Detection of turn short-circuit fault in PMSM variable speed sensorless vector control based on luenberger observer and adaptive Fuzzy Logic Controller

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Abstract: The current study describes a novel approach for controlling a Permanent Magnet Synchronous Motor (PMSM) that utilizes intelligent speed sensorless control based on Field-Oriented Control (FOC), by taking inter-turn short-circuit (ITSC) faults into account and by using a Luenberger observer and adaptive fuzzy logic. The speed loop control in conventional indirect vector control systems typically uses a traditional PI regulator with fixed gains, which may not always be enough to achieve the desired control performance. To address this limitation, a Fuzzy Logic Controller (FLC) is proposed for speed control in the field-oriented control FOC of PMSM. This approach is designed to handle the challenges posed by continuous variations in machine parameters, model uncertainties, nonlinear dynamics, and external disturbances. Additionally, the need for a rotor shaft position sensor can lead to disadvantages such as increased cost, weight and noise and reduced reliability. To overcome these issues, the speed and rotor position are estimated using a Luenberger observation, without requiring a separate sensor. In order to evaluate the efficacy of intelligent controller proposed in the present paper, digital simulations were conducted using the MATLAB&SIMULINK, under varying operating conditions. These included sudden changes in reference speed, load torque, and varying degrees of failure for healthy and degraded states. The simulation results demonstrated that the adaptive FLC outperformed the conventional PI controller in robustness, against parameter variation and stator faults. Additionally, the controller was less sensitive to external load torque disturbances and exhibited a fast dynamic response.

Keywords: Field-Oriented Control, Diagnosis, Speed Sensorless Control, Luenberger Observer, PMSM, Adaptive Fuzzy Logic Controller, Inter-Turn Short-Circuit Faults.

1. Introduction

In the field of automated machines, achieving the high dynamic performance of servo motor drives is crucial for several areas of applications. Researchers in power electronics have recently focused on AC motor control (Takahashi & Ohmori, 1989) which has led to more attention being paid to the permanent magnet synchronous motor. This type of motor is now the most used in industry sectors, due to its many advantages, including simplicity, low maintenance requirements, high efficiency and power density, excellent dynamic torque response, good torque-to-inertia ratio and lower levels of noise and vibration (Boussak, 2005).

Vector control is a widely used method for controlling PMSM systems, where the machine currents are separated into stator currents, including torque and flux, and controlled based on a fixed reference frame to stator flux or voltage, which allows for independent control of both the torque and the flux.

However, this approach requires precise values of machine parameters, which include inductors and resistors, Additionally, it does not consider the nonlinear operation of converters used to tune current controllers (Boulahia et al., 2013). Consequently, changes in machine parameters or operating conditions can significantly impact the performance of FOC method (Benmiloud et al., 2023). On the other hand, in PMSM systems, the design of the speed controller is crucial in order to achieve a high performance. A method of torque-load angle and speed control, based on PI speed controller, is commonly used due to its simplicity and the satisfactory results obtained under various operating conditions. However, in the presence of parameter variations and disturbances across different driving conditions, a fixed PI gain controller may not provide an acceptable performance (Gadoue et al., 2009).

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Fuzzy logic has gained popularity in the field of dynamic system control and identification, due to its ability to represent human experience in an algorithmic manner. However, there are certain situations where a more rigorous mathematical approach is required. Therefore, recent research has focused on combining fuzzy logic with nonlinear control methodologies to achieve improved results (Wang, 1993). For example, Palm utilized Lyapunov stability theory to develop an adaptive law and proposed a globally stable adaptive fuzzy controller (Palm, 1994). Another combined approach utilized a conjunction between fuzzy logic and sliding mode control, in which switching variables were employed to establish a fuzzy boundary layer (Chai & Tong, 1999). This control scheme has been further improved in subsequent studies, such as (Bechkaoui et al., 2015; Berstecher et al., 2001).

