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A new stator flow-oriented control method based on type-2 fuzzy logic controllers for permanent magnet synchronous motors

Introduction. *Stator flow-oriented control is currently the most widely used system in industry or in previous research for improving the quality of mechanical power generated by permanent magnet synchronous motors (PMSM).* ***Problem.*** *However, this control is often based on PI controllers, which have shown problem limitations in terms of performance and robustness. Furthermore, these controllers are not suitable for variable-structure motors, which requires the use of new, more efficient controllers that provide robust control over both internal and external changes, such as type-2 fuzzy logic controllers. The* ***goal*** *of this work is to develop a stator flow-oriented control system by replacing PI controllers with type-2 fuzzy logic controllers that are robust to both external variations, such as changes in torque resistance, and internal variations, such as changes in parameters.* ***Methodology****. To implement this control on the PMSM, we maintained the similar structure of stator flow-oriented control, but replaced the PI controllers with type-2 fuzzy controllers. The* ***results*** *of numerical simulations performed using MATLAB/Simulink show that the stator flow-oriented control based on type-2 fuzzy logic controllers achieves an ideal response time and minimal overshoot, with an exponential error close to zero in both the transient and steady states, even with the application of external variations such as resistive torque or changes to the machine's parameters. The* ***scientific novelty*** *of this work lies in replacing all the controllers in the stator flow-oriented control system with type-2 fuzzy controllers and their programming method, thus addressing the shortcomings of traditional methods. In addition, a rare type of comparative study is presented, thanks to which the effectiveness and robustness of the developed control method relative to other can be demonstrated.* ***Practical value****. The excellent results obtained with the new stator flow-oriented control method using type-2 fuzzy logic controllers suggest that it should be taught in academic circles and applied in industry.* References 30, tables 3, figures 5.

Key words: **mechanical power control, permanent magnet synchronous motor, stator flow-oriented control, type-2 fuzzy logic control.**

Вступ*. Керування, орієнтоване за потоком статора (SFOC), на сьогодні є одним із найпоширеніших підходів у промисловості та наукових дослідженнях для підвищення якості механічної потужності, що генерується синхронними двигунами з постійними магнітами (PMSM).* ***Проблема****. Проте в більшості випадків таке керування базується на ПІ-регуляторах, які мають обмеження з точки зору швидкодії та робастності. Крім того, ці регулятори є малопридатними для двигунів зі змінною структурою, що зумовлює необхідність застосування нових, більш ефективних регуляторів, здатних забезпечити робастне керування як при внутрішніх, так і зовнішніх збуреннях, зокрема регуляторів на основі нечіткої логіки типу 2.* ***Метою*** *роботи є розроблення системи керування, орієнтованої за потоком статора, шляхом заміни ПІ-регуляторів на регулятори нечіткої логіки типу 2, які є робастними як до зовнішніх змін (наприклад, зміни навантажувального моменту), так і до внутрішніх варіацій параметрів двигуна.* ***Методика****. Для реалізації запропонованого підходу в системі керування PMSM збережено структуру SFOC, однак ПІ-регулятори замінено на регулятори нечіткої логіки типу 2.* ***Результати*** *чисельного моделювання, виконаного в середовищі MATLAB/Simulink, показали, що система керування, орієнтована за потоком статора на основі нечіткої логіки типу 2, забезпечує практично ідеальний час реакції та мінімальне перерегулювання, при цьому похибка має експоненційний характер і прямує до нуля як у перехідному, так і в усталеному режимах навіть за наявності зовнішніх збурень, таких як навантажувальний момент або зміни параметрів машини.* ***Наукова новизна*** *роботи полягає у повній заміні всіх регуляторів у системі SFOC на регулятори нечіткої логіки типу 2, а також у запропонованому підході до їх програмної реалізації, що дозволяє усунути недоліки традиційних методів. Крім того, представлено рідкісний тип порівняльного дослідження, який демонструє ефективність і робастність розробленого методу керування порівняно з існуючими.* ***Практична значимість****. Отримані результати застосування нового методу керування, орієнтованого за потоком статора із використанням регуляторів нечіткої логіки типу 2, свідчать про доцільність його впровадження як у навчальному процесі, так і в промислових застосуваннях.* Бібл. 30, табл. 3, рис. 5.

