Adaptive Sensorless Control of PMSM using Back-EMF Sliding Mode Observer and Fuzzy Logic

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***Abstract*—This article presents a sensorless control system of PMSM (Permanent Magnet Synchronous Motors) using a back-EMF (back electromotive force) sliding mode observer and a main and correction fuzzy logic controllers to adapt continuously the adjustment parameters K_p and K_i of the speed controller part of the FOC (Field Oriented Control) strategy and achieving superior adjustment performance without overshooting and reduced rising and settling time. In order to achieve superior performance, a second fuzzy controller is proposed which, besides the error and the error derivate of the rotor speed as inputs will also take into account the load torque (an estimate of it) to adjust the adjustment parameter K_p differently depending on the load torque size, but also on the dynamic or stationary regime that occurs during the required speed profile tracking.**

Keywords*—adaptive sensorless control, sliding mode observer, back-EMF, PMSM, fuzzy logic

I. INTRODUCTION

The ever-growing use of PMSMs in variable speed electric drives, robot operation, computer peripherals is based on the fact that these motors have low power consumption, reduced dimensions and high duty density. The generation of the magnetic field in PMSMs is carried out by permanent magnets. Low inertia and rapid response is due to the absence of the rotor cage. Some of the general advantages of PMSMs are: easy cooling, losses concentrated in the stator, low harmonic contents in the torque, and high performance of control due to the sinusoidal form of the back-EMF [1] - [3].

By making use of the characteristics and advantages of PMSMs, algorithms and advanced control methods have been developed [4]. Modern PMSM control methods of adaptive control system type are addressed in [5], robust control system methods are presented in [6] and control techniques based on model predictive control in [7]. Among the control systems based on computational intelligence we mention the genetic algorithms and Particle Swarm Optimization (PSO) [8], [9].

In the control systems, the speed response can be acquired from transducers or can be estimated by using software implemented observers with certain advantages regarding the reliability of the global control system [10], [11].

In order to obtain good results in the electrical drives for the entire range of speed variation under the conditions of wide-ranging load torque, continuous adjustment is carried out for the adjustment parameters of the speed controller in the form of a PI controller, or even directly the current reference I_q (in the FOC control strategy the current reference I_d is set to zero) by using a fuzzy controller which, through the flexibility of inference rules can assist the global control system in achieving very good adjustment performance under the conditions presented above [12] - [14]. The control systems and the performance achieved for DC or AC electric motor drive, by using such a fuzzy controller are presented in [15] - [17]. A fuzzy control system for PMSM is presented in [18] using three fuzzy controllers, but the overshooting of the system at step signals is significant.

Starting from these, in this paper is presented a sensorless control system of PMSM using a back-EMF sliding mode observer and a main and correction fuzzy logic controllers to adapt continuously the adjustment parameters K_p and K_i of the speed controller and achieving superior adjustment performance without overshooting and reduced rising and settling time.

The rest of paper is structured as follows: in Section II is describes the equations for the mathematical model of the PMSM and back-EMF sliding mode observer together with the convergence proofing. The results of the numerical simulation, achieved in Matlab/Simulink environment for the sensorless control of a PMSM based on the back-EMF sliding mode observer and fuzzy logic controllers are presented in Section III. An improved fuzzy logic controller is presented in Section IV and the concluding section presents synthetic ideas on the fuzzy logic control of PMSM and follow-up ideas.

II. PMSM AND BACK-EMF SLIDING MODE OBSERVER – MATHEMATICAL MODEL

Following [10], [11] by using common notations, the linear model of the PMSM is obtained, by accepting a series of simplifying elements: the hysteresis losses are neglected, the temperature and frequency variation of the resistance and inductance are neglected, it is assumed that the flux from the air gap has a sinusoidal distribution and has a radial orientation. Under these conditions, the general model of PMSM is obtained:

$$\begin{aligned} U &= RI + \frac{d\psi}{dt} \\ \psi &= LI + \psi_M \end{aligned} \tag{1}$$

where ψ_M is the magnetic flux of the permanent magnet, ψ is the flux rotor, R and L respectively are the resistance and inductances of the motor coils, and U and I are the voltage and current for each coils.