In industrial environments, PMSM control has become increasingly significant, particularly for electric drives (Slotine & Li, 1991), making the diagnosis a critical aspect of the process. One of the most common and damaging defects in PMSM is the inter-turn short-circuit (ITSC) issue. Many model-based methods have been provided. These approaches typically employ the states of motor or the parameter estimation for diagnostic purposes, including online inter-turn fault detection (Hasan Ebrahimi et al., 2022), the technique of detection employing the back EMF estimator (Ping et al., 2013), and the reference (Huang et al., 2022) consisting in extracting the mechanical power second harmonic component that shows up when the machine is faulty. In non-model based methods, fault detection relies on analyzing current signals and vibration signals. However, the advancement of machine learning and artificial intelligence has led to the emergence of various methods. Some notable approaches include Neural Networks (NN) (Skowron et al., 2021), Support Vector Machines (SVM) (Shih et al., 2022), and Fuzzy Logic Systems (FLS) (Bechkaoui et al., 2015).

Moreover, precise knowledge of rotor shaft position and speed is crucial for obtaining high dynamic response speed or position control in PMSM. In order to achieve synchronization between the phase excitation pulses and the rotor position, sensors such as optical encoders or resolvers are typically used (Wang,1993). However, using of sensors amplifies the cost and complexity of the system, and also requires regular maintenance and calibration (Rouabah et al., 2013; Wang, 1993). To address these issues, researchers have proposed alternative techniques. State observer or Luenberger observer-based methods have been proposed as viable solutions for this problem, as demonstrated in studies such as (Ameur et al., 2016; Kulworawanichpong, 2009; Luo & Chen, 2012).

In this paper, a novel approach for sensorless vector control of PMSM using adaptive fuzzy logic method was presented for inter-turn short circuit fault diagnosis. The study focuses on the Luenberger observer, which involves representing the state of the dynamic model of the motor. The main objective is to identify the most robust controller that can handle variations in parameters, severity degrees of failures, and load torque. The effectiveness of this approach is demonstrated through simulations and comparisons with other methods.

2. PMSM model with inter-turns fault in abc reference frame

This section presents the model of PMSM with an inter-turn fault, expressed in the abc coordinates. This model is crucial to understand the effects of such faults on PMSM drives. While several models have been proposed to describe AC machines with inter-turn short-circuit faults, they do not consider the effects of spatial harmonics (Bechkaoui et al., 2015).

When a stator winding short-circuit occurs in PMSM, the magnitude of the impact of the fault significantly depends on two factors, the actual speed of the motor, and the ratio $\mu = Ncc/N$, where Ncc is the number of short-circuited inter-turns and N is the total number of turns in a particular phase. The severity of the fault can also be indicated by the resistance value rf which is associated with the current flowing through the short-circuited turns. A lower value of rf is an indicative of a more severe inter-turn short-circuit condition.

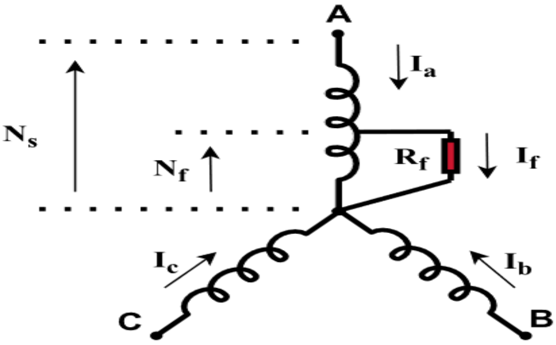

Figure 1. Illustration of a turn fault in PMSM stator winding

The diagram shows the inter-turn short-circuit occurring in one of the turns of the "a" phase winding. The fault is represented by a resistor (*rf*) in parallel with the short-circuited turn. According to Figure 1, the voltage equation can be represented by the equation (1):

$$[\mathrm{V}_s] = R_s[I_s] + L\,\frac{d\,[I_s]}{dt} + [E_s] - N_{cc}R_sT_{s/c}I_f - \sqrt{\frac{3}{2}}N_{cc}L_{ps}T_{32}\begin{bmatrix}\cos(\theta_{cc})\\ \sin(\theta_{cc})\end{bmatrix}\frac{d\left[I_f\right]}{dt} - N_{cc}L_sT_{s/c}\,\frac{d\left[I_f\right]}{dt} \tag{1}$$

where θ_{cc} corresponds to the electrical angle of the stator at the location of the inter-turn short-circuit fault. It is equal to 0, 2π/3, or 4π/3 for a short-circuit on phase A, phase B, or phase C, respectively.