Ключові слова: **механічне керування потужністю, синхронний двигун з постійними магнітами, керування орієнтоване за потоком статора, керування на основі нечіткої логіки типу 2.**

Introduction. In industrial settings, permanent magnet synchronous motors (PMSMs) are highly favored [1, 2]. Their popularity stems from their simplicity, reliability, and compact footprint, which outshines that of DC motors [3, 4]. Their design is simpler as they lack mechanical switches, which enhances their longevity and obviates the necessity for frequent maintenance [5, 6]. Moreover, their operation in explosive environments is feasible due to the absence of spark generation. Additionally, they offer superior power output relative to their mass, distinguishing them from DC machines that demand more power sources and exhibit a lower power-to-weight ratio [7, 8].

It is well known that AI techniques have a great deal of promise for solving problems in industrial processes, particularly in domains like parameter estimation, control, and system identification. More and more, induction machines are being controlled and adjusted using fuzzy logic, a prominent AI technology. Building systems that can do cognitive tasks similar to human reasoning is the ultimate objective of AI research [9–11].

Classical fuzzy logic, now called type-1 fuzzy logic, has been generalised into a new type-2 fuzzy logic (T2FL). When it's tough to pin down precise membership functions for a fuzzy system, T2FL comes in handy. With this new logic, we may include uncertainty in the rules, which will improve the system's output [12–15].

Currently, the most popular method in industry and previous research such as those reported in [16, 17] to enhance the mechanical power produced by PMSM is stator flow-oriented control (SFOC) based on PI controllers. Unfortunately, these PI controllers have shown performance and durability issues. Furthermore, these controllers are not suitable for motors with variable structure. In the present work the contribution consists in proposing the replacement of PI controllers by type-2 fuzzy controllers to further improve the static and dynamic performance in response to internal (such as parameter changes) and external (such as torque resistance) fluctuations.

The **goal** of this work is to develop a stator flow-oriented control system by replacing PI controllers with type-2 fuzzy logic controllers that are robust to both external variations, such as changes in torque resistance, and internal variations, such as changes in parameters.

Modelling of the PMSM and its converters. In order to simulate the behavior of the PMSM and to develop control techniques for this machine, it is important to model PMSM and its converters individually:

- the permanent magnet synchronous motor;
- the motor-side converter (two-level inverter), utilizing a two-level inverter, facilitates the implementation of commands to regulate the mechanical power produced;
- the grid-side converter, featuring a two-level rectifier, emerges as an effective solution for enhancing the power factor on the grid side and regulating the DC bus.

PMSM model. The PMSM mathematical model needs to be formatted in order to study its control and simulation in different operating systems [18, 19]:

$$\begin{cases} \dfrac{\mathrm{d}}{\mathrm{d}t} I_{ds} = \dfrac{1}{L_d}\left(V_{ds} - R_s I_{ds} + \Omega L_q I_{qs}\right); \\ \dfrac{\mathrm{d}}{\mathrm{d}t} I_{qs} = \dfrac{1}{L_q}\left(V_{qs} - R_s I_{qs} - \Omega L_d I_{ds} + \Omega \phi_f\right); \\ C_e = \dfrac{3}{2} p\left[(L_d - L_q) I_{qs} I_{ds} + \phi_f I_{qs}\right]; \\ C_e - C_r - f\Omega = J\dfrac{\mathrm{d}}{\mathrm{d}t}\Omega, \end{cases} \quad (1)$$

$$\frac{\mathrm{d}}{\mathrm{d}t}[X] = [A][X] + [B][V], \quad (2)$$

where:

$$[X] = \begin{bmatrix} I_{ds} & I_{qs} \end{bmatrix}^T; \; [V] = \begin{bmatrix} V_{ds} & V_{qs} & \phi_f \end{bmatrix}^T;$$

$$\begin{bmatrix} I_{ds} \\ I_{qs} \end{bmatrix} = \begin{bmatrix} \dfrac{-R_s}{L_d} & \Omega\dfrac{L_q}{L_d} \\ \Omega\dfrac{-L_d}{L_q} & \dfrac{-R_s}{L_q} \end{bmatrix} \begin{bmatrix} I_{ds} \\ I_{qs} \end{bmatrix} + \begin{bmatrix} \dfrac{1}{L_d} & 0 & 0 \\ 0 & \dfrac{1}{L_q} & -\dfrac{\Omega}{L_q} \end{bmatrix} \begin{bmatrix} V_{ds} \\ V_{qs} \\ \phi_f \end{bmatrix}. \quad (3)$$

