UDC 621.314 https://doi.org/10.20998/2074-272X.2025.6.07

Y. Laamari, N. Boukhennoufa, H. Benderradji, S. Allaoui

Fuzzy logic-based vector control of permanent magnet synchronous motor drives under inter-turn short-circuit fault conditions

***Introduction**. Permanent magnet synchronous motors (PMSMs) are widely used in industrial and automotive applications due to their high efficiency and power density. **Problem**. However, their performance can be significantly affected by faults such as inter-turn short-circuits faults (ITSCFs) in the stator windings. These faults introduce oscillations in rotor speed and electromagnetic torque, increase total harmonic distortion (THD), and degrade the overall reliability of the system drive. Conventional field-oriented control (FOC) methods, particularly, those employing PI controllers, often struggle to maintain stability under such fault conditions. **Goal**. This study aims to develop and evaluate a fuzzy logic-based control strategy to enhance the fault tolerance of PMSM drives under ITSCFs conditions. **Methodology**. To achieve this, a mathematical model of the PMSM is developed to represent both healthy and faulty operating states. This model is integrated into a vector control framework where two types of speed controllers are compared: a conventional PI controller and a fuzzy PI controller. The proposed fuzzy logic controller is implemented within the FOC scheme and evaluated through simulation. **Results.** Simulation results demonstrate that the fuzzy vector control approach significantly reduces rotor speed and electromagnetic torque ripples under both healthy and faulty conditions, while maintaining stable torque output and minimizing THD. It consistently outperforms the conventional PI controller. **Scientific novelty**. Unlike traditional FOC methods, this study introduces a fuzzy logic-enhanced control strategy specifically designed to improve PMSM performance under fault conditions. The integration of fuzzy logic with vector control offers superior dynamic response and enhanced resilience. **Practical value**. The proposed approach improves the robustness and reliability of PMSM drives, particularly in fault-sensitive applications such as industrial automation and electric vehicles. This contributes to extended system lifespan and improved operational stability.* References 26, tables 2, figures 13.

Key words: **permanent magnet synchronous motor, field-oriented control, inter-turn short-circuit, PI controller, fuzzy logic controller.**

***Вступ**. Синхронні двигуни з постійними магнітами (PMSMs) широко використовуються в промисловості та автомобілебудуванні завдяки своїй високій ефективності та питомій потужності. **Проблема**. Однак на їх продуктивність можуть суттєво впливати такі несправності, як міжвиткові короткі замикання (ITSCFs) в обмотках статора. Ці несправності призводять до коливань швидкості ротора та електромагнітного моменту, збільшують коефіцієнт гармонічних спотворень (THD) та знижують загальну надійність приводу системи. Традиційні методи управління з орієнтацією по полю (FOC), зокрема, з використанням ПІ-регуляторів, часто не забезпечують стійкість у таких умовах. **Мета**. Дане дослідження спрямоване на розробку та оцінку стратегії управління на основі нечіткої логіки для підвищення стійкості до відмови PMSMs в умовах ITSCFs. **Методологія**. Для досягнення цієї мети розроблено математичну модель PMSMs, яка описує як справні, так і несправні робочі стани. Ця модель інтегрована у систему векторного управління, де порівнюються два типи регуляторів швидкості: звичайний ПІ-регулятор та нечіткий ПІ-регулятор. Запропонований нечіткий логічний контролер реалізовано в рамках FOC схеми та оцінено за допомогою моделювання. **Результати** моделювання показують, що підхід з нечітким векторним управлінням значно знижує частоту обертання ротора і пульсації електромагнітного моменту як у справному, так і несправному стані, зберігаючи при цьому стабільний вихідний крутний момент і мінімізуючи сумарний THD. Він стабільно перевершує традиційний ПІ-регулятор. **Наукова новизна**. На відміну від традиційних FOC методів, це дослідження пропонує стратегію керування з покращеною нечіткою логікою, спеціально розроблену для покращення продуктивності PMSM в умовах несправності. Інтеграція нечіткої логіки з векторним управлінням забезпечує чудовий динамічний відгук та підвищену стійкість. **Практична цінність**. Пропонований підхід підвищує надійність та стійкість PMSMs, особливо у чутливих до відмов сферах, таких як промислова автоматика та електромобілі. Це сприяє збільшенню терміну служби системи та підвищенню експлуатаційної стабільності.* Бібл. 26, табл. 2, рис. 13.

Ключові слова: **синхронний двигун з постійними магнітами, полеорієнтоване керування, міжвиткове замикання, ПІ-регулятор, нечіткий логічний регулятор.**

Introduction. Permanent magnet synchronous motors (PMSMs) have garnered significant attention in industrial applications, particularly in the traction and auxiliary machinery, due to their superior efficiency, high torque-to-inertia ratio, and high power density [1–3]. However, during its operation, PMSMs are subjected to various stresses, including fluctuating power supply conditions, load variations, and thermal stresses on the stator winding that can lead to performance degradation and eventual failure. These effects are further accelerated when the motor is driven by inverter-based power systems [4, 5]. PMSM failures are typically classified into 3 categories: electrical, mechanical, and magnetic. Among these, stator inter-turn short-circuit faults (ITSCFs) are the most common electrical faults, accounting for approximately 30–40 % of all PMSM failures [6–8].

ITSCFs create imbalances in the phase currents, leading to rotor speed oscillations, fluctuations in electromagnetic torque, increased total harmonic distortion (THD), and mechanical vibrations which can accelerate the degradation on both mechanical and electrical components. Therefore, early detection and real-time compensation of these faults are critical for ensuring service continuity and enhancing motor longevity [2].

