting the motor.

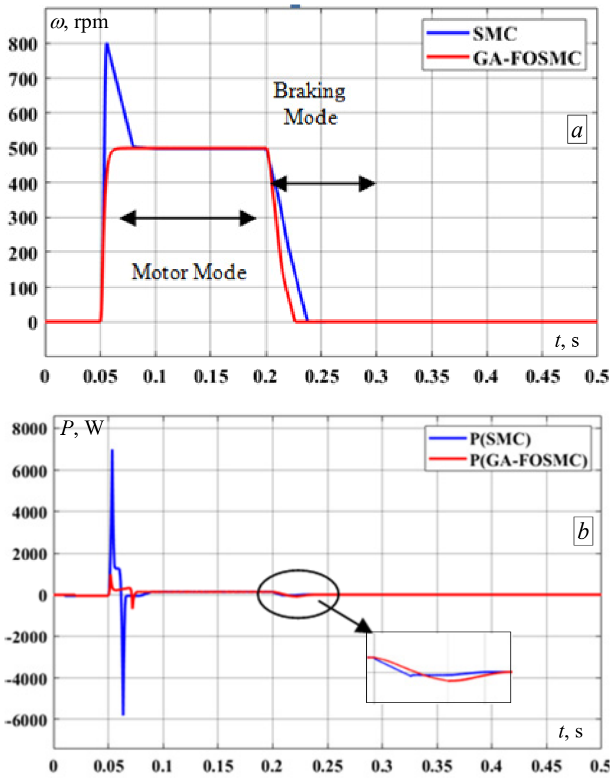

Fig. 4. Response of BLDC by GA-FOSMC and CSMC controllers: *a* – speed reference 500 rpm; *b* – battery power

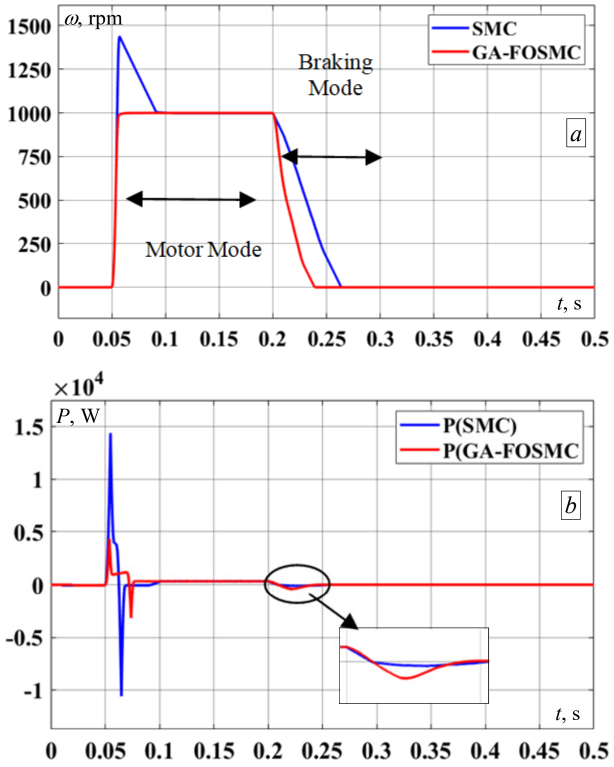

Fig. 5. Response of BLDC by GA-FOSMC and CSMC controllers: *a* – speed reference 1000 rpm; *b* – battery power