We define:

$$[A] = \begin{bmatrix} \dfrac{-R_s}{L_d} & 0 \\ 0 & \dfrac{-R_s}{L_q} \end{bmatrix} + \begin{bmatrix} 0 & \dfrac{L_q}{L_d} \\ \dfrac{-L_d}{L_q} & 0 \end{bmatrix}; \quad (4)$$

$$[B] = \begin{bmatrix} \dfrac{1}{L_d} & 0 & 0 \\ 0 & \dfrac{1}{L_q} & 0 \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -\dfrac{1}{L_q} \end{bmatrix} \Omega, \quad (5)$$

where C_r, C_e, Ω, f, J, p are the resistance torque, motor torque, mechanical speed, viscous friction factor, moment of inertia, number of pairs of poles, respectively; I_d, I_q, V_d, V_q, L_d, L_q, φ_d, φ_q are the dq components of the stator current, voltage, inductance and flux linkage, respectively; φ_f is the rotor flux linkage generated by the permanent magnets; R_s is the stator resistance.

Motor-side converter model. To control the PMSM effectively, a static converter a two-level inverter is employed to energize its stator. This converter primarily aims to modulate the DC bus voltage to power the stator winding and facilitate the execution of commands for regulating the mechanical power output [20, 21]:

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \frac{E}{6} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix}, \quad (6)$$

where V_A, V_B, V_c are the line voltages; S_1–S_3 are the switching states; E is the DC source.

Grid-side converter model. The grid-side converter, resembling the machine-side converter established earlier, shares a similar design. Apart from its bidirectional power flow capability, the grid-side converter boasts the advantage of regulating the DC bus voltage consistently and setting the reference reactive power to zero, thereby preserving the grid's quality by maintaining a unity power factor [22, 23]:

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} = \begin{bmatrix} -\dfrac{R}{L} & 0 & 0 \\ 0 & -\dfrac{R}{L} & 0 \\ 0 & 0 & -\dfrac{R}{L} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} + \begin{bmatrix} V_1 + V_{an} \\ V_2 + V_{bn} \\ V_3 + V_{cn} \end{bmatrix}; \quad (7)$$

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \frac{U_c}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix}; \quad (8)$$

$$\frac{U_c}{i_s} = \frac{R_{ch}}{1 + R_{ch} C p}. \quad (9)$$

On the grid side, this converter can be controlled using voltage oriented control, comprising two internal loops for regulating the phase currents, while an external loop oversees the output voltage regulation:

$$\begin{cases} V_{pd} = V_d - R i_d - L\dfrac{di_d}{dt} + Lwi_q; \\ V_{pq} = V_q - R i_q - L\dfrac{di_q}{dt} - Lwi_d; \end{cases} \quad (10)$$

$$P = \left[V_d i_d + V_q i_q\right]; \quad Q = \left[V_q i_d + V_d i_q\right]. \quad (11)$$

We define:

$$P_{ref} = U_{cmes} I_{red-ref}; \quad (12)$$

$$Q_{ref} = 0, \quad (13)$$

where i_A, i_B, i_C, v_1, v_2, v_3, v_{an}, v_{bn}, v_{cn} are the components of the stator currents, stator voltage, and simple voltage, inductance and flux linkage, respectively; L, R are the inductance and resistance of the line; U_c is the DC voltage; C is the capacity of the capacitor in parallel; V_{pd}, V_{pq}, V_d, V_q, i_{pq}, i_{pq} are the dq components of the line voltage, grid voltages and currents respectively; P, Q are the active and reactive powers; w is the pulsation.

Mechanical power control. In order to obtain high quality control of the mechanical power produced by a PMSM, it is necessary to select suitable control techniques to control the mechanical power generated by the rotor of this machine. To do this, it is necessary to select suitable control techniques that allow the speed and mechanical torque to be controlled at the reference speed to ensure that our system is more efficient.

Stator flow-oriented control based on PI controller. One technique to maximize the quality of the mechanical energy generated is this control. This method, we suggest a control algorithm that is based on the machine's stator flux orientation, which highlights the relationships between the mechanical power quantities (speed and electromagnetic torque) and the stator voltages produced by the inverter (Fig. 1). These relationships allow action to be taken on the stator signals in order to independently control the exchange of the speed generated at the machine's rotor [24, 25].