[V_s], [I_s] and [E_s] are the stator voltage, current and electromotive forces vector, respectively:

$$\left[\mathrm{V}_s\right] = \left[v_{as} \quad v_{bs} \quad v_{cs}\right]^T$$

$$\left[I_s\right] = \left[i_{as} \quad i_{bs} \quad i_{cs}\right]^T$$

$$\left[E_s\right] = \left[e_{as} \quad e_{bs} \quad e_{cs}\right]^T$$

Rs denotes the phase resistance, while [*L*] represents the inductance matrix of the PMSM in a healthy state:

$$[\mathrm{L}] = \begin{bmatrix} L_{ls}+L_{ps} & \frac{-L_{ps}}{2} & \frac{-L_{ps}}{2} \\ \frac{-L_{ps}}{2} & L_{ls}+L_{ps} & \frac{-L_{ps}}{2} \\ \frac{-L_{ps}}{2} & \frac{-L_{ps}}{2} & L_{ls}+L_{ps} \end{bmatrix}$$

where the stator synchronous inductance is denoted by: $L_s = \frac{3}{2}L_{ps} + L_{ls}$

Additionally, the equation for the short-circuit fault component is given by equation (2):

$$0 = N_{cc}R_sT_{s/c}{}^T\left[I_s\right] + \sqrt{\frac{3}{2}}N_{cc}L_{ps}\left(T_{32}\begin{bmatrix}\cos(\theta_{cc})\\ \sin(\theta_{cc})\end{bmatrix}\right)^T\frac{d\left[I_s\right]}{dt} - N_{cc}T_{s/c}{}^T\left[E\right] + N_{cc}R_sI_f \tag{2}$$

The short–circuit matrix is the following:

$$[T_{s/c}] = \frac{1}{3}\begin{bmatrix} 1+2\cos(\theta_{cc}) \\ 1+2\cos\left(\theta_{cc}-\frac{2\pi}{3}\right) \\ 1+2\cos\left(\theta_{cc}-\frac{4\pi}{3}\right) \end{bmatrix} \left(= \begin{bmatrix}1\\0\\0\end{bmatrix} if\,\theta_{cc} = 0; = \begin{bmatrix}0\\1\\0\end{bmatrix} if\,\theta_{cc} = \frac{2\pi}{3}; = \begin{bmatrix}0\\0\\1\end{bmatrix} if\,\theta_{cc} = \frac{4\pi}{3} \right)$$

The electromagnetic torque (Te) and the mechanical equation can be expressed by (3):

$$\begin{aligned} T_e &= \frac{[E_s][I_s]-e_{a2}i_f}{\Omega} \\ T_e - T_l &= J\,\frac{d\Omega_r}{dt} \end{aligned} \qquad (3)$$

where

J is the moment of inertia,

T_l is the load torque and

Ω_r is the mechanical angular speed.

3. Vector control

The PMSM can be transformed into a structure similar to a DC machine with separate excitation using the vector control strategy, which ensures that changes in the electromagnetic torque do not affect the flux. Under ideal conditions, the main inductor flux is proportional to the excitation current, and the electromagnetic torque is proportional to the inductor current for a constant flux. This approach allows for faster response times and more precise control of the electromagnetic torque.

In this study, the speed controller determines the desired value for the electromagnetic torque produced by the stator current i_{Sq}. The flux generating stator current i_{Sd} was intentionally set to zero, as presented in Figure 2, meaning that there is no additional flux component besides the permanent magnet Q_e. The actual values of i_{Sq} and i_{Sd} are compared to their respective reference values, and the resulting error signals are passed through their corresponding current controllers, in order to produce the corresponding reference voltage components for the stator u_{Sq} and u_{Sd}, respectively. It is important to note that these reference voltage components are interdependent due to mutual coupling.