The flux generated by the permanent magnet, in a, b, c frame is in the form:

$$\begin{aligned} \psi_{ma} &= \lambda_0 \cos(\theta_e) \\ \psi_{mb} &= \lambda_0 \cos\left(\theta_e - \frac{2\pi}{3}\right) \\ \psi_{mc} &= \lambda_0 \cos\left(\theta_e + \frac{2\pi}{3}\right) \end{aligned} \tag{2}$$

And the currents are given by:

$$\begin{aligned} \frac{di_a}{dt} &= -\frac{R}{L} i_a - \frac{1}{L} e_a + \frac{1}{L} u_a \\ \frac{di_b}{dt} &= -\frac{R}{L} i_b - \frac{1}{L} e_b + \frac{1}{L} u_b \\ \frac{di_c}{dt} &= -\frac{R}{L} i_c - \frac{1}{L} e_c + \frac{1}{L} u_c \end{aligned} \tag{3}$$

The back EMF voltages are obtained from equation (2):

$$\begin{aligned} e_a &= \frac{d\psi_{ma}}{dt} = -\lambda_0 \omega_e \sin(\theta_e) \\ e_b &= \frac{d\psi_{mb}}{dt} = -\lambda_0 \omega_e \sin\left(\theta_e - \frac{2\pi}{3}\right) \\ e_c &= \frac{d\psi_{mc}}{dt} = -\lambda_0 \omega_e \sin\left(\theta_e + \frac{2\pi}{3}\right) \end{aligned} \tag{4}$$

The current equations in α, β frame are obtained using the usual Clarke transformation:

$$\begin{aligned} \frac{di_\alpha}{dt} &= -\frac{R}{L} i_\alpha - \frac{1}{L} e_\alpha + \frac{1}{L} u_\alpha \\ \frac{di_\beta}{dt} &= -\frac{R}{L} i_\beta - \frac{1}{L} e_\beta + \frac{1}{L} u_\beta \end{aligned} \tag{5}$$

The back-EMF from (4) becomes:

$$\begin{aligned} e_\alpha &= \frac{d\psi_{m\alpha}}{dt} = -\lambda_0 \omega_e \sin(\theta_e) \\ e_\beta &= \frac{d\psi_{m\beta}}{dt} = -\lambda_0 \omega_e \cos(\theta_e) \end{aligned} \tag{6}$$

Using a sliding mode observer [10], [11] can be estimated the back-EMF e_α and e_β and from these the rotor and speed position. The equations of the observer can be described as:

$$\begin{aligned} \frac{d\hat{i}_\alpha}{dt} &= -\frac{R}{L}\hat{i}_\alpha + \frac{1}{L}u_\alpha - \frac{l_1}{L} sign(\hat{i}_\alpha - i_\alpha) \\ \frac{d\hat{i}_\beta}{dt} &= -\frac{R}{L}\hat{i}_\beta + \frac{1}{L}u_\beta - \frac{l_1}{L} sign(\hat{i}_\beta - i_\beta) \end{aligned} \tag{7}$$

After a limited time if $l_1 > \max(|e_\alpha|, |e_\beta|)$ a sliding mode is enforced. Defining errors as $\bar{i}_\alpha = \hat{i}_\alpha - i_\alpha$ and $\bar{i}_\beta = \hat{i}_\beta - i_\beta$, using the equations (5) and (7) are obtained:

$$\begin{aligned} \frac{d\bar{i}_\alpha}{dt} &= -\frac{R}{L}\bar{i}_\alpha - \frac{1}{L}e_\alpha - \frac{l_1}{L} sign(\bar{i}_\alpha) \\ \frac{d\bar{i}_\beta}{dt} &= -\frac{R}{L}\bar{i}_\beta - \frac{1}{L}e_\beta - \frac{l_1}{L} sign(\bar{i}_\beta) \end{aligned} \tag{8}$$