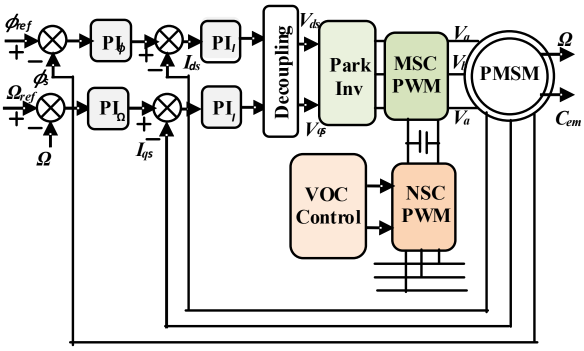

Fig. 1. Stator flow-oriented control based on PI controllers

In order to obtain control similar to that of separately excited DC machines, it is necessary to maintain i_{ds} at zero and control the speed or position via the current i_{qs}:

$$i_{ds} = 0\,; \tag{14}$$

$$i_{qs} = i_s\,; \tag{15}$$

$$\begin{cases} V_{ds} = R_s i_{ds} + L_d \dfrac{\mathrm{d}i_{ds}}{\mathrm{d}t} - wL_q i_{qs}; \\ V_{qs} = R_s i_{qs} + L_q \dfrac{\mathrm{d}i_{qs}}{\mathrm{d}t} + w\left(L_d i_{ds} + \phi_f\right); \end{cases} \tag{16}$$

$$\begin{cases} V_{ds} = V_{d1} - e_d; \\ V_{qs} = V_{q1} + e_q; \end{cases} \tag{17}$$

$$\begin{cases} V_{d1} = R_s i_{ds} + L_d \dfrac{\mathrm{d}i_{ds}}{\mathrm{d}t}; \\ V_{q2} = R_s i_{qs} + L_q \dfrac{\mathrm{d}i_{qs}}{\mathrm{d}t}; \end{cases} \tag{18}$$

$$\begin{cases} e_{ds} = wL_q i_{qs}; \\ e_{qs} = w\left(L_d i_{ds} + \phi_f\right). \end{cases} \tag{19}$$

Stator flow-oriented control based on T2FL controller. A fuzzy system is said to be of type-2 if it contains at least one fuzzy set of type-2 in membership functions that specify its premises or consequences. Fuzzy reasoning in this type of system leads to fuzzy sets of type-2 outputs. The configuration of a type-2 fuzzy system closely resembles that of a type-1 fuzzy system. It comprises a rule base, a fuzzification and defuzzification blocks and an inference mechanism. The only difference is in the output. In type-2, the defuzzification block is preceded by a reduction block [26–28].

To implement this control on the PMSM, we maintained the similar structure of stator flow-oriented control but replaced the PI controllers with T2FL controllers of the same types, which have the same membership functions (Fig. 2). The difference lies in the normalisation gains.

In reference to the choice of membership function configurations within the defuzzification block of the control variation and the fuzzification block for the mistake and its variation [29, 30]. We opted for the Gaussian shape shown in Fig. 3.

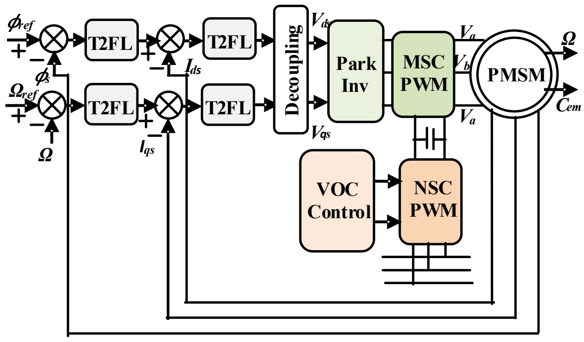

Fig. 2. Stator flow-oriented control based on T2FL controllers

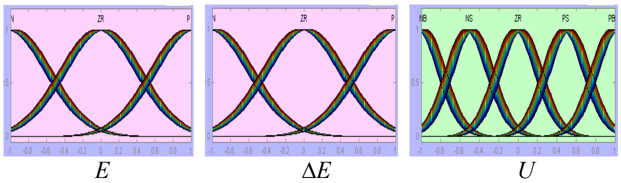

Fig. 3. The employed membership functions

Decision rules for the type-2 fuzzy controller are represented in Table 1.

