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Robustness of the Fuzzy Adaptive Speed Control of a Multi-Phase Asynchronous Machine

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Abstract: Fuzzy controllers are a powerful tool for controlling complex processes. However, its robustness capacity remains moderately limited because it loses its property for large ranges of parametric variations. In this paper, the proposed control method is designed, based on a fuzzy adaptive controller used as a remedy for this problem. For increase the robustness of the vector control and to maintain the performance of the five-phase asynchronous machine despite the presence of disturbances (variation of rotor resistance, rotor inertia variations, sudden variations in the load etc.), by applying the method of behaviour model control (BMC). The results of simulation show that the fuzzy adaptive control provides best performance and has a more robustness as the fuzzy (FLC) and as a conventional (PI) controller.

Keywords: Five-phase, Asynchronous machine, Vector control, Fuzzy adaptive control, Behaviour model control (BMC).

Introduction

The DC machine was for a long time the most used for its capacity of speed variation and its great flexibility of operation. Its control is simple because the two magnitudes torque and flux are naturally decoupled. Nevertheless, the DC machine has many disadvantages related to its mechanical commutate. Indeed, the collector increases the cost of manufacture and maintenance of the machine and limits its use in explosive and/or corrosive environments. This is why researchers have turned to the control of alternating current machines. The growth in electrical energy consumption and high power electrical applications have led to the use of multi-phrase machines (whose number of phases is greater than three) to segment the power. In addition to this advantage, multi-phrase machines have several other advantages such as power segmentation without increasing the currents per phase and the minimization of iron losses. Through these advantages, the multi-phrase machine is used in several applications, especially in the field of high power, among other things, in wind power generation.

Multi-phase machines have obvious potential because of their reliability and their possibility of operating in degraded operation. Despite all these advantages, its control remains quite complicated compared to that of the DC machine, because its mathematical model is nonlinear and strongly coupled. Modern control techniques lead to a control of asynchronous machines comparable to that of the DC machine. Among these techniques, we find direct torque control, state feedback control, vector control and adaptive control. These techniques use both conventional and modern regulators which make the controls mentioned above robust.

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Traditionally, because of its simplicity, a PI controller is used for both current and speed regulation. However, the main disadvantage of using PI controller is that performance degrades under external disturbances and machine parameter variations. To solve this problem, several researchers have proposed intelligent controllers like fuzzy logic, sliding mode control, adaptive control and neural network control. The authors concluded that fuzzy controller has capable of improving the tracking performance under external disturbances and more robust control method than usual PI control. However, the speed adjustment is carried out using a fuzzy controller but its capacity of robustness remains moderately limited, because it loses its property for the large ranges of parametric variations (speed for example). To overcome this problem, is reasonable to combine the adaptive control with the fuzzy robust controller.

Behavior Model Control Principals

In this paper, the "mod" subscript is used to define model values (e.g. Y_{mod} , the model output). P(S) and M(S) are transfer functions. The Behavior Model Control aims to define a complementary control function (value) to that defined by the main controller in order to enhance the control algorithm performance. It requires at least two controllers, a model and the process to be controlled (Fig. 1).

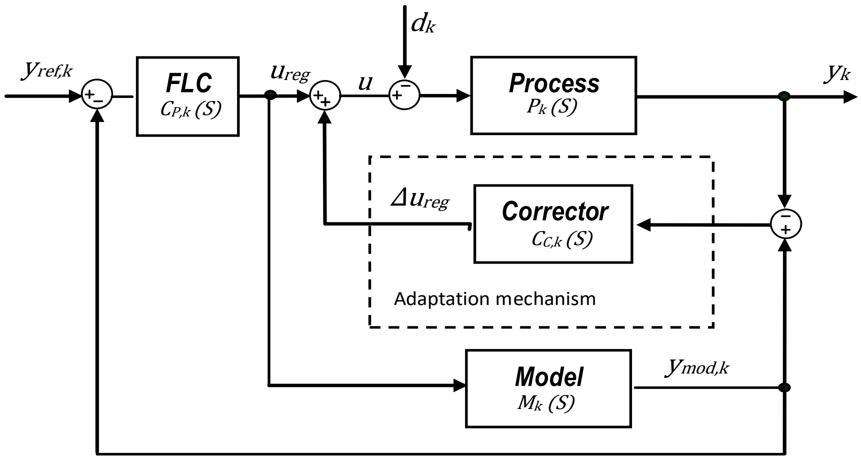


Figure 1. Behavior model control (Functional block)