Several studies have been directed at fault detection and mitigation. For instance, authors [3] proposed a detection technique based on stator current analysis, while in [4] were utilized thermal sensors for fault identification. However, these methods primarily focus on fault detection rather than active compensation.

Furthermore, traditional control strategies, such as field-oriented control (FOC) paired with conventional PI controllers, tend to perform poorly under fault conditions due to their limited adaptability to dynamic system changes [5]. Most modern industrial processes require speed drives with great performance, good steady-state accuracy, high overload capability over the whole speed range and robust operation. In fact, many control techniques have been developed to achieve high efficiency. Among these techniques, FOC allows PMSM to be controlled like an independently excited DC machine providing natural flux-torque decoupling and enabling a rapid torque response [9, 10].

The FOC structure with conventional PI controllers is widely preferred in many applications [10, 11]. However, due to their fixed proportional gain and integral time constant, the static and dynamic performance of PI controllers is significantly affected by parameter variations, load disturbances, and speed fluctuations. To overcome these limitations and improve the robustness of FOC, reducing its sensitivity to parametric variations, faults, and their effects, the implementation of modern and intelligent controllers has become more necessary [12, 13]. Recently, new control techniques for PMSM that are more competitive, able to surmount the nonlinearities and more robust were proposed in the literature such as adaptive control [13], fuzzy logic control [14–16], sliding mode control (SMC) [17, 18] and direct torque control (DTC) [19]. In most of these cited works, the PMSM models were considered without failures (healthy state). In [20] authors show guidelines for the search and choice of PMSM control strategies under different type of faults. They found that adaptive control based on the extended Kalman filter [21] is the best estimation system states, but a drawback complexity. SMC has been widely used for controlling nonlinear systems, providing excellent stability, robustness, and reliable performance even in the presence of uncertainties and external disturbances. Indeed, for the SMC as given in [22], the chattering phenomenon still remains the major problem of this method. On the other hand, various studies have shown that DTC offers several advantages over conventional FOC [19, 23]. However, DTC has notable drawbacks, including high flux and electromagnetic torque ripples, as well as variable switching frequency due to the use of hysteresis controllers [24]. To overcome these limitations, AI techniques, such as neural networks and fuzzy logic, have recently been introduced by researchers to enhance the performance of PMSM drive controllers [15–17]. The neural network technique offers high performance; however, it requires a training process, which can slow down the controller's response. In contrast, fuzzy logic control is an intelligent strategy that emulates human decision-making [16, 17]. Fuzzy logic controllers (FLC) are particularly effective in handling systems with uncertainties or parameter variations. The performance of FLC can be tuned through its internal components, including fuzzy rules, fuzzification, and defuzzification blocks.

Goal. The study aims to develop an advanced vector control strategy incorporating fuzzy logic to enhance fault tolerance in PMSM drives by replacing the conventional PI controller with a FLC. Instead, it relies on a set of linguistic rules derived from expert knowledge, allowing for adaptive and intelligent control. The primary objective is to evaluate the effectiveness of the FLC in terms of reducing torque and speed ripples while preserving overall system performance during fault conditions.

To demonstrate the effectiveness of the proposed method, a comparative study between fuzzy FOC and conventional FOC is conducted under short-circuit fault conditions in various operating scenarios. Simulation results confirm the superiority of fuzzy control in terms of robustness and efficiency in handling ITSCFs. A mathematical fault model of a PMSM driven by a pulse width modulation (PWM) inverter is utilized to analyze various inter-turn fault conditions and severity levels. In an open-loop framework, the system's basic behavior is observed. However, in a closed-loop configuration, the controller actively regulates the *d-q* currents, influencing the motor's fault response [12].

Modeling of PMSM under ITSCFs. Figure 1 shows the PMSM stator with an inter-turn fault, accounting for resistance, self-inductance, back electromotive force (EMF) and mutual inductance between faulty and healthy windings [25].

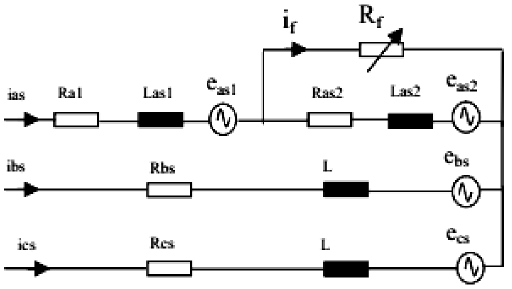


Fig. 1. PMSM stator with ITSCF in phase (*as*)

ITSCF refers to a fault among 2 stator windings within the same phase. To model this fault the affected phase (*as*) is divided into 2 sub-windings, representing the healthy and faulty branches. ITSCF is represented by a resistance whose value varies based on fault severity [25, 26]. As the fault resistance R_f approaches 0, the insulation failure progresses to a full inter-turn short-circuit. The fault current through R_f is denoted as i_f. To quantify the fault severity, a parameter μ is introduced, defined as the ratio of short-circuited turns N_f to the total number of turns in a phase N_s. Fault severity is characterized by 2 key parameters – the short-circuit percentage μ and the resistance (R_f). The resistances of healthy and faulty sections of the stator winding are:

$$R_{as1}=(1-\mu)R_{as};\ R_{as2}=\mu R_{as};\ \mu=\frac{N_{as2}}{N_{as1}+N_{as2}}=\frac{N_f}{N_s}. \quad (1)$$