Table 1

Decision rules for the type-2 fuzzy controller

Control		Error		
		N	EZ	P
Derived from error	N	NG	NP	PP
	EZ	NG	EZ	PG
	P	NP	PP	PG

Comparative analysis between the controls developed. In order to evaluate the difference between the two controls implemented on our PMSM in this work, we shall do a comparative analysis of these controls. This research was replicated under identical condition.

Qualitative comparisons. This comparison relies on observing results obtained through simulating our motor within the MATLAB/Simulink environment, using the two control techniques developed. In this comparison, we carried out the test by implementing a resistive torque (C_r = 6 N·m) as an external variation of the instants (t = 0.5 s and t = 1.5 s) and a speed set point equal to the nominal speed of the PMSM (1000 rpm) (Fig. 4).

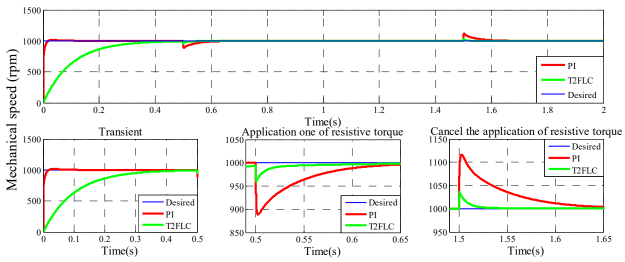

Fig. 4. Mechanical speed produced for the two controls with a zoom (external variation)

With an application and cancellation of external variation (resistive torque), the simulation results demonstrate that the mechanical speed adheres to their reference in both control types; however, the reaction time, overshoot, and exponential convergence of the errors for the steady state are not. When SFOC based on T2FL is used, the best value for these is evidently reached, making it the most effective and best-performing control when compared to the other control.

Quantitative comparisons. Our comparison is based on 4 criteria, all of which are derived from the quantitative findings of our PMSM control approaches and their application to simulations.

1) The integral error squared:

$$ISE = \int_0^t e^2(t)\mathrm{d}t\,. \qquad (20)$$

2) The integral of the absolute value of the error:

$$IAE = \int_0^t \left|e\ (t)\right|\mathrm{d}t\,. \qquad (21)$$

3) Integral of the time multiplied by the absolute value of the error:

$$ITAE = \int_0^t t\left|e(t)\right|\mathrm{d}t\,. \qquad (22)$$

4) Integral of the time multiplied by the squared error:

$$ITSE = \int_0^t te^2\mathrm{d}t\,. \qquad (23)$$

The results of the simulation (Table 2) indicate that SFOC based on T2FL controllers outperforms the other controls in minimising all criteria (ISE, IAE, ITAE, ITSE), yielding the lowest values.

Table 2

Quantitative comparison between the different controllers for external variations

Controlled variables	Criterion	Controls developed	
		SFOC PI	SFOC T2FL
Speed	*ISE*	277.140	12.1679
	IAE	4.9382	1.1503
	ITAE	2.6872	0.6643
	ITSE	144.7328	6.3375

Robustness comparisons. The final assessment focuses on conducting robustness tests for the proposed control strategies, which tests the impact of parametric changes (internal variation) of the PMSM on their performance. Being aware that these parameters can fluctuate in a real motor due to a variety of physical events (such as resistor heating, etc.), to apply this comparison we will decompose our state model of the machine as follows:

$$[A]=\left[\frac{R_s}{L_d}\begin{bmatrix}-1 & 0\\ 0 & 0\end{bmatrix}+\frac{R_s}{L_q}\begin{bmatrix}0 & 0\\ 0 & -1\end{bmatrix}+\frac{L_q}{L_d}\begin{bmatrix}0 & 1\\ 0 & 0\end{bmatrix}+\frac{L_d}{L_q}\begin{bmatrix}0 & 0\\ -1 & 0\end{bmatrix}\right];\qquad (24)$$

$$[B]=\left[\frac{1}{Ld}\begin{bmatrix}1 & 0 & 0\\ 0 & 0 & 0\end{bmatrix}+\frac{1}{L_q}\begin{bmatrix}0 & 0 & 0\\ 0 & 1 & 0\end{bmatrix}+\frac{1}{L_q}\begin{bmatrix}0 & 0 & 0\\ 0 & 0 & -1\end{bmatrix}\right]\Omega\,. \qquad (25)$$

In this comparison, we have plotted the mechanical velocity curve to show the robustness of the proposed controls (Fig. 5). The variation of the parameters will be applied between the instants $t = 0.8$ s and $t = 1.3$ s.