According to the set-point (reference) Y_{ref} , the main controller $C_p(S)$ delivers an output value u_{reg} . The issued control value u_{reg} from the main controller is applied to a predefined model M(S) called the Behavior Model(BM). The BM define a model output value Y_{mod}. The second controller called "The Behavior Controller or the Adaptation Corrector" uses the gap between the process output value Y and the model output value Y_{mod} , to define the complementary control function (value) Δu_{reg}.

By cancelling the error (Y - Y_{mod}), the process behaviour becomes similar to that of the predefined model, hence the term Behavior Model Control. The complementary control function (value) Δu_{reg} is added to the output value u_{reg} and then applied to the process P(S) as an input value.

As a result, this auxiliary control algorithm increases the robustness of the global control algorithm; it indirectly rejects various disturbances, facilitates the synthesis of classical control and allows the linearization of a non-linear process through a linear model.

It should be noted that the main controller serves to eliminate the error between the set-point (reference) Y_{ref} and output value. This later, can be the output of the model Y_{mod} or that of the process Y. Therefore, one can define two structure of BMC: BMC based on the predefined model output, and BMC based on the process output. According to the scheme of Fig. 1, the following expressions are deduced:

$$\begin{cases} Y(S) = \left[U_{reg}(S) + \Delta U_{reg}(S) - d\right]P(S) \\ \Delta U_{reg}(S) = \left[M(S) + U_{reg}(S) - Y(S)\right]C_C(S) \end{cases} \quad (1)$$

Following the calculation, one arrive at the system that expresses the process output Y as well as that of the model Y_{mod}.

$$\begin{cases} Y(S) = \dfrac{P(S)(1+M(S).C_c(S))}{1+P(S).C_c(S)} U_{reg}(S) \\ \qquad - \dfrac{P(S)}{1+P(S).C_c(S)}.d \\ Y(S) = M(S).U_{reg}(S) \end{cases} \tag{2}$$

Where d : represents the disturbance.

In order to simplify this system, the correction controller $C_C(S)$ must satisfy the following assumptions:

$$\begin{cases} |M(S).C_C(S)| >> 1 \\ |P(S).C_C(S)| >> 1 \end{cases} \tag{3}$$

After simplification, the following is obtained:

$$\begin{cases} Y(S) = M(S).U_{reg}(S).\dfrac{1}{C_c(S)}.d \\ Y_{mod}(S) = M(S).U_{reg}(S) \end{cases} \tag{4}$$

Which gives the following result:

$$Y(S) = Y_{mod}(S) - \frac{1}{C_c(S)}.d \tag{5}$$

The process output (Y) is the same as that of the model (Y_{mod}) at small disturbance. If this disturbance $\dfrac{d}{C_c(S)}$ is negligible compared to the process output Y, it follows perfectly the model output. This condition is written:

$$\frac{d}{C_c(S)} << M(S).U_{reg}(S) \tag{6}$$

Considering the return coming from the model output Y_{mod}, the system (2) becomes:

$$\begin{cases} Y_{\text{mod}}(S) = \dfrac{M(S).C_p(S)}{1+M(S).C_p(S)}.Y_{ref}(S) \\ Y(S) = \dfrac{P(S)(1+M(S).C_c(S))}{M(S)(1+P(S).C_c(S))}.Y_{mod}(S) \\ \qquad - \dfrac{P(S)}{1+P(S).C_c(S)}.d \end{cases} \tag{7}$$