When sliding mode occurs, the error is null thus $\bar{i}_\alpha = 0$ and $\bar{i}_\beta = 0$ and also: $\frac{d\bar{i}_\alpha}{dt} = 0$ and $\frac{d\bar{i}_\beta}{dt} = 0$. Using the switching quantities equivalent values are obtained the desired back-EMF quantities e_α and e_β:

$$\begin{aligned} \left(l_1 sign(\bar{i}_\alpha)\right)_{eq} &= e_\alpha \\ \left(l_1 sign(\bar{i}_\beta)\right)_{eq} &= e_\beta \end{aligned} \tag{9}$$

Due the switching operation at high frequency, a low pass filter is used for reduction of the chattering, and the equation (9) has the next form:

$$\begin{aligned} z_\alpha(t) + \Delta_\alpha(t) &= e_\alpha \\ z_\beta(t) + \Delta_\beta(t) &= e_\beta \end{aligned} \tag{10}$$

where Δ_α and Δ_β are the errors, and z_a and z_b are the low pass filtered result ($\hat{e}_\alpha$ and $\hat{e}_\beta$).

The convergence of the observer is demonstrated by a Lyapunov technique [10], [11], and the estimated rotor speed $\hat{\omega}_e$ is given by:

$$\hat{\omega}_e = \frac{\sqrt{\hat{e}_\alpha^2 + \hat{e}_\beta^2}}{\lambda_0} \tag{11}$$

The estimated rotor position is obtained $\hat{\theta}$ by integrating the quantity $\hat{\omega}_e$.

The block diagram of the Matlab/Simulink implementation of the back-EMF sliding mode observer described is presented in Figure 1. The intermediate filtering block of the back-EMF sliding mode observer was introduced additionally in the structure of the observer, to achieve a trademark between the delay introduced in the calculation of the observer and the smoothness of the back-EMF e_α and e_β.

The intermediate filtering block of the back-EMF is achieved by using low-pass filters with a cut-off frequency of 500Hz. A precise estimation of the rotor speed ω_e is provided by a good smoothness of the back-EMF e_α and e_β.

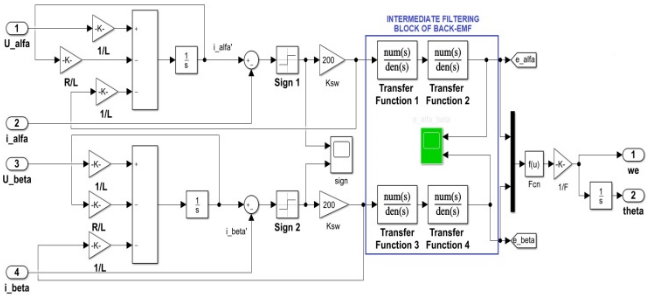

Fig. 1. Back-EMF and rotor speed sliding mode observer – Matlab/Simulink implementation

Since the start of a PMSM in the absence of the speed transducer is carried out in a special mode (in practical implementation with DSP the PMSM starts from a position stored from the previous start or the control is achieved in open loop after a predefined sequence), in the simulation performed the first 100ms the feedback information for the closed loop control is provided by a speed sensor to allow the correct initialization of the sliding mode observer. Then the feedback information is switched from the sensor to the observer.

Figure 2 presents the time evolution of the quantities provided by the sliding mode observer. The input quantities of the sliding mode observer are I_α, I_β and U_α, U_β and the output quantities are the back-EMF e_α, e_β, the rotor speed and position. For the reasons given above, the observer is bypassed the first 100ms. In accordance with the FOC type PMSM control strategy [11], [14], in d-q frame in Figure 2 it is noticed that the current reference I_d is set to 0 (the I_d current has an oscillating evolution around this value). After applying a 300 rpm step signal, it is noticed that the sliding mode observer accurately estimates the speed and position of the rotor.

III. Sensorless Control of PMSM Using Fuzzy Logic

By using Matlab/Simulink, this section presents the results of the numerical simulation for the sensorless control of PMSM with back-EMF sliding mode observer and a fuzzy logic controller. For the PMSM speed control system, the FOC control strategy is used, where the speed controller is PI type, and the adjustment parameters K_p and K_i, are adjusted by using the fuzzy logic. The proposed controller has a high performance and robustness compared to the regular PI controller in sensorless control of PMSM.