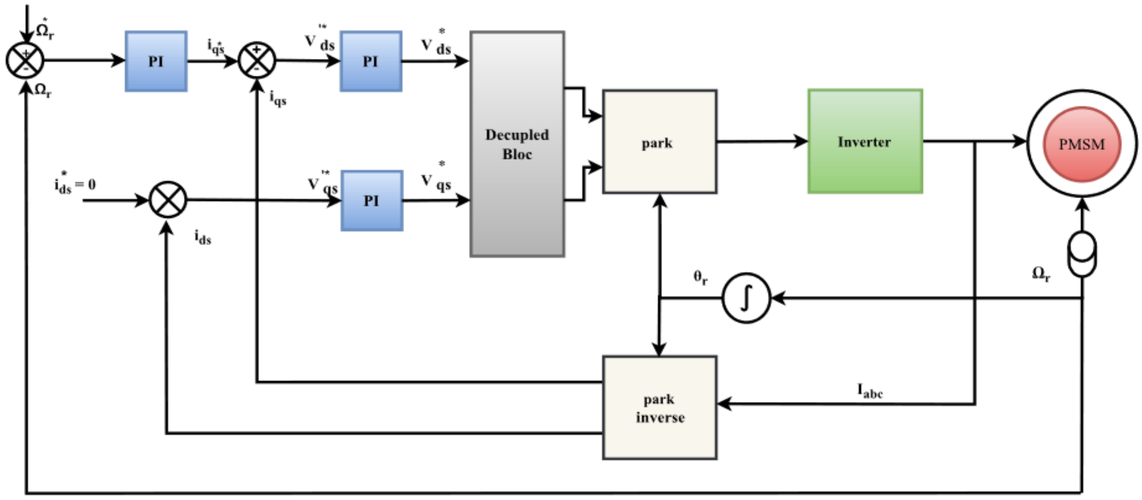

Figure 2. Vector Control structure for PMSM

4. Speed estimation using luenberger observer

This section presents the Luenberger observer technique used for estimating the rotor speed and position of the PMSM without the use of mechanical sensors (Zheng, 2008). The observer is designed based on the model of the PMSM, and it estimates the rotor position and the speed by observing the stator currents and voltages.

The observer consists of a state and an output and it can be written as equation (4):

$$\begin{aligned} \dot{\hat{X}} &= A.\hat{X} + B.U \\ \hat{y} &= C.\hat{X} \end{aligned} \tag{4}$$

where the state equation of the Luenberger observer for the PMSM can be expressed as illustrated in Figure 3 (Kulworawanichpong, 2009):

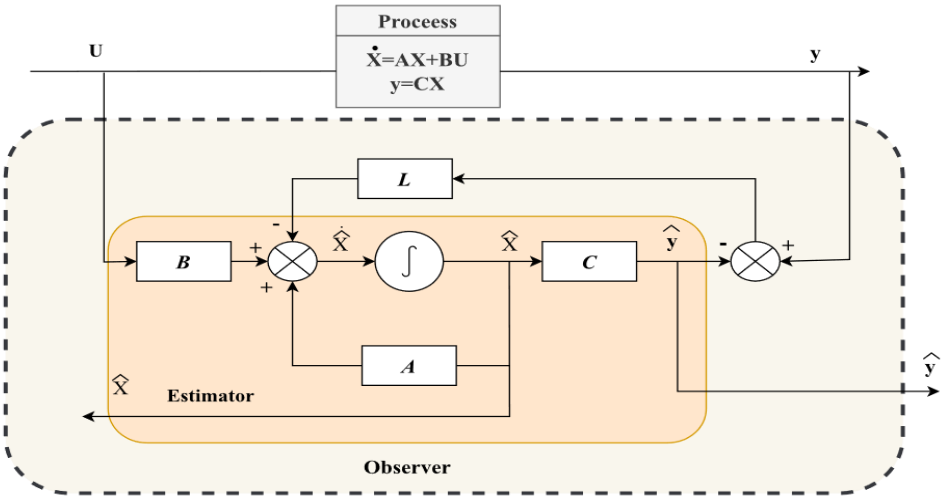

Figure 3. Principle Observer diagrams

$$\begin{aligned} \dot{\hat{X}} &= A.\hat{X} + B.U + L\left(y - \hat{y}\right) \\ \hat{y} &= C.\hat{X} \end{aligned} \tag{5}$$