To simplify the transfer function $\dfrac{Y}{Y_{mod}}$, let us suppose the following hypothesis:

$$|M(S).C_c(S)| >> 1 \tag{8}$$

Correction Controller (Used in The Speed Loop)

The correction controller used in the speed loop allows to cancel the error between the output speed of the machine Ω and that of the model Ω_{mod}. So it is very convenient to use this error as well as its derivative as inputs to this corrector. By integrating the output of the latter, we obtain the correction signal ΔT_e which allows the two machines to have a similar behavior to that of the model. The internal structure of the "Correction Controller" block FLCR is identical to that of an FLC (Main Controller), i.e it consists of three blocks: Fuzzification (F), Knowledge Base and the Inference (I) and defuzzification (D).

where : u represents the stator currents ($i_{sd}$and i_{sq}) and speed Ω for the five-phase machine.

As with the design process of the main controller FLC, each input is represented by seven fuzzy sets. This leads to a rule base of forty-nine (49) rules. The inference method used is that of Mamdani (Max-Min). While defuzzification is achieved by the Center of Area (COA) method is employed. The membership functions of input variables E and ΔE respectively and output variable, which are with conventional triangular shapes. Each membership is divided into seven and three fuzzy sets for speed and stator currents respectively (Fig.2).

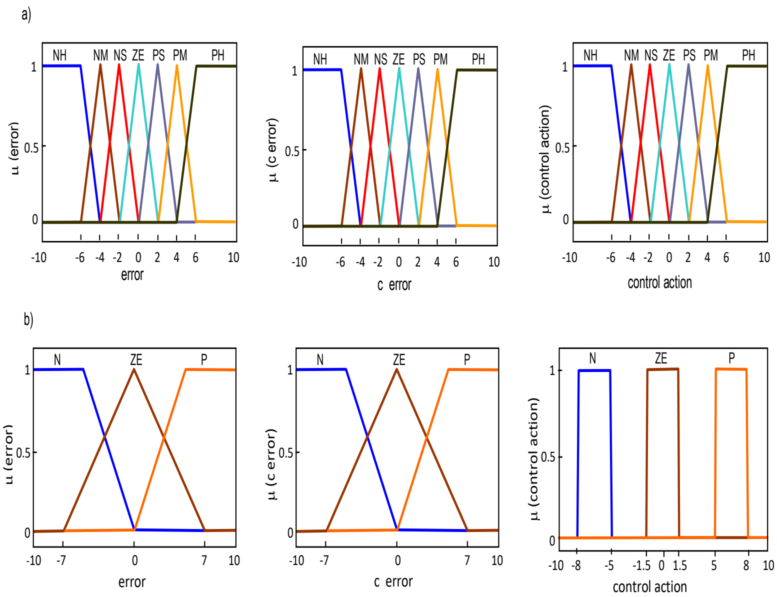


Figure 2. Membership functions of input/output variables: a) Speed,b) Currents

Mathematical Model for Five-Phase Asynchronous Machine

The electric equation of a five-phase an asynchronous machine in the natural base is given by the following expression for each phase:

$$\begin{cases} [V_s]=[R_s][I_s]+\dfrac{d[\phi_s]}{dt} \\ [V_r]=[R_r][I_r]+\dfrac{d[\phi_r]}{dt} \end{cases} \quad (9)$$

Where: $[V_s] = [v_{sa}\ v_{sb}\ v_{sc}\ v_{sd}\ v_{se}]$; $[I_s] = [i_{sa}\ i_{sb}\ i_{sc}\ i_{sd}\ i_{se}]$; $[V_r] = [v_{ra}\ v_{rb}\ v_{rc}]$; $[I_r] = [i_{ra}\ i_{rb}\ i_{rc}]$;

$R_s = R_{sa} = R_{sb} = R_{sc} = R_{sd} = R_{se}$; $R_r = R_{ra} = R_{rb} = R_{rc}$;

$[\phi_s]=[\phi_{sa}\ \phi_{sb}\ \phi_{sc}\ \phi_{sd}\ \phi_{se}]$; $[\phi_r]=[\phi_{ra}\ \phi_{rb}\ \phi_{rc}]$