In this test, we visualized the velocity shape. The two proposed controls are very reliable and perform well even with small parameter fluctuations; However, the SFOC based on T2FL seems to be the best control, since it has an almost smooth speed curve and good tracking of the set point curve, followed by the SFOC based on PI corrector which gives us remarkable ripples compared with the other control.

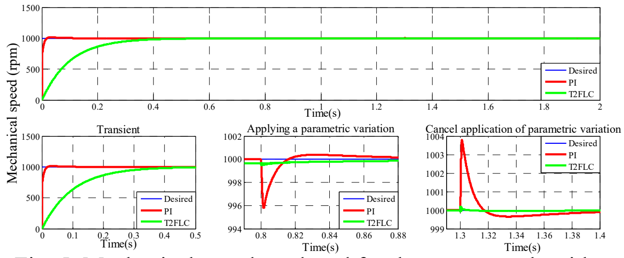

Fig. 5. Mechanical speed produced for the two controls with a zoom (internal variation)

Table 3 shows the comparison values for a robustness test between the two controls developed. The simulation results indicate that SFOC based on T2FL performs best for minimises error compared with stator flow-oriented control.

Table 3

Quantitative comparison between different controllers for robustness testing

Controlled variables	Criterion	Controls developed	
		SFOC PI	SFOC T2FL
Speed	*ISE*	0.1276	0.0057
	IAE	0.0957	0.0374
	ITAE	0.1037	0.0360
	ITSE	0.1329	0.0049

Conclusions. In this work, we developed a stator flow-oriented method using type-2 fuzzy logic controllers to solve parametric and external variation problems and achieve positive mechanical power output performance. Finally, a comparative study is conducted between this method and the one based on PI controllers where they obtained results clearly show that the SFOC based on T2FL controllers is the most efficient and effective PMSM control compared to the stator flux orientation control based on PI controllers both in transient and steady state, even with the application of external variations (EV) such as resistive torque or parametric variations (PV) of our machine.

The latter achieved:

- high response time R_t: R_t(EV) = 0.03 s, R_t(PV) = 0 s for SFOC based on T2FL and R_t(EV) = 0.15 s, R_t(PV) = = 0.2 s for SFOC based on PI.

- minimal overshoot (Mo): Mo(EV) = 40 rpm, Mo(PV) = 0 rpm for SFOC based on T2FL and Mo(EV) = = 110 rpm, Mo(PV) = 4 rpm for SFOC based on PI.

- *ITAE* that is close to 0: *ITAE*(EV) = 0.6643, *ITAE*(PV)= 0.036 for SFOC based on T2FL and *ITAE*(EV) = = 2.6872, *ITAE*(PV)=0.1037 for SFOC based on PI.

These results obtained with the new stator flow-oriented control based on T2FL controllers call for the teaching of this method in academic circles and also for its application in industrial circles.

Conflict of interest. The authors declare that they have no conflicts of interest.

REFERENCES

1. Yazdan T., Humza M., Cho H.-W. Three-Phase Dual-Winding Multitasked PMSM Machine Using Double Layer Concentrated Winding for HEV Application. *IEEE Access*, 2023, vol. 11, pp. 36682-36691. doi: https://doi.org/10.1109/ACCESS.2023.3264568.

2. Thangavel S., Mohanraj D., Girijaprasanna T., Raju S., Dhanamjayulu C., Muyeen S.M. A Comprehensive Review on Electric Vehicle: Battery Management System, Charging Station, Traction Motors. *IEEE Access*, 2023, vol. 11, pp. 20994-21019. doi: https://doi.org/10.1109/ACCESS.2023.3250221.