with:

$$\hat{X} = [\hat{I}_{sd} \ \ \hat{I}_{sq}]^T \qquad U = \left[v_{ds} \ v_{qs}\right]$$

$$A = \begin{bmatrix} -\frac{r}{L_d} & p\Omega_r \\ -p\Omega_r & -\frac{r}{L_d} \end{bmatrix}, \quad B = \frac{1}{L_d}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad C = \begin{bmatrix} 0 \\ \frac{-\varphi_e}{L_d} \, p\Omega_r \end{bmatrix}$$

L is the gain matrix.

Also, from equation (5), the speed estimator may be derived as:

$$\frac{d\hat{\Omega}_r}{dt} = \frac{1}{J}\left(\frac{3}{2} \ p\left(\left(L_d - L_q\right)\hat{i}_{ds} \ \hat{i}_{qs} + \varphi_e \ \hat{i}_{qs}\right) - T_l\right) \tag{6}$$

The rotor position $\hat{\theta}_r$ can be determined by integrating the estimated rotor speed.

5. Fuzzy logic speed controller

In this study, a fuzzy logic speed controller for the PMSM is implemented. Unlike a PI controller, which uses a fixed set of rules to determine the control input, a fuzzy logic controller uses a set of fuzzy rules to determine the control input, based on the current state of the system. The fuzzy logic controller consists of three main components: a fuzzifier, a rule base, and a defuzzifier (Luo & Chen, 2012). The PI speed controller gains were obtained by using two FLCs with two inputs and a single output, as depicted in Figure 4. The input gains of the PI controller comprise the normalized error between the actual and the reference rotor speeds $e(k)=\omega_r^*(k)-\omega_r(k)$ and the normalized change in flux error $\Delta e(k)=e(k)-e(k-1)$. The study uses the centroid defuzzification algorithm, which calculates the center of gravity of the membership function to determine the output fuzzy variable value.

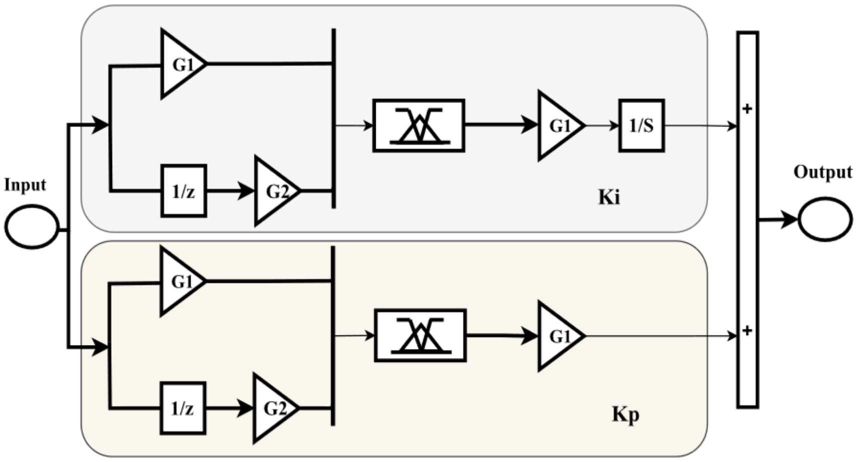

Figure 4. General structure of adaptive FLC

6. Simulation results

The effectiveness of the presented method for PMSM speed control using a hybrid sensorless vector control with an adaptive fuzzy logic controller was evaluated through simulations. The simulations included speed variation tests with the application of varying load torques and the introduction of a fault in the inter-turn winding, which was simulated by controlling the resistance value of *Rf* in the model. In the case of a healthy machine, the value of *Rf* is set to 200 ohms while, if the machine has inter-turn faults, the estimated value of *Rf* drops to 0 ohms. The results of the simulations demonstrated the improved performance of the proposed method in controlling the speed of the PMSM, even in the presence of load variations and faults.