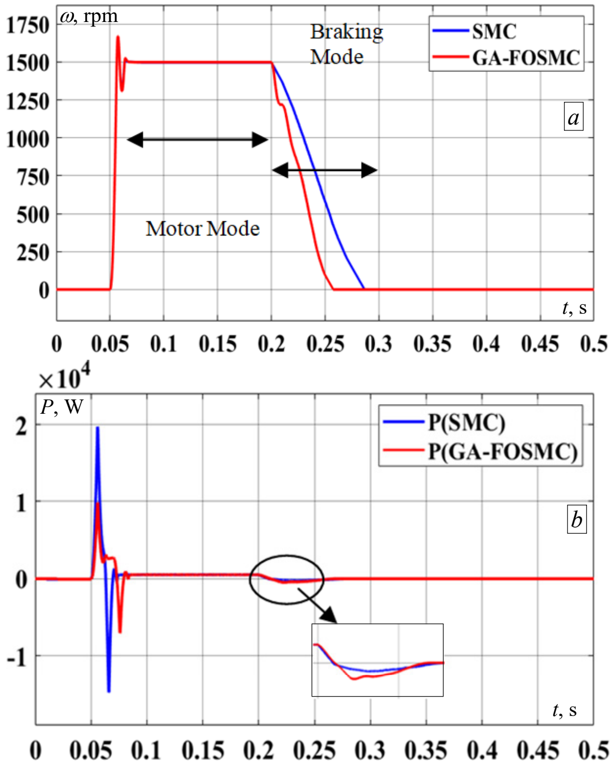

Fig. 6. Response of BLDC by GA-FOSMC and CSMC controllers: *a* – speed reference 1500 rpm; *b* – battery power

Conclusions. Fractional order sliding mode controller (FOSMC) treats the chattering phenomena in conventional sliding mode controller (CSMC) to optimally control the speed and regenerative braking of the brushless DC motor via the voltage source inverter circuit, where the firing signal is generated using the pulse-width modulation method. The comparison between the FOSMC and CSMC, which includes several levels of speed references, and using the genetic algorithm to find the best parameters of the FOSMC through the results of the simulation turns out the superior FOSMC over the CSMC where the lowest integral time absolute error in tracking the motor speed 500, 1000 and 1500 rpm for the FOSMC (0.028, 0.046 and 0.075) respectively. The overshoot by FOSMC is (0 and 11.4), while in CSMC (60.4, 43.7, and 11.2). In braking mode for FOSMC was the power recovery from motor to battery (1.96, 9, and 17.76), while in CSMC, it was (0.99, 4.49, and 11.98). Furthermore, the braking duration was quicker, and the initial power consumption from the battery decreased at the starting.

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Conflict of interest. The authors declare that there is no conflict of interest.

REFERENCES

1. Saiteja P., Ashok B., Mason B., Kumar P.S. Assessment of Adaptive Self-Learning-Based BLDC Motor Energy Management Controller in Electric Vehicles Under Real-World Driving Conditions for Performance Characteristics. *IEEE Access*, 2024, vol. 12, pp. 40325-40349. doi: https://doi.org/10.1109/ACCESS.2024.3375753.

2. Mohanraj D., Aruldavid R., Verma R., Sathiyasekar K., Barnawi A.B., Chokkalingam B., Mihet-Popa L. A Review of BLDC Motor: State of Art, Advanced Control Techniques, and Applications. *IEEE Access*, 2022, vol. 10, pp. 54833-54869. doi: https://doi.org/10.1109/ACCESS.2022.3175011.

3. Patel A.N. Slot opening displacement technique for cogging torque reduction of axial flux brushless DC motor for electric two-wheeler application. *Electrical Engineering & Electromechanics*, 2023, no. 2, pp. 7-13. doi: https://doi.org/10.20998/2074-272X.2023.2.02.

4. Prabhu N., Thirumalaivasan R., Ashok B. Design of sliding mode controller with improved reaching law through self-learning strategy to mitigate the torque ripple in BLDC motor for electric vehicles. *Computers and Electrical Engineering*, 2024, vol. 118, art. no. 109438. doi: https://doi.org/10.1016/j.compeleceng.2024.109438.

5. Akrami M., Jamshidpour E., Nahid-Mobarakeh B., Pierfederici S., Frick V. Sensorless Control Methods for BLDC Motor Drives: A Review. *IEEE Transactions on Transportation Electrification*, 2024, pp. 1–1. doi: https://doi.org/10.1109/TTE.2024.3387371.

6. Saha B., Singh B. Torque Ripple Mitigation in Sensorless PMBLDC Motor Drive With Adaptive Observer for LEV. *IEEE Transactions on Power Electronics*, 2025, vol. 40, no. 1, pp. 1739-1747. doi: https://doi.org/10.1109/TPEL.2024.3457677.

7. Khemis A., Boutabba T., Drid S. Model reference adaptive system speed estimator based on type-1 and type-2 fuzzy logic sensorless control of electrical vehicle with electrical differential. *Electrical Engineering & Electromechanics*, 2023, no. 4, pp. 19-25. doi: https://doi.org/10.20998/2074-272X.2023.4.03.