3. Khowja M.R., Singh K., la Rocca A., Vakil G., Ramnathan R., Gerada C. Fault-Tolerant Dual Channels Three-Phase PMSM for

Aerospace Applications. *IEEE Access*, 2024, vol. 12, pp. 126845-126857. doi: https://doi.org/10.1109/ACCESS.2024.3451705.
4. Li S., Xu Y., Zhang W., Zou J. A Novel Two-Phase Mode Switching Control Strategy for PMSM Position Servo Systems With Fast-Response and High-Precision. *IEEE Transactions on Power Electronics*, 2023, vol. 38, no. 1, pp. 803-815. doi: https://doi.org/10.1109/TPEL.2022.3200969.
5. Jin L., Mao Y., Wang X., Shi P., Lu L., Wang Z. Optimization-Based Maximum-Torque Fault-Tolerant Control of Dual Three-Phase PMSM Drives Under Open-Phase Fault. *IEEE Transactions on Power Electronics*, 2023, vol. 38, no. 3, pp. 3653-3663. doi: https://doi.org/10.1109/TPEL.2022.3222224.
6. Guezi A., Bendaikha A., Dendouga A. Direct torque control based on second order sliding mode controller for three-level inverter-fed permanent magnet synchronous motor: comparative study. *Electrical Engineering & Electromechanics*, 2022, no. 5, pp. 10-13. doi: https://doi.org/10.20998/2074-272X.2022.5.02.
7. Petkar S.G., Thippiripati V.K. A Novel Duty-Controlled DTC of a Surface PMSM Drive With Reduced Torque and Flux Ripples. *IEEE Transactions on Industrial Electronics*, 2023, vol. 70, no. 4, pp. 3373-3383. doi: https://doi.org/10.1109/TIE.2022.3181405.
8. Huang Y., Zhao M., Zhang J., Lu M. The Hall Sensors Fault-Tolerant for PMSM Based on Switching Sensorless Control With PI Parameters Optimization. *IEEE Access*, 2022, vol. 10, pp. 114048-114059. doi: https://doi.org/10.1109/ACCESS.2022.3218325.
9. Aib A., Khodja D.E., Chakroune S. Field programmable gate array hardware in the loop validation of fuzzy direct torque control for induction machine drive. *Electrical Engineering & Electromechanics*, 2023, no. 3, pp. 28-35. doi: https://doi.org/10.20998/2074-272X.2023.3.04.
10. Wadawa B., Errami Y., Obbadi A., Sahnoun S. Robustification of the H_∞ controller combined with fuzzy logic and PI&PID-F_d or hybrid control of wind energy conversion system connected to the power grid based on DFIG. *Energy Reports*, 2021, vol. 7, pp. 7539-7571. doi: https://doi.org/10.1016/j.egyr.2021.10.120.
11. Sathish Babu P., Sundarabalan C.K., Balasundar C., Santhana Krishnan T. Fuzzy logic based optimal tip speed ratio MPPT controller for grid connected WECS. *Materials Today: Proceedings*, 2021, vol. 45, pp. 2544-2550. doi: https://doi.org/10.1016/j.matpr.2020.11.259.
12. Jasmine Gnana Malar A., Agees Kumar C., Gnana Saravanan A. Iot based sustainable wind green energy for smart cites using fuzzy logic based fractional order darwinian particle swarm optimization. *Measurement*, 2020, vol. 166, art. no. 108208. doi: https://doi.org/10.1016/j.measurement.2020.108208.
13. Verma P., Garg R., Mahajan P. Asymmetrical interval type-2 fuzzy logic control based MPPT tuning for PV system under partial shading condition. *ISA Transactions*, 2020, vol. 100, pp. 251-263. doi: https://doi.org/10.1016/j.isatra.2020.01.009.
14. Kececioglu O.F., Gani A., Sekkeli M. Design and Hardware Implementation Based on Hybrid Structure for MPPT of PV System Using an Interval Type-2 TSK Fuzzy Logic Controller. *Energies*, 2020, vol. 13, no. 7, art. no. 1842. doi: https://doi.org/10.3390/en13071842.
15. Benghanem M., Chettibi N., Mellit A., Almohamadi H. Type-2 fuzzy-logic based control of photovoltaic-hydrogen production systems. *International Journal of Hydrogen Energy*, 2023, vol. 48, no. 91, pp. 35477-35492. doi: https://doi.org/10.1016/j.ijhydene.2023.05.360.
16. Zellouma D., Bekakra Y., Benbouhenni H. Field-oriented control based on parallel proportional–integral controllers of induction motor drive. *Energy Reports*, 2023, vol. 9, pp. 4846-4860. doi: https://doi.org/10.1016/j.egyr.2023.04.008.