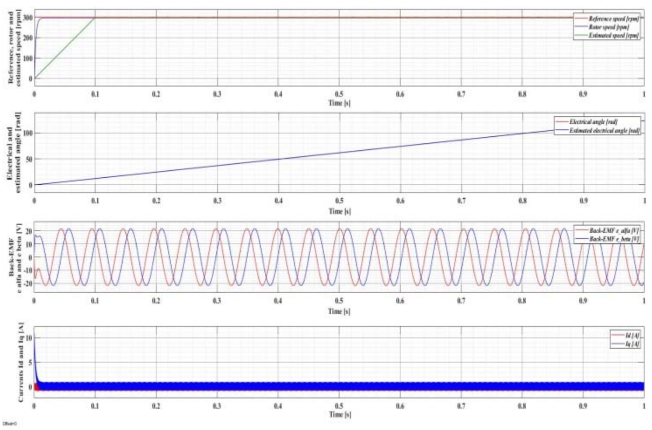

Fig. 2. Time evolution simulation of back-EMF, rotor position and rotor speed from sliding mode observer

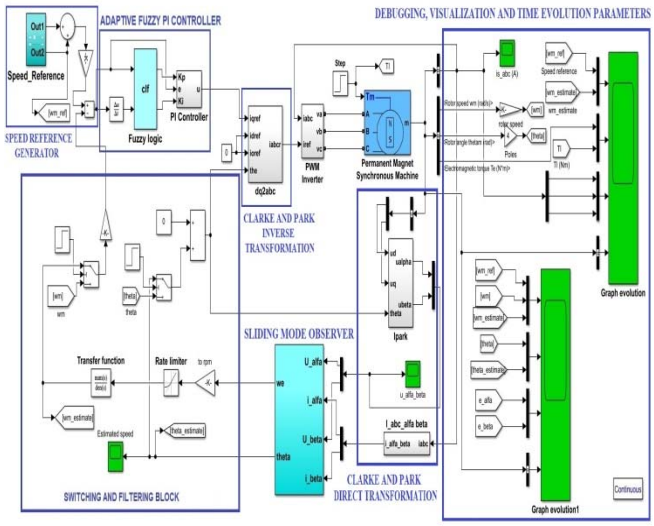

Fig. 3. Matlab/Simulink implementation block diagram for sensorless control of PMSM using back-EMF sliding mode observer and fuzzy logic control

The nominal parameters of PMSM are: the stator resistance R_s=2.875Ω; q and d inductance L_q=L_d=0.0085H; the combined inertia of rotor and load J=0.8e-3kg·m^2; the combined viscous friction of rotor and load B=0.005 N·m·s/rad; the induced flux by the permanent magnets of the rotor in the stator phases λ_{af}=0.175; and the pole pairs number P=4.

In Figure 3 is presented the block diagram for the Matlab/Simulink implementation of the sensorless speed control system of PMSM and fuzzy logic control. The main functional blocks from Figure 3 are: the speed controller, the Clarke and Park transforms blocks, inverter block, PMSM block, the back-EMF sliding mode observer block and a switching and filtering block. The switching and filtering block realize the bypass of the sliding mode observer like in previous section.

The transfer function of the speed controller is given by:

$$H_{PI}(s) = K_p + K_i \frac{1}{s} \tag{12}$$

where K_p is the proportional term and K_i is the integral term.

For the numerical simulation, the quantization of equation (12) is carried out by using the Tustin substitution:

$$s = \frac{2}{T_s}\frac{z-1}{z+1} \tag{13}$$

where T_s is sampling period and in the numerical simulations presented T_s=2·10^{-6} seconds. The s and z are the continuous and discrete variables respectively.

The block diagram implemented in Matlab/Simulink of the adaptive fuzzy logic controllers is presented in Figure 4. This is a part of the adaptive fuzzy PI controller which, based on the rules implemented in the fuzzy controllers will continuously adapt the adjustment parameters K_p and K_i.