8. Lee H.-Y., Cha K.-S., Kwon S.-O., Yoon S.-Y., Seok C.-H., Lim M.-S. Efficiency Analysis of BLDC Motor With Delta Connection According to Magnitude of Circulating Current. *IEEE Transactions on Magnetics*, 2024, vol. 60, no. 12, pp. 1-5. doi: https://doi.org/10.1109/TMAG.2024.3465879.

9. Sakri D., Laib H., Farhi S.E., Golea N. Sliding mode approach for control and observation of a three phase AC-DC pulse-width modulation rectifier. *Electrical Engineering & Electromechanics*, 2023, no. 2, pp. 49-56. doi: https://doi.org/10.20998/2074-272X.2023.2.08.

10. Mohammed H.A., Alsammak A.N.B. An Intelligent Hybrid Control System using ANFIS-Optimization for Scalar Control of an Induction Motor. *Journal Européen Des Systèmes Automatisés*, 2023, vol. 56, no. 5, pp. 857-862. doi: https://doi.org/10.18280/jesa.560516.

11. Li K., Ding J., Sun X., Tian X. Overview of Sliding Mode Control Technology for Permanent Magnet Synchronous Motor System. *IEEE Access*, 2024, vol. 12, pp. 71685-71704. doi: https://doi.org/10.1109/ACCESS.2024.3402983.

12. Ibrahim M.A., Alsammak A.N.B. Adaptive PID Control for 8/6 Switched Reluctance Motor Drive Based on BFO. *Journal Européen Des Systèmes Automatisés*, 2023, vol. 56, no. 4, pp. 539-546. doi: https://doi.org/10.18280/jesa.560403.

13. Ibrahim M.A., Alsammak A.N.B. Switched Reluctance Motor Drives Speed Control Using Optimized PID Controller. *Przeglad Elektrotechniczny*, 2022, vol. 98, no. 11, pp. 46-50. doi: https://doi.org/10.15199/48.2022.11.7.

14. Alnaib I.I., Alsammak A.N. Optimization of fractional PI controller parameters for enhanced induction motor speed control via indirect field-oriented control. *Electrical Engineering & Electromechanics*, 2025, no. 1, pp. 3-7. doi: https://doi.org/10.20998/2074-272X.2025.1.01.

15. Younus S.M.Y., Kutbay U., Rahebi J., Hardalaç F. Hybrid Gray Wolf Optimization–Proportional Integral Based Speed Controllers for Brush-Less DC Motor. *Energies*, 2023, vol. 16, no. 4, art. no. 1640. doi: https://doi.org/10.3390/en16041640.

16. Ok S., Xu Z., Lee D.-H. A Sensorless Speed Control of High-Speed BLDC Motor Using Variable Slope SMO. *IEEE Transactions on Industry Applications*, 2024, vol. 60, no. 2, pp. 3221-3228. doi: https://doi.org/10.1109/TIA.2023.3348081.

17. Kheel A.M., Al-Shamaa N.K., Hawas M.N. Sliding Mode Controller Enchancement for Speed Control of BLDC Motor Based On Dragonfly Algorithm. *2023 International Conference on Converging Technology in Electrical and Information Engineering (ICCTEIE)*, 2023, pp. 135-141. doi: https://doi.org/10.1109/ICCTEIE60099.2023.10366754.

18. Basci A., Derdiyok A., Can K., Orman K. A Fractional-Order Sliding Mode Controller Design for Trajectory Tracking Control of An Unmanned Aerial Vehicle. *Elektronika Ir Elektrotechnika*, 2020, vol. 26, no. 4, pp. 4-10. doi: https://doi.org/10.5755/j01.eie.26.4.25846.

19. El Idrissi A.L., Bouchnaif J., Mokhtari M., Bensliman A. Comparative study between pi speed control and sliding mode control of bldc motor. *Lecture Notes in Electrical Engineering*, 2020, vol. 684 LNEE, pp. 309-317. doi: https://doi.org/10.1007/978-3-030-53187-4_35.

20. Soni N., Barai M. Performance Study of Regenerative Braking of BLDC Motor targeting Electric Vehicle Applications. *2022 2nd Asian Conference on Innovation in Technology (ASIANCON)*, 2022, pp. 1-6. doi: https://doi.org/10.1109/ASIANCON55314.2022.9909322.