6.1. Healthy motor

In the first test, both AFLC-VC and PI-VC controllers were tested for their speed response and disturbance rejection capabilities. The test was performed on the PMSM, when it was operating at a constant speed of 100 rad/sec, under no load conditions. Suddenly, load torque variations of 1N.m, 3N.m, and 5N.m were applied at t= [0.1s, 0.2s, 0.3s] respectively, followed by an abrupt change in the reference speed to -100 rad/sec at t=0.4s. Figure 5 clearly demonstrates that the AFLC-VC controller performs better than the PI-VC controller in terms of load disturbance rejection, as it rapidly responded to the load torque variations and reached the new reference speed with no overshoot and negligible steady-state error, compared to PI-VC.

It can be noted that, with the use of AFLC-VC, both the oscillations and the error decrease, when compared to those of PI-VC.

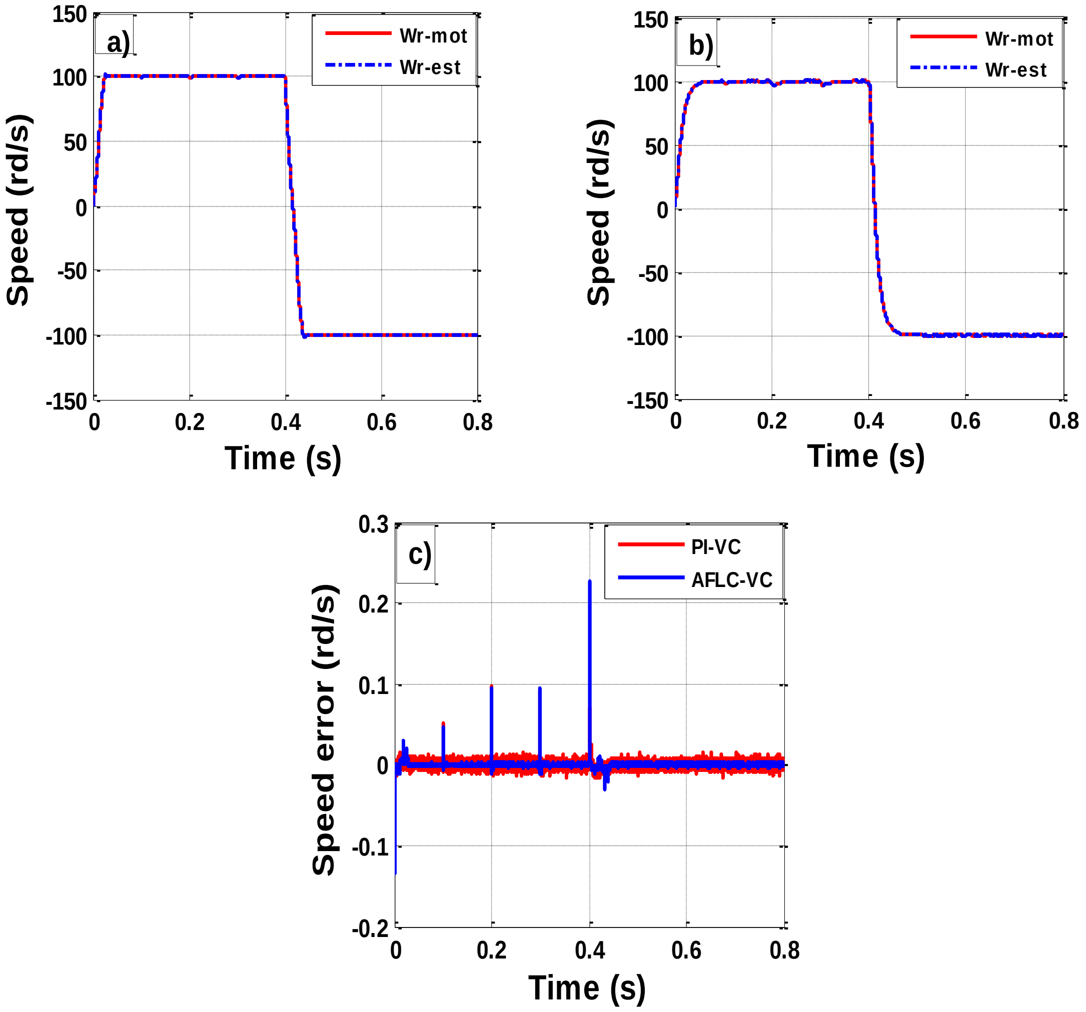

Figure 5. Evolution the speed of the motor for: a) AFLC-VC; b) PI- VC; c) speed error