The inputs of the adaptive fuzzy PI controller are the error and the error derivate of the rotor speed. The output of the adaptive fuzzy PI controller is represented by the current reference I_q.

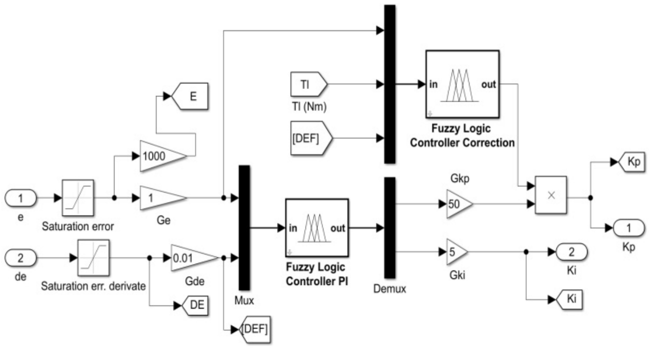

Fig. 4. Matlab/Simulink implementation block diagram for the adaptive fuzzy logic controllers

Due to the fact that the speed of a PMSM can vary rapidly within a wide range, but also due to the load torque which can also exhibit significant variations, by using the Ziegler-Nichols type adjustment method for the PI controller, good results are generally obtained only around a static operating point by portion linearization or by dividing by intervals the significant operating parameters (input sizes, parameters and measurable disturbances) and obtaining a set of adjustment values K_p and K_i for each of these intervals. Thus the need to use the fuzzy logic for the adjustment of the PI controller occurs inherently.

In this respect, in this approach, in order to be able to achieve an adjustment of the PI controller allowing, together with the proposed control structure, to track a high dynamic speed profile, with minimum rise time and response time and with no overshooting, under the conditions of wide-ranging load torque, two fuzzy controllers are proposed to be used, within the adaptive fuzzy PI controller.

The first fuzzy controller has input quantities represented by the error and the error derivate of the rotor speed, and it can work independently by adjusting the adjustment parameters K_p and K_i. In order to achieve superior performance, a second fuzzy controller is proposed which, besides the error and the error derivative of the rotor speed as inputs will also take into account the load torque (an estimate of it) to adjust the adjustment parameter K_p differently depending on the load torque size, but also on the dynamic or stationary regime that occurs during the required speed profile tracking. This fuzzy controller runs in tandem only with the first fuzzy controller and it will be described in the next section. In this section we assume that this fuzzy controller is bypassed.

For the Matlab/Simulink implementation of the fuzzy logic controller, the error and the error derivate of the rotor speed, two linguistic values E and DE will be used as input quantities, and two linguistic variables Kp and Ki will be used as the output quantities. Quantities E and DE are normalized in the range [-1, 1] and have the linguistic values {NB, NS, ZO, PS, and PB}, which represent: negative big, negative small, zero, positive small, and positive big. For the output variables Kp, Ki, the linguistic values are {Z, S, M, B} and represent: zero, small, medium, big.

The membership functions of the linguistic variables E, DE, Kp and Ki are triangular functions. The implementation in Fuzzy Toolbox from Matlab of the membership functions for the inputs and outputs of the fuzzy logic controller are presented in Figure 5 and Figure 6. The rules base defined for the fuzzy logic controller is presented in Figure 7.