21. Saha B., Singh B., Sen A. SMO Based Position Sensorless BLDC Motor Drive Employing Canonical Switching Cell Converter for Light Electric Vehicle. *IEEE Transactions on Industry Applications*, 2023, vol. 59, no. 3, pp. 2974-2984. doi: https://doi.org/10.1109/TIA.2023.3241607.

22. Prabhu N., Thirumalaivasan R., Ashok B. Critical Review on Torque Ripple Sources and Mitigation Control Strategies of BLDC Motors in Electric Vehicle Applications. *IEEE Access*, 2023, vol. 11, pp. 115699-115739. doi: https://doi.org/10.1109/ACCESS.2023.3324419.

23. Azab M. Comparative Study of BLDC Motor Drives with Different Approaches: FCS-Model Predictive Control and Hysteresis Current Control. *World Electric Vehicle Journal*, 2022, vol. 13, no. 7, art. no. 112. doi: https://doi.org/10.3390/wevj13070112.

24. Bazi S., Benzid R., Bazi Y., Rahhal M.M.Al. A Fast Firefly Algorithm for Function Optimization: Application to the Control of BLDC Motor. *Sensors*, 2021, vol. 21, no. 16, art. no. 5267. doi: https://doi.org/10.3390/s21165267.

25. Ullah A., Pan J., Ullah S., Zhang Z. Robust Speed Control of Permanent Magnet Synchronous Motor Drive System Using Sliding-Mode Disturbance Observer-Based Variable-Gain Fractional-Order Super-Twisting Sliding-Mode Control. *Fractal and Fractional*, 2024, vol. 8, no. 7, art. no. 368. doi: https://doi.org/10.3390/fractalfract8070368.

26. Mohd Zaihidee F., Mekhilef S., Mubin M. Robust Speed Control of PMSM Using Sliding Mode Control (SMC) – A Review. *Energies*, 2019, vol. 12, no. 9, art. no. 1669. doi: https://doi.org/10.3390/en12091669.

27. Lin X., Liu J., Liu F., Liu Z., Gao Y., Sun G. Fractional-Order Sliding Mode Approach of Buck Converters With Mismatched Disturbances. *IEEE Transactions on Circuits and Systems I: Regular Papers*, 2021, vol. 68, no. 9, pp. 3890-3900. doi: https://doi.org/10.1109/TCSI.2021.3092138.

28. Zaihidee F.M., Mekhilef S., Mubin M. Application of Fractional Order Sliding Mode Control for Speed Control of Permanent Magnet Synchronous Motor. *IEEE Access*, 2019, vol. 7, pp. 101765-101774. doi: https://doi.org/10.1109/ACCESS.2019.2931324.

29. Zhao B., Chen W.-N., Wei F.-F., Liu X., Pei Q., Zhang J. PEGA: A Privacy-Preserving Genetic Algorithm for Combinatorial Optimization. *IEEE Transactions on Cybernetics*, 2024, vol. 54, no. 6, pp. 3638-3651. doi: https://doi.org/10.1109/TCYB.2023.3346863.

30. Patel A.N., Suthar B.N. Performance optimisation of axial flux permanent magnet brushless DC motor for electric vehicle application with the genetic algorithm (GA) approach. *International Journal of Ambient Energy*, 2024, vol. 45, no. 1, art. no. 2370850. doi: https://doi.org/10.1080/01430750.2024.2370850.

31. Baszynski M., Pirog S. Unipolar Modulation for a BLDC Motor With Simultaneously Switching of Two Transistors With Closed Loop Control for Four-Quadrant Operation. *IEEE Transactions on Industrial Informatics*, 2018, vol. 14, no. 1, pp. 146-155. doi: https://doi.org/10.1109/TII.2017.2723962.

32. Mishra A.K., Singh A.K., Vishwanath G.M. A Fuel-Efficient BLDC Motor-Driven Light Electric Vehicle With Single-Stage Onboard Charging System. *IEEE Transactions on Transportation Electrification*, 2023, vol. 9, no. 4, pp. 4909-4921. doi: https://doi.org/10.1109/TTE.2022.3226536.

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