To model the PMSM drive, the following assumptions are made: no magnetic saturation, negligible temperature effects, sinusoidal flux and magnetomotive force distribution, and the exclusion of higher harmonics [10]. Additionally, the following relationships are generally recognized:

$$\begin{cases} R_s = R_{as} = R_{as1} + R_{as2}; \\ L = L_{as1} + L_{as2} + 2M_{a1a2}; \\ M = M_{a1b} + M_{a2b} = M_{a1c} + M_{a2c}; \\ e_{as} = e_{as1} + e_{as2} = e_{as1} + e_f. \end{cases} \quad (2)$$

In general, the stator phases are connected in a star configuration, ensuring that: $i_{as}+i_{bs}+i_{cs}=0$. Under these conditions, the homopolar current component is 0, and the phase currents are limited solely by the cyclic inductance: $L_s=L-M$. Consequently, the voltage equations of PMSM with an ITSCF in phase (*as*), as shown in Fig. 1, can be expressed in the (*abcf*) reference frame as follows:

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \\ 0 \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 & -R_{as2} \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_s & 0 \\ -R_{as2} & 0 & 0 & R_{as2}+R_f \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \\ i_f \end{bmatrix} + \begin{bmatrix} L_s & 0 & 0 & -L_{as2}+M_{a1a2} \\ 0 & L_s & 0 & -M_{a2b} \\ 0 & 0 & L_s & -M_{a2c} \\ -L_{as2}-M_{a1a2} & -M_{a2b} & -M_{a2c} & L_{as2} \end{bmatrix} \frac{\mathrm{d}}{\mathrm{d}t} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \\ i_f \end{bmatrix} + \begin{bmatrix} p\Omega\varphi_f \sin\theta \\ p\Omega\varphi_f \sin(\theta-\frac{2\pi}{3}) \\ p\Omega\varphi_f \sin(\theta+\frac{2\pi}{3}) \\ -\mu p\Omega\varphi_f \sin\theta \end{bmatrix}, \quad (3)$$

where R_s, L_s are the resistance and self-inductance of healthy stator phase windings with $R_{as}=R_{bs}=R_{cs}=R_s$; R_{as2}, L_{as2} are the resistance and self-inductance of the faulty sub-coil (*as*2); M_{a1a2}, M_{a2b}, M_{a2c} are the mutual inductances between sub-coil ($as1$) and coils ($as2$), (bs), and (cs), respectively; M_{a1b}, M_{a1c} are the mutual inductance between sub-coil ($as1$) and coils (bs) and (cs); M_{ab} is the mutual inductance between coils (as) and (bs).

Thus, (3) can be expressed in a more compact form:

$$\left[V_{abcf}\right]=\left[R_s\right]\left[i_{abcf}\right]+\left[L_s\right]\frac{\mathrm{d}}{\mathrm{d}t}\left[i_{abcf}\right]+\left[E_{abcf}\right], \qquad (4)$$

where $[V_{abcf}]$, $[i_{abcf}]$, $[E_{abcf}]$ are the stator voltage, current and back-EMF vectors, respectively.

Based on the power conservation principle, the electromagnetic torque under a short-circuit fault is given as:

$$C_{em}=\frac{e_{as}i_{as}+e_{bs}i_{bs}+e_{cs}i_{cs}-e_f i_f}{\Omega}. \qquad (5)$$

The motor's dynamic behavior is described by the following mechanical equation:

$$C_{em}-C_L-f\Omega=J\frac{\mathrm{d}\Omega}{\mathrm{d}t}, \qquad (6)$$

where f is the friction coefficient; J is the rotor moment of inertia; C_L is the load torque; Ω is the rotor's mechanical speed. Identifying the inductances of a faulty motor is crucial, as they contain essential fault-related information. Two methods are employed to determine the faulty inductances of a PMSM by applying a simple percentage adjustment to the parameters of the healthy state [26].

In this study we adopt a method where the self-inductances of the faulty and healthy winding ($as1$, $as2$) are proportional to the square of the number of shorted turns. Additionally, the mutual inductance depends on the turn count of both sections [25]:

$$\begin{aligned}&L_{as1}=(1-\mu)^2L_{as};\quad L_{as2}=\mu^2L_s;\\&M_{a1a2}=\mu(1-\mu)L_s;\quad M_{a2b}-M_{a2c}=\mu M;\\&M_{a1b}=M_{a1c}=(1-\mu)M,\end{aligned} \qquad (7)$$

where μ is the fraction of shorted turns.

Since the PMSM model is a multi-variable, non-linear and strongly coupled system. Hence, to surmount this difficulty and to obtain a model similar to that of the separately DC machine, the most popular control strategy of PMSM named FOC was established.

Proposed method. This approach involves replacing the conventional PI controller with a FLC in the FOC scheme for a PMSM drive, aiming to enhance performance under short-circuit faults in various operating conditions. FOC is the most used technique to drive the PMSM; it is based on the use of a transformation that takes machine's electrical variables from (abc) stationary referential into (d-q) rotating referential with the flux vector. Consequently, this makes it possible to control the flux with the stator current i_d, while, the component i_q allows to control the electromagnetic torque [9, 10]. When i_d=0, the relationship between C_{em} and i_q becomes linear, and PMSM will be equivalent to a DC motor with separate excitation. As shown in Fig. 2, FOC can achieve closed-loop speed control. The speed PI controller generates reference quadrature current i_q^*, or reference of the output torque:

$$C_{em}=1.5pi_q^*\varphi_f, \qquad (8)$$

where φ_f is the permanent magnet flux; p is the number of pole pairs of the motor.