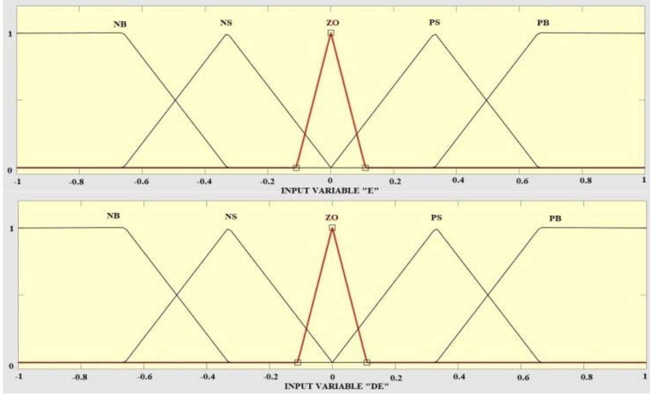

Fig. 5. Input membership functions of the main fuzzy logic controller

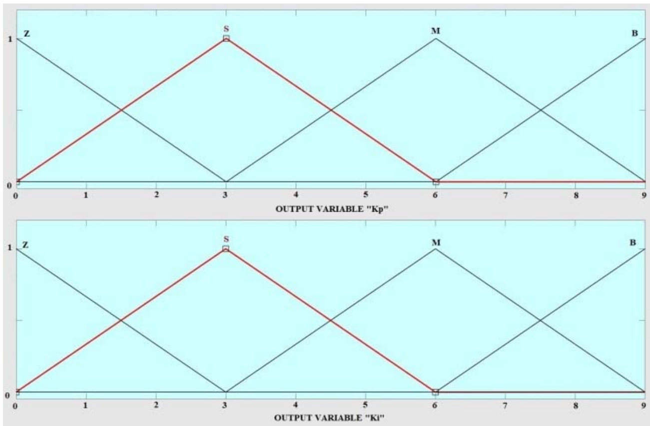

Fig. 6. Output membership functions of the main fuzzy logic controller

The adjustment of the output sizes (the adjustment parameters K_p and K_i of the PI controller) is carried out according to the values of the error and error derivate of the rotor speed, and implements in fuzzy logic the general knowledge for the adjustment of a PI controller in order to obtain minimum rise time and response time, an overshooting as low as possible, and zero steady-state error. Mamdani's fuzzy inference method is the most commonly seen fuzzy methodology and was adopted for the fuzzy controllers. The inference method is of min-max type, and the defuzzification method is that of center of gravity.

Figure 8 presents the time evolution simulation for the rotor speed, in the case of a reference speed profile consisting of step signals. It also presents the time evolution simulation for the error and error derivate of the rotor speed, the adjustment parameters K_p and K_i, and load and electromagnetic torque.

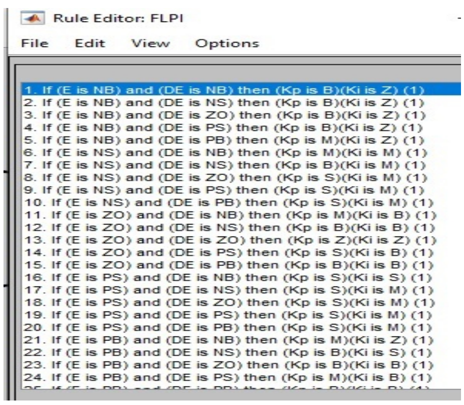

Fig. 7. Rules base of the main fuzzy logic controller

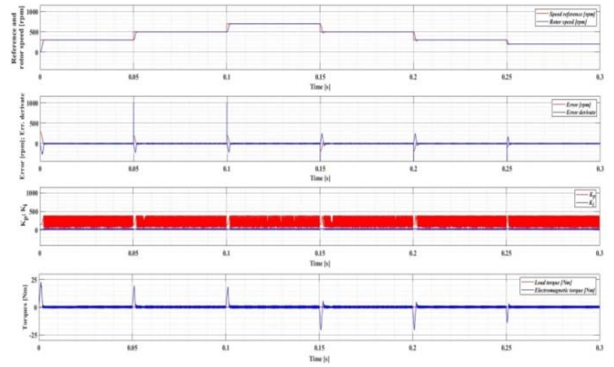

Fig. 8. Time evolution simulation of the sensorless control system with the main fuzzy logic controller

It is noticed that the system behaves with good results with no overshooting for rising steps reference, with very low response and rise time. For a falling steps reference, low overshooting can be noticed to occur, which can be explained by the fact that the engine switches from high speed to low speed, and low or medium load torque will cause the engine speed to drop sharply below the reference value. The fuzzy controller will respond fast and the steady-state error will be zero. To remove such behavior in the case of a high dynamic speed profile and a wide-ranging load torque, the next section presents an improved version of the adaptive fuzzy PI controller, in which the second fuzzy logic controller also intervenes.