17. Khanday S.A., Bhat A.H., Sekhar O.C. Performance Analysis of Space Vector Approach Based Field Oriented Control of Indirect Matrix Converter Fed PMSM Drive. *2023 7th International Conference on Computer Applications in Electrical Engineering-Recent Advances (CERA)*, 2023, pp. 1-6. doi: https://doi.org/10.1109/CERA59325.2023.10455147.
18. Wu T., Lyu M., Wu X., Yang M., Wang Y., Huang S., Ouyang X., Rodriguez J. Enhanced Model Predictive Control for PMSM Based on Reference Voltage Predictive Model. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 2023, vol. 11, no. 5, pp. 5290-5300. doi: https://doi.org/10.1109/JESTPE.2023.3307469.
19. Hossain M.S., Said N.A.M., Hasan M.A., Halim W.A., Munim W.N.W.A., Jidin A. Performance evaluation of a nearest level control-based TCHB multilevel inverter for PMSM motors in electric vehicle systems. *Results in Engineering*, 2025, vol. 25, art. no. 103949. doi: https://doi.org/10.1016/j.rineng.2025.103949.
20. Benzouaoui A., Khouidmi H., Bessedik B. Parallel model predictive direct power control of DFIG for wind energy conversion. *International Journal of Electrical Power & Energy Systems*, 2021, vol. 125, art. no. 106453. doi: https://doi.org/10.1016/j.ijepes.2020.106453.
21. Zamzoum O., Derouich A., Motahhir S., El Mourabit Y., El Ghzizal A. Performance analysis of a robust adaptive fuzzy logic controller for wind turbine power limitation. *Journal of Cleaner Production*, 2020, vol. 265, art. no. 121659. doi: https://doi.org/10.1016/j.jclepro.2020.121659.
22. Acikgoz H., Yildiz C., Coteli R., Dandil B. DC-link voltage control of three-phase PWM rectifier by using artificial bee colony based type-2 fuzzy neural network. *Microprocessors and Microsystems*, 2020, vol. 78, art. no. 103250. doi: https://doi.org/10.1016/j.micpro.2020.103250.
23. Kou L., Liu C., Cai G., Zhang Z., Zhou J., Wang X. Fault diagnosis for three-phase PWM rectifier based on deep feedforward network with transient synthetic features. *ISA Transactions*, 2020, vol. 101, pp. 399-407. doi: https://doi.org/10.1016/j.isatra.2020.01.023.
24. Darsouni Z., Rezgui S.E., Benalla H., Rebahi F., Boumendjel M.A.M. Ensuring service continuity in electric vehicles with vector control and linear quadratic regulator for dual star induction motors. *Electrical Engineering & Electromechanics*, 2025, no. 2, pp. 24-30. doi: https://doi.org/10.20998/2074-272X.2025.2.04.
25. Kuczmann M., Horvath K. Tensor Product Alternatives for Nonlinear Field-Oriented Control of Induction Machines. *Electronics*, 2024, vol. 13, no. 7, art. no. 1405. doi: https://doi.org/10.3390/electronics13071405.
26. 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.
27. Rouabhi R., Herizi A., Djeriou S., Zemmit A. Hybrid type-1 and 2 fuzzy sliding mode control of the induction motor. *Revue Roumaine des Sciences Techniques Serie Electrotechnique et Energetique*, 2024, vol. 69, no. 2, pp. 147-152. doi: https://doi.org/10.59277/RRST-EE.2024.2.5.
28. Srinivas G., Durga Sukumar G., Subbarao M. Total harmonic distortion analysis of inverter fed induction motor drive using neuro fuzzy type-1 and neuro fuzzy type-2 controllers. *Electrical Engineering & Electromechanics*, 2024, no. 1, pp. 10-16. doi: https://doi.org/10.20998/2074-272X.2024.1.02.
29. Rouabhi R., Zemmit A., Herizi A., Moussa O., Djeriou S. Hybrid type-2 fuzzy backstepping control of doubly fed induction generator for wind energy conversion systems. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 2025, vol. 47, no. 1, art. no. 24. doi: https://doi.org/10.1007/s40430-024-05293-z.
30. Rouabhi R., Herizi A., Djerioui A. Performance of Robust Type-2 Fuzzy Sliding Mode Control Compared to Various Conventional Controls of Doubly-Fed Induction Generator for Wind Power Conversion Systems. *Energies*, 2024, vol. 17, no. 15, art. no. 3778. doi: https://doi.org/10.3390/en17153778.

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