To generate gating signals for the inverter, PWM is applied to produce the reference signals. Figure 2 shows the block diagram of the FOC for PMSM drive under ITSCF.

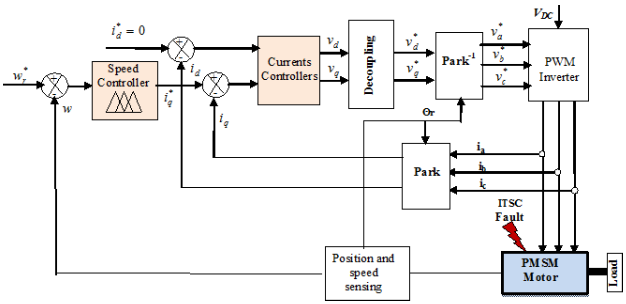


Fig. 2. Block diagram of the FOC for PMSM under faults

Classical PI speed controller. The PI controller is a feedback control loop method which is widely used in control systems in industries [13, 14]. It is defined by the following action law:

$$i_q^*=k_p(\omega_r^*-\omega)+k_i\int(\omega_r^*-\omega)\mathrm{d}t, \qquad (9)$$

where k_p, k_i are the PI parameters which represent gains determined by pole placement method.

Fuzzy PI speed controller. Note that conventional PI controllers have certain limitations, such as overshoot and undershoot in the response, particularly when the system is affected by unknown nonlinearities [15, 16]. On the other hand, FLCs are able to overcome these disadvantages. Similar to human reasoning, FLC handles imprecise information through 3 steps: fuzzification, inference and defuzzification. Fuzzification converts crisp values into fuzzy values using membership functions. Inference applies rules to link inputs and outputs, while defuzzification converts the fuzzy output back to a crisp value. Figure 3 gives the whole framework of the FOC method containing 3 regulators, 2 conventional PI for the currents i_d and i_q (inner loops) and 1 regulator for the speed (outer loop). The proposed fuzzy PI speed controller is of Mamdani type with 3 linguistic variables: 2 inputs (error e and its variation de) and 1 output (control action current i_q^*). The error speed e and its change de are:

$$\begin{cases}e(k)=\omega_{ref(k)}-\omega(k);\\de(k)=e(k)-e(k-1).\end{cases} \qquad (10)$$

In Fig. 3 gains k_e, k_{de} are scaling factors used to adjust controller input values for best performances.

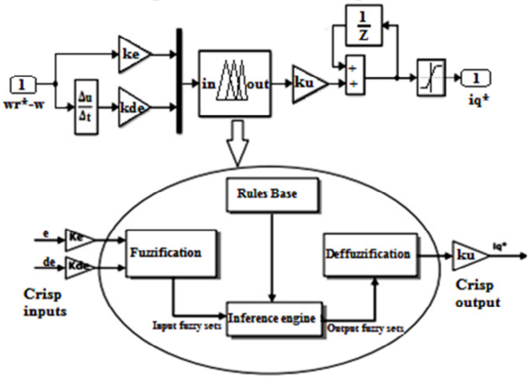


Fig. 3. Block framework of the fuzzy PI controller

The fuzzy PI control law is expressed as:

$$u(k)=u(k-1)+k_u du(k), \qquad (11)$$

where k_u is the control gain.

Each linguistic variable's universe of discourse is divided into 7 fuzzy subsets, defined by the following membership functions (Fig. 4): **NB** (Negative Big); **NM** (Negative Medium); **NS** (Negative Small); **ZE** (Zero); **PS** (Positive Small); **PM** (Positive Medium); **PB** (Positive Big).

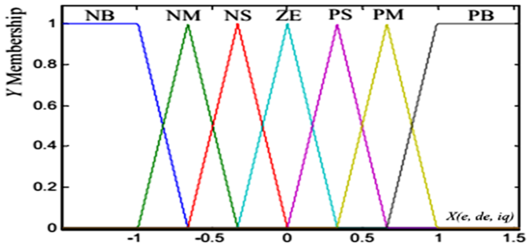


Fig. 4. Inputs and output FLC membership functions

Controller fuzzy rules are given in Table 1. Used rules have the following *If-Then* form:

$R^{(l)}$: if e is A^l, and de is B^l, Then i_q^* is C^l,

where (l) is the rule number; A^l, B^l are input membership functions; C^l is the output membership function.

Defuzzification process is based on the popular centre of gravity method.

Table 1

Speed fuzzy controller rules

de / e	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	ZE
NM	NB	NM	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NS	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PM	PB
PB	ZE	PS	PS	PM	PB	PB	PB

Simulation and results. All results presented here are based on the assumption that the fault parameters μ and R_f are known. The simulations are performed in MATLAB/Simulink environment. The nominal parameters of the PMSM used in this study are listed in Table 2. To analyze the motor's behavior under an inter-turn fault in the stator winding, both healthy and faulty operating conditions were considered.