IV. Improved Fuzzy Logic Control

Starting from the results obtained in the previous section, we propose the improvement of the adaptive fuzzy PI controller by adding a second fuzzy logic controller which, besides the error and the error derivative of the rotor speed as inputs will also take into account the load torque (an estimate of it) to adjust the adjustment parameter K_p differently depending on the load torque size, but also on the dynamic or stationary regime that occurs during the required speed profile tracking. Considering (12) which represent the operating equation for the PI controller, we consider that it is sufficient to use the second fuzzy controller to adjust only the K_p parameter, and not the K_i parameter, to make sure that a steady-state error is obtained in any required speed variation conditions.

For the Simulink implementation of the correction fuzzy logic controller, the error and the error derivate of the rotor speed and the load torque, three linguistic variables E, DE, and Tl will be used for the inputs, and the linguistic variable Kp will be used for the output. Quantities E and DE are normalized in the range [-1, 1] and have the linguistic values {N, Z, P}, which represent: negative, zero, positive, and Tl has the linguistic values {L, M, H} which represent: low, medium and high. For the output variable Kp the linguistic values are {VL, L, M, H} which represent: very low, low, medium and high. The value of this output Kp of the correction fuzzy logic controller is multiplied by the output value Kp of the main fuzzy logic controller, carrying out an adequate weighting in order to obtain the adjustment value of K_p of the PI speed controller.

The membership functions of the linguistic variables E, DE, Tl and Kp are triangular functions. The implementation in Fuzzy Toolbox from Matlab of the membership functions for the inputs and output of the correction fuzzy logic controller are presented in Figure 9 and Figure 10.

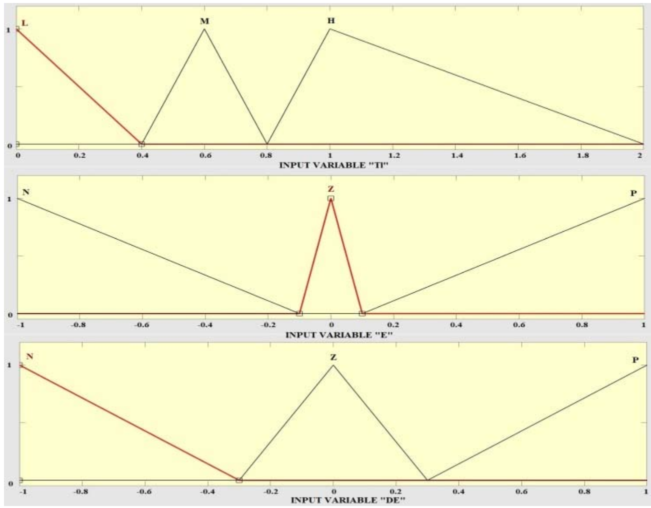

Fig. 9. Input membership functions of the correction fuzzy logic controller

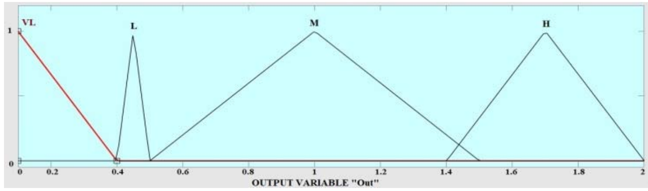

Fig. 10. Output membership functions of the correction fuzzy logic controller

The rules base defined for the correction fuzzy logic controller is presented in Figure 11. Similarly to the main fuzzy logic controller, the min-max type inference method is used also for the correction fuzzy logic controller, and the defuzzification method is that of center of gravity. We specify that although one of the inputs of the correction fuzzy logic controller is the load torque, the required estimation is of a fuzzy type according to the linguistic values: low, medium and high. The main rules of the correction fuzzy logic controller adjusts separately (with different weights) the value of the adjustment parameter K_p depending on the dynamic or static regime of the required speed profile tracking, but also on the linguistic value of the load torque. Thus, in Figure 11, by analyzing the fuzzy inference rules proposed, it is noted that for very low values of E and DE, corresponding to a speed tracking stationary regime, the value of the Kp parameter is low, medium or high according to the linguistic value of the load torque. In the dynamic regime, when E and DE have high or medium values, regardless of the linguistic value of the load torque, the K_p parameter is weighted by the correction fuzzy logic controller and is set to very low linguistic value. This will prevent the overshooting even for a profile of the speed reference consisting of falling steps.