The model of five-phase an asynchronous machine is as follows after converting Phase variables into *d-q* variables:

$$\begin{cases} V_{sd} = [R_s]i_{sd} - \omega_s \phi_{sq} + \dfrac{d\phi_{sd}}{dt} \\ V_{sq} = [R_s]i_{sq} + \omega_s \phi_{sd} + \dfrac{d\phi_{sq}}{dt} \\ V_{rd} = [R_r]i_{rd} - (\omega_s - \omega_r)\phi_{rq} + \dfrac{d\phi_{rd}}{dt} \\ V_{rq} = [R_r]i_{rq} + (\omega_s - \omega_r)\phi_{rd} + \dfrac{d\phi_{rq}}{dt} \end{cases} \tag{10}$$

The electromagnetic torque for asynchrounous machine is equal to:

$$T_e = \frac{5}{2} pL_m\left(\phi_{rd}.i_{sq} - \phi_{rq}.i_{sd}\right) \tag{11}$$

On the other hand, the mechanichal equation of the machine is:

$$J\frac{d\Omega_r}{dt} = T_e - T_r - f_m.\Omega_r \tag{12}$$

This set of equations allows characterizing the electromechanical behaviour of a five-phase PMSM machine.

Indirect Vector Control for Five-Phase Asynchronous Motor Drive

Vector control technique aims to make equivalence between the five-phase asynchronous motor drive and DC motor. This objective can be achieved by controlling the q-axis flux component to zero. Stator flux and rotor flux orientation are examples of field oriented control techniques for an asynchronous machine. The stator current space vector for an asynchronous machine has two components i_{sd} and i_{sq}.

The i_{ds} produces the rotor flux component and i_{qs} produces the torque-producing component in rotor flux orientation. The rotary flow direction control model is given by the following equation:

$$\begin{cases} i_{rq} = 0 \\ i_{rd}^* = \phi \end{cases} \tag{13}$$

The simplified model of the machine as follows:

$$\begin{cases} \sigma L_s \dfrac{di_{sd}}{dt} = -\left(R_s + \dfrac{L_m^2}{L_r^2}R_r\right)i_{sd} + \sigma L_s \omega_s i_{sq} + \dfrac{L_m}{L_r.T_r}\phi_r + V_{sd} \\ \sigma L_s \dfrac{di_{sq}}{dt} = -\left(R_s + \dfrac{L_m^2}{L_r^2}R_r\right)i_{sq} - \sigma L_s \omega_s i_{sd} - \dfrac{L_m}{L_r.T_r}\omega_r \phi_r + V_{sq} \\ \dfrac{d\phi_r}{dt} = \dfrac{L_m}{T_r}i_{sd} - \dfrac{1}{T_r}\phi_r \\ T_e = p\dfrac{L_m}{T_r}\phi_r i_{sq} \\ \omega_r = \dfrac{M}{T_r}.\dfrac{1}{\phi_r}.i_{sq} \\ J\dfrac{d\Omega_r}{dt} = T_e - L_r - f\Omega_r \end{cases} \tag{14}$$

With $T_s = L_s / R_s$: stator time constant ; $T_r = L_r / R_r$: rotor time constant ; $\sigma = 1 - \frac{L_m^2}{L_r.L_s}$: Total leakage coefficient.

Dynamic Model of Flux and Torque

The rotor flux and the electromagnetic torque can be estimated from the currents i_{sd} and i_{sq} , stator quantities accessible from the measurement of real currents stator subject to the realization of the Park transformation.