Table 2

Parameters of PMSM used in simulation

Components	Value
Number of pole pairs, p	8
Number of winding turns /slot, N_s	40
Rated power, P_n, kW	5
Rated current, I_n, A	19
Stator resistance/phase, R_s, Ω	0.44
Stator inductance/phase, L_s, mH	2.82
Synchronous speed, Ω_s, rpm	1000
Magnetic flux, φ_f, Wb	0.108
Moment of inertia, J, kg·m^2	0.0006
Friction coefficient, f, N·m·s/rad	0.007
Nominal torque, C_n, N·m	10

PMSM in healthy case. In this section, the performances of the vector control drive of PMSM, under healthy conditions are tested. In Fig. 5, 6 the rotor speed, the electromagnetic torque and the stator phase currents in the Park's frame for the healthy PMSM associated to the FOC with both classical PI and fuzzy PI speed controllers are respectively presented. The vector control robustness is tested under the application of a load torque at t=0.15 s followed by an application of a reversing speed from 100 rad/s to –100 rad/s at time t=0.25 s. It can be seen that obtained results with the classic PI speed regulator are almost similar to those obtained by the fuzzy PI regulator, but with a slight superiority of the later in terms of response time and load disturbance rejection. In addition, the three phase stator currents in (*abc*) reference frame as shown in Fig. 5,*a* and Fig. 6,*a* are balanced and sinusoidal.

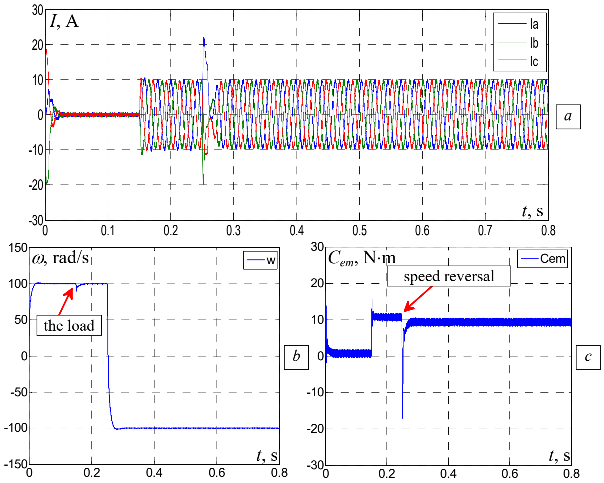


Fig. 5. Simulation results with *classical* PI speed controller in healthy case: *a*) stator phase currents; *b*) rotor speed; *c*) electromagnetic torque

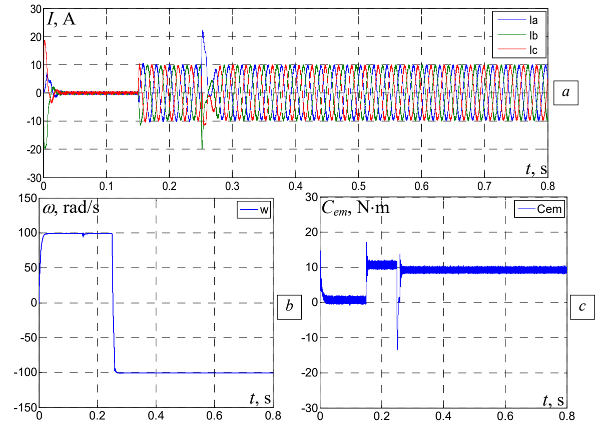
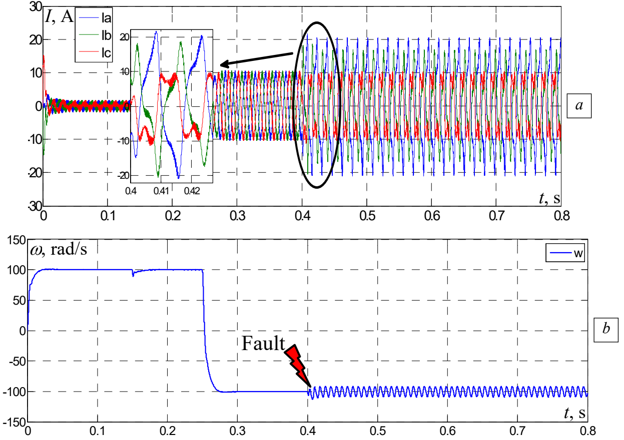


Fig. 6. Simulation results with *fuzzy* PI speed controller in healthy case: *a*) stator phase currents; *b*) rotor speed; *c*) electromagnetic torque

PMSM in faulty case. In this case, we will consider the FOC comportment of the PMSM drive with the presence of ITSCF. We test the robustness with the application of a load torque of 10 N·m at t=0.15 s followed by a speed reversing from 100 rad/s to –100 rad/s at time t=0.25 s as shown in Fig. 7,*b*,*c* and Fig. 8,*b*,*c*. Consider that the phase (*as*) is affected by a short-circuit fault introduced at t=0.4 s with μ=20 %, which corresponds to 32 turns out of 160 being faulty. The resistance R_f is fixed to 0.1 Ω. As shown in Fig. 7,*a* and Fig. 8,*a* the current magnitude in the faulty phase (*as*) is higher compared to the other healthy phases (*bs*, *cs*) and the unbalance of the phase currents becomes more important.