Thus Figure 12 presents the time evolution simulation of the rotor speed, in the case of a reference speed profile consisting of step signals and ramp signals. It is noticed that the system behaves with good results with no overshooting, with very low response and rising time.

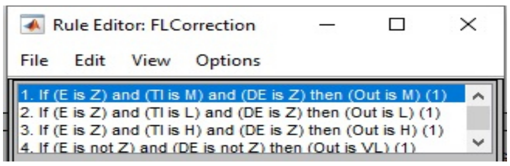

Fig. 11. Rules base of the correction fuzzy logic controller

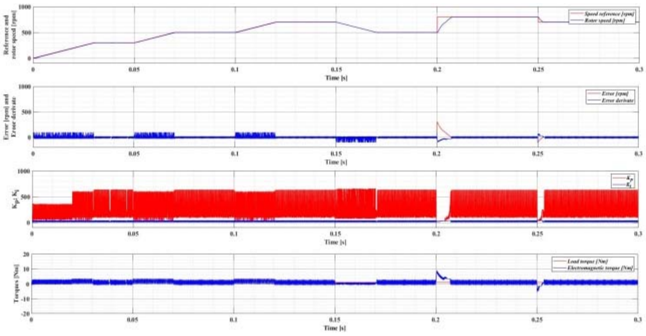

Fig. 12. Time evolution simulation of the sensorless control system with the main and correction fuzzy logic controllers

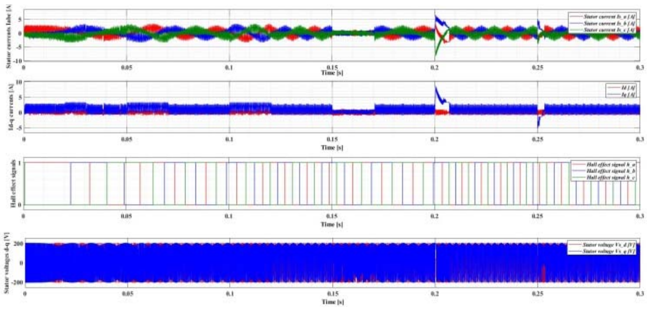

Fig. 13. Time evolution simulation of the electrical parameters of the sensorless control system with the main and correction fuzzy logic controllers

The time evolution simulation for the error and error derivate of the rotor speed, the adjustment parameters K_p and K_i, and the load and electromagnetic torque are also are presented. Figure 13 shows the time evolution of the stator currents $I_{s\_a,b,c}$, the $I_{d,q}$ currents, the hall effect commutation signals $h\_{a,b,c}$, and the stator voltages $V_{s\_d,q}$.

V. Conclusions

This article presents a sensorless control system of PMSM using a back-EMF sliding mode observer and a main and correction fuzzy logic controllers to continuously adapt the adjustment parameters K_p and K_i of the speed controller.

The sliding mode observer provides the back-EMF e_α and e_β from which can be obtained the estimations of the rotor speed and position. The article presents the operating equations and the main blocks of the Matlab/Simulink implementation of the FOC control strategy, where the I_d reference is set to zero, and the reference for I_q is set by the speed controller whose adjustment parameters K_p and K_i are continuously adjusted by the fuzzy controllers.

The main objective of the presented sensorless control system of PMSM consists in tracking a high dynamic speed profile, with minimum rise time and response time, and with no overshooting, under the conditions of wide-ranging load torque.

Based on the good results obtained from numerical simulations, future approaches will deal with the implementation of a multi-motors PMSM sensorless control system using the adaptive fuzzy PI logic control.

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