$$\begin{cases} \hat{\phi}_r + T_r \dfrac{d}{dt}\hat{\phi}_r = L_m i_{sd} \\ \hat{T}_e = p\dfrac{L_m}{T_r}\hat{\phi}_r i_{sq} \\ \hat{\omega}_s - \omega_r = \dfrac{L_m}{T_r}.\dfrac{1}{\hat{\phi}_r}.i_{sq} \\ \hat{\theta}_s = \int \hat{\omega}_s dt \end{cases} \Rightarrow \begin{cases} \hat{\phi}_r = \dfrac{L_m}{1+T_r} i_{sd} \\ \hat{T}_e = p\dfrac{L_m}{T_r}\hat{\phi}_r i_{sq} \\ \hat{\omega}_s - \omega_r = \dfrac{L_m}{T_r}.\dfrac{1}{\hat{\phi}_r}.i_{sq} \\ \hat{\theta}_s = \int (p\Omega_r \dfrac{L_m}{T_r}.\dfrac{1}{\hat{\phi}_r}.i_{sq})dt \end{cases} \quad (15)$$

Decoupling by Compensation

The decoupling principle amounts to defining two new control variables v_{sd1} and v_{sq1} such as v_{sd1} only acts on i_{sd} and v_{sq1} on i_{sq}. So, we can write the voltages v_{sd} and v_{sq} as a function of v_{sd1} and v_{sq1} as follows:

$$\begin{cases} v_{sd} = v_{sd1} - e_1 \\ v_{sq} = v_{sq1} - e_2 \end{cases} \quad (16)$$

With:

$$\begin{cases} e_1 = \sigma L_s \omega_s i_{sq} + \dfrac{L_m R_r}{L_r^2}\phi_r \\ e_2 = -\sigma L_s \omega_s i_{sd} - \dfrac{L_m}{L_r}\omega_s \phi_r \end{cases} \quad (17)$$

Defluxing

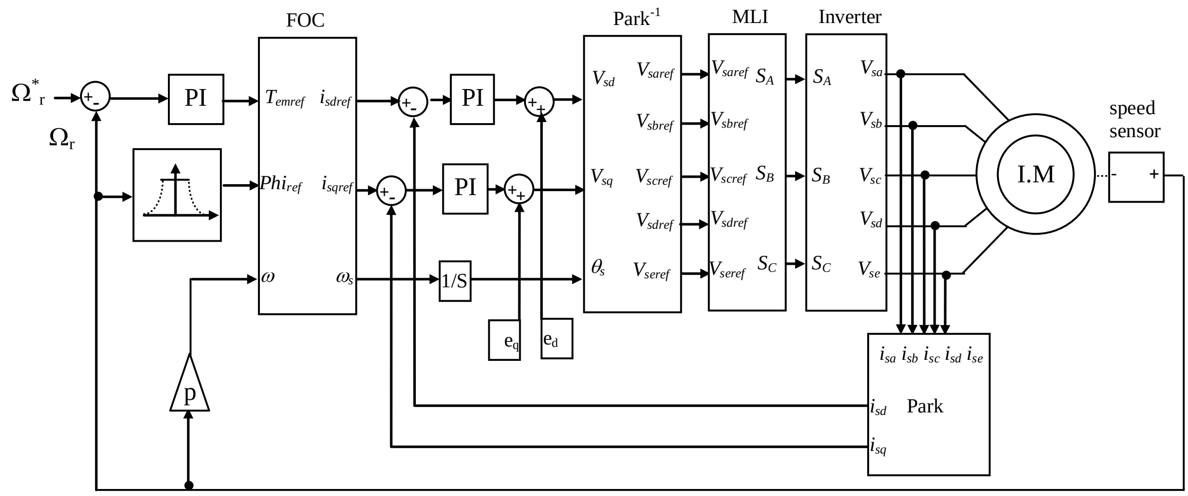


Figure 3. Vector control for a five-phase an asynchronous machine.

The defluxing block are written as follows

$$\phi_r^* = \begin{cases} \phi_{rn} & if \quad \Omega_r < \Omega_{rn} \\ \dfrac{\phi_{rn}\Omega_{rn}}{\Omega_r} & if \quad \Omega_r > \Omega_{rn} \end{cases} \tag{18}$$

A system illustration of the vector control of five-phase an asynchronous motor is given in Figure 3.