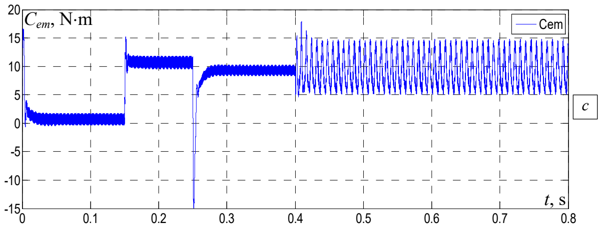


Fig. 7. Simulation results with *classical* PI speed controller (μ=20 % and R_f=0.1 Ω): *a*) three phase stator currents; *b*) rotor speed; *c*) electromagnetic torque

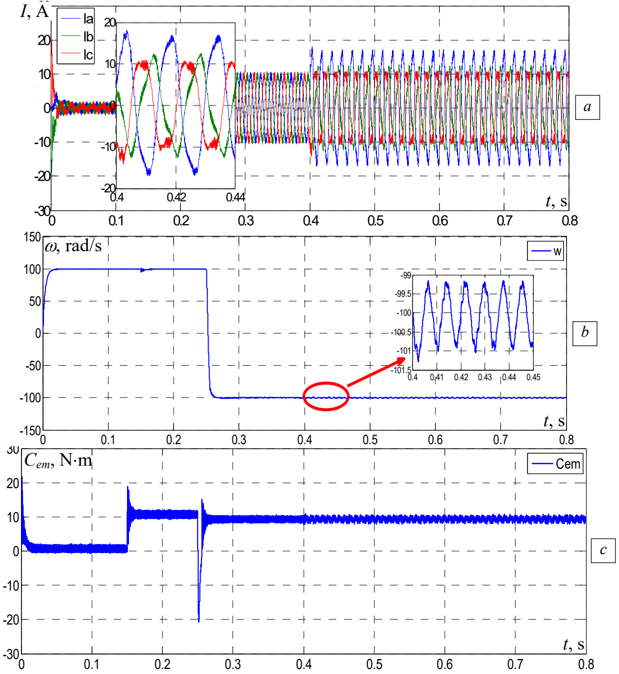


Fig. 8. Simulation results with *fuzzy* PI speed controller (μ=20 % and R_f=0.1 Ω): *a*) three phase stator currents; *b*) rotor speed; *c*) electromagnetic torque

Comparison and discussion. Figures 9, 10 show the rotor speed and electromagnetic torque for a healthy PMSM. For the fuzzy PI controller, the ripples magnitude is smaller compared to that obtained with the conventional PI controller. In what follows, and for comparison purposes, consider that the phase (*as*) is now affected by a short-circuit fault introduced at t=0.4 s with μ=50 %, which corresponds to 80 turns out of 160 being faulty.

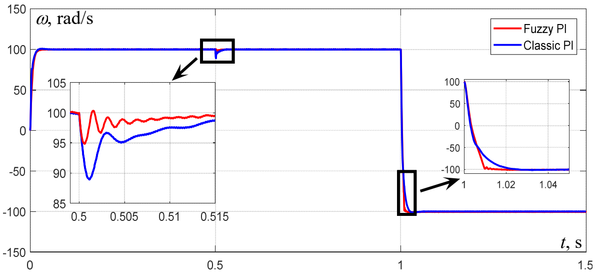


Fig. 9. Rotor speed of healthy PMSM

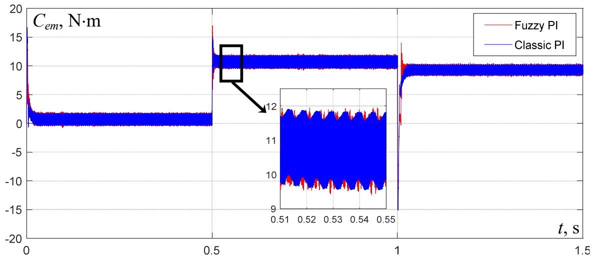


Fig. 10. Electromagnetic torque of healthy PMSM

Figures 11, 12 show the rotor speed and the electromagnetic torque, in which we note that the ripples increase significantly when μ increases to 50 % ITSCF with the fault resistance R_f=0.1 Ω. Comparing the classic PI controller with the fuzzy controller, we see that: 1) fuzzy control reduces efficiently ripples magnitude while utilizing the defective phase to maintain maximum torque capacity; 2) provides faster responses and more efficient load disturbance rejection in both cases, healthy and faulty ones. This control can be used in a situation where the fault severity is estimated to be safe to keep the motor running.

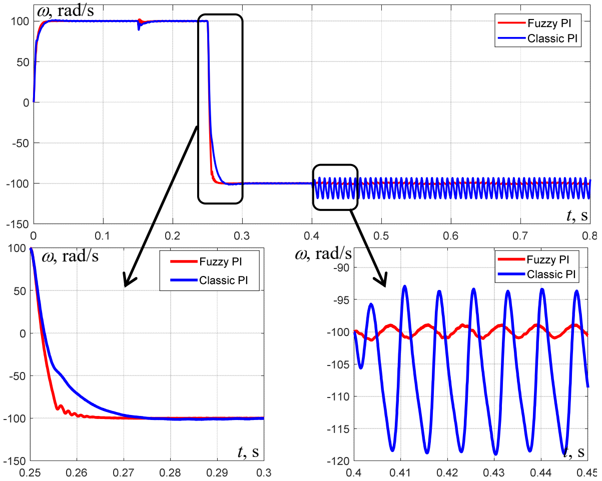


Fig. 11. Rotor speed of PMSM under short-circuit fault (μ=50 % and R_f =0.1 Ω)

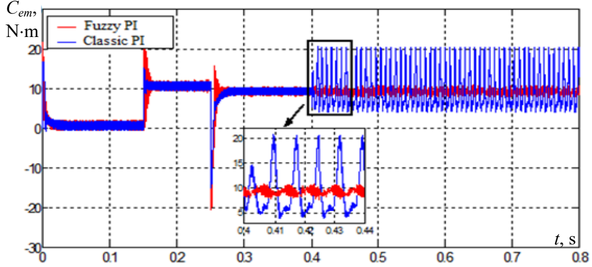


Fig. 12. Electromagnetic torque for PMSM under short-circuit fault (μ=50 % and R_f=0.1 Ω)

Figure 13 shows the rotor speed and electromagnetic torque spectra using MATLAB's fast Fourier transform (FFT) toolbox to analyze frequency components and THD.