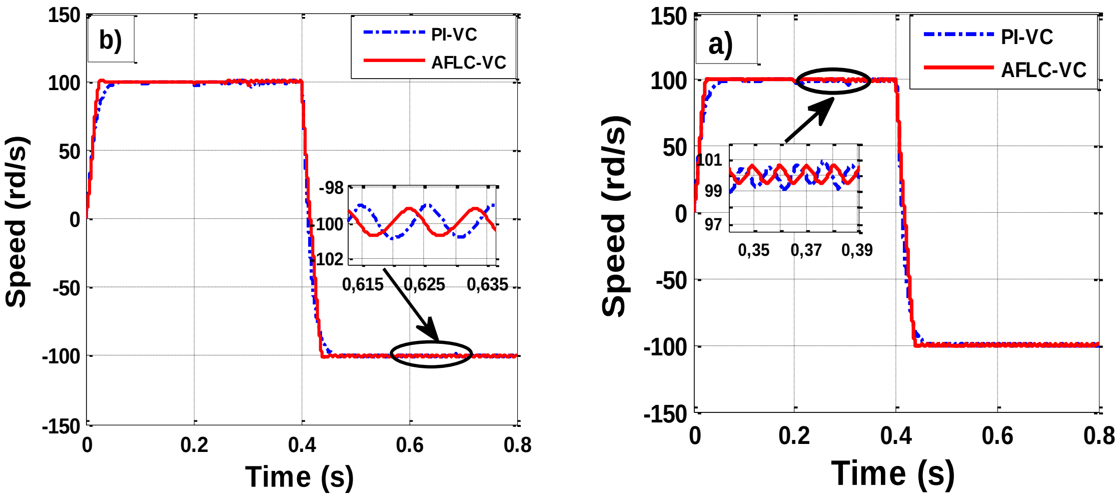

Figure 6. Analysis of the speed of the motor for two controllers with inter-turn short-circuit fault at t=0.25 with: a) 25 sp-cc; b) 35 sp-cc

6.2. Faulty motor

In this subsection, the proposed method was tested for robustness in the presence of inter-turn short-circuit faults in the motor. Two numbers of inter-turn shor0t-circuits were introduced with keeping *Rf* value fixed at 0 ohms.

The speed profiles for both the AFLC and PI controllers are presented in Figure 6. It can be observed that the speed remains stable and insensitive, even if the number of short-circuited turns in the motor changes when using the AFLC controller. This demonstrates the superior robustness of the AFLC controller, when compared to the PI controller. The improved robustness of the AFLC controller can lead to a longer stator winding lifetime, promoting the durability and reliability of the motor.

7. Conclusion

The study introduces a robust sensorless vector control approach for Permanent Magnet Synchronous Motors (PMSMs) using a combination of Luenberger observer and Adaptive Fuzzy Logic Control with Vector Control (AFLC-VC). The AFLC-VC controller demonstrated superior performance during the tests, on both a healthy motor under load disturbances and a faulty motor with inter-turn short circuit faults. In the healthy motor scenario, AFLC-VC outperformed the traditional PI-VC controller, by quickly responding to load torque variations, and by achieving the reference speed with minimal overshoot and steady-state error. In the faulty motor scenario, AFLC-VC showcased remarkable robustness, maintaining stable speed profiles, despite changes in the number of short-circuited turns. Simulation results consistently favored the AFLC-VC controller, demonstrating its effectiveness in minimizing torque ripple under varying conditions and stator faults.

The study concludes by highlighting the need for future real-world implementations to validate the performance of the proposed control system in practical PMSM applications. The promising results suggest that AFLC-VC has the potential to enhance the longevity and reliability of PMSMs in diverse operational settings.

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