Results and Discussion

Fig. 4 shows the performances of the behaviour model control of a five-phase an asynchronous induction machine. The simulation results are intended to simulate the application of fuzzy adaptive controller (BMC) on the speed control of a five-phase induction machine. The first step is reserved for the simulation of the no-load start, followed by the application of a load torque equal of 20 Nm at t = 2s, with a reversal of direction of rotation at time t = 3s from +100 rad / s to -100 rad / s under a speed of 50 rad / s (five-phase IM). The responses in terms of speeds, torques and stator currents are illustrated in Fig. 4. It is clear that the dynamic performances of five-phase IM are acceptable.

System Robustness

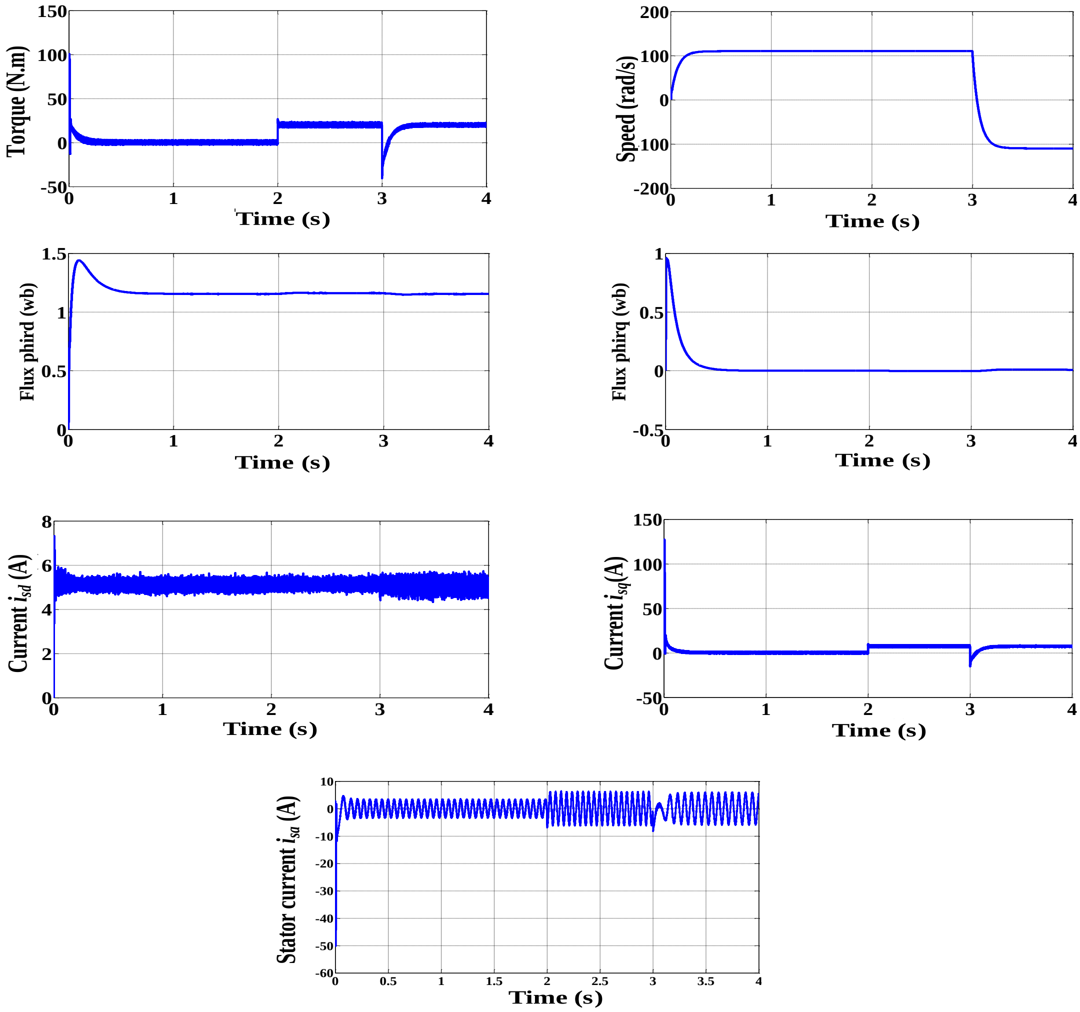
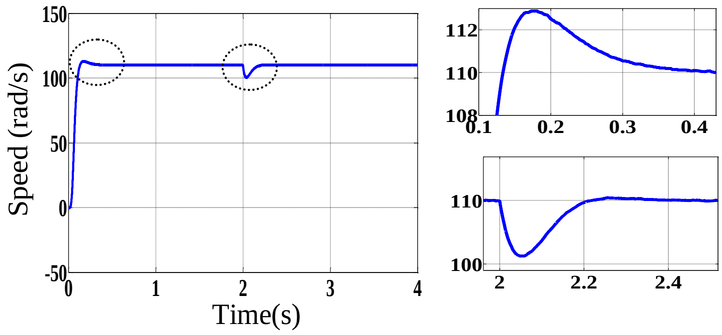