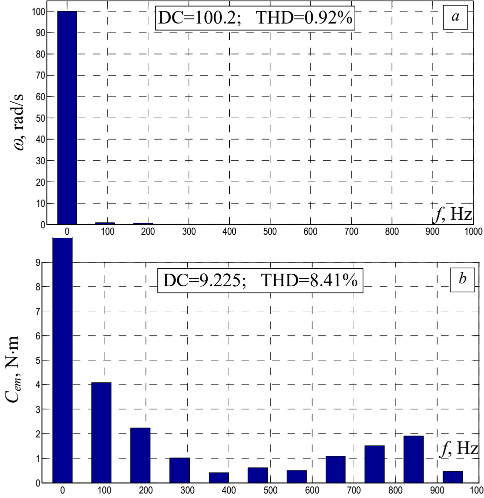


Fig. 13. Frequency analysis under ITSCF conditions in the fuzzy vector control (R_f=0.1 Ω and μ=50 %): *a*) rotor speed spectral analysis; *b*) electromagnetic torque spectral analysis

Under ITSCF conditions, harmonic frequencies appear, and their amplitude increases with the severity of the fault.

The results show that the fuzzy controller is more robust than the classical PI, exhibiting fewer ripples and lower THD.

Conclusions. In this study, the PMSM model, incorporating ITSCF in the stator winding, was integrate with vector control in a closed loop scheme using 2 types of controllers. The simulation results confirmed the superiority of the fuzzy PI controller over the conventional PI, especially in the presence of an ITSCF. Fuzzy logic based vector control ensures a high-quality dynamic response and robust control under load torque disturbances, speed reversals, and stator short faults. In addition, the FLC provides excellent dynamic and steady state responses for torque and motor speed, with reduced ripple content that can accelerate stator winding degradation. This advantage extends the winding's lifespan and enhances the predictive diagnosis of turn damage. In conclusion, it can be seen that our approach based on the FLC provides better results than the conventional method and makes the system much more robust to faults. In fact, the proposed scheme has the capability to reduce significantly the torque ripples and the fluctuations in the rotor speed. So, the controller does not just perform control tasks, but is also able to maintain protection when faults happening in the system and can be easily adapted to changes in machine parameters.

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

REFERENCES

1. Khaneghah M.Z., Alzayed M., Chaoui H. Fault Detection and Diagnosis of the Electric Motor Drive and Battery System of Electric Vehicles. *Machines*, 2023, vol. 11, no. 7, art. no. 713. doi: https://doi.org/10.3390/machines11070713.

2. Niu G., Dong X., Chen Y. Motor Fault Diagnostics Based on Current Signatures: A Review. *IEEE Transactions on Instrumentation and Measurement*, 2023, vol. 72, pp. 1-19. doi: https://doi.org/10.1109/TIM.2023.3285999.

3. Hu R., Wang J., Mills A.R., Chong E., Sun Z. Current-Residual-Based Stator Interturn Fault Detection in Permanent Magnet Machines. *IEEE Transactions on Industrial Electronics*, 2021, vol. 68, no. 1, pp. 59-69. doi: https://doi.org/10.1109/TIE.2020.2965500.

4. Mohammed A., Melecio J.I., Djurovic S. Open-Circuit Fault Detection in Stranded PMSM Windings Using Embedded FBG Thermal Sensors. *IEEE Sensors Journal*, 2019, vol. 19, no. 9, pp. 3358-3367. doi: https://doi.org/10.1109/JSEN.2019.2894097.

5. Sergakis A., Salinas M., Gkiolekas N., Gyftakis K.N. A Review of Condition Monitoring of Permanent Magnet Synchronous Machines: Techniques, Challenges and Future Directions. *Energies*, 2025, vol. 18, no. 5, art. no. 1177. doi: https://doi.org/10.3390/en18051177.

6. Mazzoletti M.A., Bossio G.R., De Angelo C.H. Interturn short-circuit fault diagnosis in PMSM with partitioned stator windings. *IET Electric Power Applications*, 2020, vol. 14, no. 12, pp. 2301-2311. doi: https://doi.org/10.1049/iet-epa.2020.0080.

7. Pietrzak P., Wolkiewicz M. On-line Detection and Classification of PMSM Stator Winding Faults Based on Stator Current Symmetrical Components Analysis and the KNN Algorithm. *Electronics*, 2021, vol. 10, no. 15, art. no. 1786. doi: https://doi.org/10.3390/electronics10151786.

8. Huang W., Chen J., Hu J., Lv K., Liu H. Search-Coil Based Stator Interturn Fault Detection in Permanent Magnet Machines Running under Dynamic Condition. *Electronics*, 2023, vol. 12, no. 13, art. no. 2827. doi: https://doi.org/10.3390/electronics12132827.

9. Pietrzak P., Wolkiewicz M., Orlowska-Kowalska T. PMSM Stator Winding Fault Detection and Classification Based on Bispectrum Analysis and Convolutional Neural Network. *IEEE Transactions on Industrial Electronics*, 2023, vol. 70, no. 5, pp. 5192-5202. doi: https://doi.org/10.1109/TIE.2022.3189076.

10. Setiawan M.H., Ma'arif A., Saifuddin M.F., Salah W.A. A Comparative Study of PID, FOPID, ISF, SMC, and FLC Controllers for DC Motor Speed Control with Particle Swarm Optimization. *International Journal of Robotics and Control Systems*, 2025, vol. 5, no. 1, pp. 640-660. doi: https://doi.org/10.31763/ijrcs.v5i1.1764.

11. Khanh P.Q., Dat N.T., Anh H.P.H. Optimal Fuzzy-PI PMSM Speed Control Using Evolutionary DE Algorithm Implemented on DSP Controller. *2023 International Conference on System Science and Engineering (ICSSE)*, 2023, pp. 206-211. doi: https://doi.org/10.1109/ICSSE58758.2023.10227151.

12. Moussaoui L., Aouaouda S., Rouaibia R. Fault tolerant control of a permanent magnet synchronous machine using multiple constraints Takagi-Sugeno approach. *Electrical Engineering & Electromechanics*, 2022, no. 6, pp. 22-27. doi: https://doi.org/10.20998/2074-272X.2022.6.04.

13. Chaabane H., Khodja D.E., Chakroune S., Hadji D. Model reference adaptive backstepping control of double star induction machine with extended Kalman sensorless control. *Electrical Engineering & Electromechanics*, 2022, no. 4, pp. 3-11. doi: https://doi.org/10.20998/2074-272X.2022.4.01.

14. Zhang B., Niu P., Guo X., He J. Fuzzy PID control of permanent magnet synchronous motor electric steering engine by improved beetle antennae search algorithm. *Scientific Reports*, 2024, vol. 14, no. 1, art. no. 2898. doi: https://doi.org/10.1038/s41598-024-52600-8.

15. 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.

16. Deng Y., Wang J., Li H., Liu J., Tian D. Adaptive sliding mode current control with sliding mode disturbance observer for PMSM drives. *ISA Transactions*, 2019, vol. 88, pp. 113-126. doi: https://doi.org/10.1016/j.isatra.2018.11.039.

17. 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.

18. Bhuiyan E.A., Akhand M.M.A., Das S.K., Ali M.F., Tasneem Z., Islam M.R., Saha D.K., Badal F.R., Ahamed M.H., Moyeen S.I. A Survey on Fault Diagnosis and Fault Tolerant Methodologies for Permanent Magnet Synchronous Machines. *International Journal of Automation and Computing*, 2020, vol. 17, no. 6, pp. 763-787. doi: https://doi.org/10.1007/s11633-020-1250-3.

19. Dan L. EKF-based fault detection and isolation for PMSM inverter. *Sustainable Energy Technologies and Assessments*, 2022, vol. 52, art. no. 101846. doi: https://doi.org/10.1016/j.seta.2021.101846.

20. Oualah O., Kerdoun D., Boumassata A. Comparative study between sliding mode control and the vector control of a brushless doubly fed reluctance generator based on wind energy conversion systems. *Electrical Engineering & Electromechanics*, 2022, no. 1, pp. 51-58. doi: https://doi.org/10.20998/2074-272X.2022.1.07.

21. Zhang J., Zhan W., Ehsani M. Fault-Tolerant Control of PMSM With Inter-Turn Short-Circuit Fault. *IEEE Transactions on Energy Conversion*, 2019, vol. 34, no. 4, pp. 2267-2275. doi: https://doi.org/10.1109/TEC.2019.2936225.

22. 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.

23. Bdewi M.Y., Mohammed A.M., Ezzaldean M.M. Design and Performance Analysis of Permanent Magnet Synchronous Motor for Electric Vehicles Application. *Engineering and Technology Journal*, 2021, vol. 39, no. 3A, pp. 394-406. doi: https://doi.org/10.30684/etj.v39i3A.1765.

24. Bensalem Y., Abbassi R., Jerbi H. Fuzzy Logic Based-Active Fault Tolerant Control of Speed Sensor Failure for Five-Phase PMSM. *Journal of Electrical Engineering & Technology*, 2021, vol. 16, no. 1, pp. 287-299. doi: https://doi.org/10.1007/s42835-020-00559-7.

25. Vaseghi B., Takorabet N., Nahid-Mobarakeh B., Meibody-Tabar F. Modelling and study of PM machines with inter-turn fault dynamic model–FEM model. *Electric Power Systems Research*, 2011, vol. 81, no. 8, pp. 1715-1722. doi: https://doi.org/10.1016/j.epsr.2011.03.017.

26. Zafarani M., Bostanci E., Qi Y., Goktas T., Akin B. Interturn Short-Circuit Faults in Permanent Magnet Synchronous Machines: An Extended Review and Comprehensive Analysis. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 2018, vol. 6, no. 4, pp. 2173-2191. doi: https://doi.org/10.1109/JESTPE.2018.2811538.

Received 08.04.2025
Accepted 21.05.2025
Published 02.11.2025

Y. Laamari[1]*, PhD, Associate Professor,*
N. Boukhennoufa[1]*, PhD, Associate Professor,*
H. Benderradji[1]*, PhD, Associate Professor,*
S. Allaoui[2]*, PhD, Assistant Professor.*
[1] University of Batna2, Algeria,
e-mail: y.laamari@univ-batna2.dz (Corresponding Author)
[2] Higher National School of Renewable Energies,
Environment & Sustainable Development, Batna, Algeria

How to cite this article:
Laamari Y., Boukhennoufa N., Benderradji H., Allaoui S. Fuzzy logic-based vector control of permanent magnet synchronous motor drives under inter-turn short-circuit fault conditions. *Electrical Engineering & Electromechanics*, 2025, no. 6, pp. 51-56. doi: https://doi.org/10.20998/2074-272X.2025.6.07