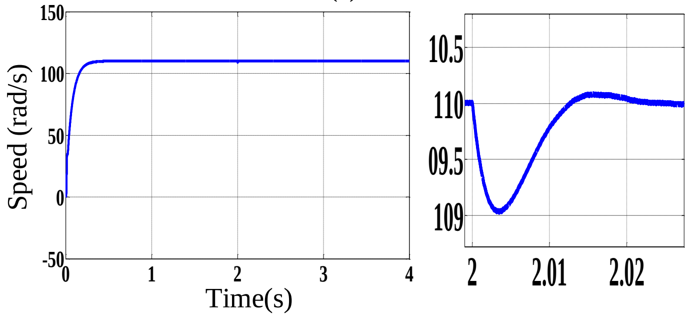
Figure 4. Indirect vector control performance of the five-phase IM with fuzzy adaptive regulators in speed reversal

Figs. 5, the five-phase an asynchronous I.M driver controlled by BCM, FLC and conventional PI of the system under variation of the load and inertial moment (200% *Jn*). At the bottom of the Fig.5, it shows that with BMC, the process is less disturbed by an external disturbance than by compared to the conventional control (PI) and the FLC control. In addition, it is noted that the BMC provides means to better control the transient error due to external disturbance. Finally, the speed response is without overshoot, without static error and with very fast disturbance rejection. Despite internal and external disturbances, the adaptive control maintains the desired performance.

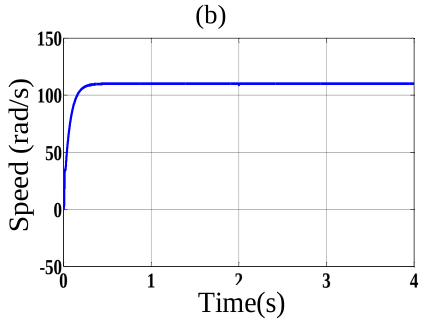
Variation of Rotor Inertia J=200% Jn



(a)



(b)



(c)

Figure 5. Comparison between BMC, FLC and PI conventional
a) PI, b) FLC, c) BMC)

Conclusion

The work carried out is a numerical simulation of the adaptive control within the direct vector control of a voltage-fed asynchronous machine. The proposed adaptive control is with a reference model whose adaptation mechanism is in parallel with the FLC of the inner loop. The performance of the fuzzy logic adaptive controller has been tested. The results obtained by simulation show that BMC is very robust with respect to the disturbances due to the variations of the load, the moment of inertia. The speed response correctly follows the chosen reference model despite the disturbances.

Induction Motor Data

Rated power P_n= 3kW, nominal currant I_n= 3.6/6.2A, stator resistance R_s= 2.5Ω, rotor resistance R_r=1.9Ω, stator inductance L_s= 0.24H, rotor inductance L_r= 0.24H, mutual inductance L_m= 0.226H, rated phase stator voltage V_n = 380V, pole pair number P=2, rotor speed N = 1499tr/min, viscous friction coefficient K_f= 0.0006Nms/rad, Rotor inertia J= 0.031kg.m2.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements or Notes

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