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Speed Control Of The Interior Permanent Magnet Synchronous Motor Over A Wide Range Using Fuzzy Logic Controller

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ABSTRACT

This paper presents a Fuzzy Logic Controller (FLC) scheme for speed control of an interior permanent magnet synchronous motor (IPMSM) drive over a wide speed range. The proposed FLC is designed based on maximum torques per ampere operation below the rated speed and the field weakening operation above the rated speed, respectively. The main features of the proposed scheme using a fuzzy controller to control both flux and torque simultaneously, in whole speed range. The effectiveness of the proposed FLC is investigated for a 40kW IPMSM and simulated using MatLab/Simulink. The simulation results are compared to those obtained from the conventional PI controller base drive at various conditions such as: step change of command speed and load torque, the disconnection of one phase and parameter variations. Simulation results demonstrate the appropriate dynamic response, robustness again changes, capability in removing load disturbances, without overshoot and undershoot, minimum settling time and lowest steady-state error of the proposed controller over a wide speed range.

1. INTRODUCTION

In recent years, interior permanent magnet synchronous motors (IPMSM) have been increasingly used in industrial applications due to their different properties and advantages compared to AC and DC motors [1-4]. Some advantages are: high efficiency, few ripples in torque, low cost of maintenance and high reliability. These properties made interior permanent magnet synchronous motors an appropriate choice for many applications requiring high efficiency and accurate response such as tractions, robotics and hybrid electric vehicles. Some of common controllers used for controlling motors speeds in industry are fixed gain proportional- integral and proportional-integral-differential controllers which are used in many applications due to their simplicity. However, such controllers may not response appropriately in a wide range of speed because of problems including sensitivity to motor parameters under different conditions, speed step variation and load torque variation. Some other controllers used to control these motors speeds can be mentioned of sliding mode controller [5-8] and adaptive back stepping controller [5, 9-14]. But since these controllers are elaborate and dependent on motor parameters, using them creates challenges in practice. The other type of controllers used for controlling interior permanent magnet drive speed is intelligent

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controllers such as neural network and fuzzy logic controllers. Among various intelligent controllers, fuzzy logic controller has the simplest design and implementation to control the speed of high performance permanent magnet synchronous drives. Since this controller is based on lingual control rules founded on human lingual logic, it outperforms compared to other common controllers for not being sensitive to parameters variation, load torque variation, proper response time, shortened settling time and stability. Flux control hasn't been considered in many researches using fuzzy logic controllers for interior permanent magnet synchronous drive. In such works it is designed so that current of axis d is considered to be equal to zero and the nonlinear term of reluctance is neglected. If flux weakening wasn't controlled appropriately, the controller would be saturated in high speeds and its controllability would be failed. A comparison is conducted in [15] among neural-fuzzy, neural network and fuzzy smart controllers for an IPM motor. The design disadvantage is that in these controllers, current of axis d is considered zero and this causes the design to be inapplicable in speeds higher than nominal and used only for nominal and below rated speeds. In [16] genetic algorithm is used to optimize fuzzy controller parameters and in the controller suggested current of axis q and speed error are considered as FLC inputs. It also used a second order objective function for optimization in genetic algorithm. In [17] two different designs for fuzzy logic controller were compared, one is based on considering zero the current of axis d and the other is designed based on maximum torque per ampere in FLC; and the results indicate that if FLC performance is considered with MTPA, motor speed oscillations are so less and stator phase current is of shorter amplitude. In [18] in designing fuzzy logic controller it is used a first order adaptive filter its gain of which is adjusted adaptively by changing torque range.

This paper is organized as follow: in section 2 mathematical model of interior permanent magnet motor is provided. Section 3 discusses about general principles of magnet motor control. Section 4 includes designing fuzzy logic controller suggested in the paper. The control results of suggested controller simulation and its comparison with classic integral-proportional controller are explained in section 5. Conclusions of using fuzzy logic controller suggested are submitted in section 6.

2. IPMSM MODEL

Mathematical model of an interior permanent magnet synchronous motor in rotor reference coordinates is:

$$\dot{i}_d = (1/L_d)(v_d - R_s i_d + P\omega_r L_q i_q) \tag{1}$$

$$\dot{i}_q = (1/L_q)(v_q - R_s i_q - P\omega_r L_d i_d + P\omega_r \lambda_f) \tag{2}$$

$$\dot{\omega}_r = \frac{1}{J}(T_e - B_m \omega_r - T_L) \tag{3}$$

$$T_e = \frac{3}{2}P((L_d - L_q)i_d i_q + \lambda_f i_q) \tag{4}$$

Where parameters used in equations are:

Vd and Vq are voltages of axes d, q; id and iq currents of axes d and q; Ld and Lq are inductances of axes d and q; J inertial moment of motor and load; Rs resistance of each stator phase; Te and TL electromagnet torque and load torque; P number of motor pole pairs; Bm motor friction constant and λ_f magnetic flux of permanent magnets.

3. CONTROL PRINCIPLE

According to equation (4), IPM motor torque consists of two terms: the first term which is created by the difference between inductances of two axes d and q and is known as reluctance torque and the other term is produced by permanent magnets and is the product of permanent magnets flux by current of axe q and is known as magnetizing torque. Reluctance torque term is used for motor operating in flux weakening range in order to control interior permanent magnet synchronous motor speed in higher than nominal speed. Most of researchers consider current of axis d as zero for simplicity. So torque equation is transformed into a linear function of the current of axis q. However the assumption of id=0 leads the motor flux not to be controllable appropriately. So occasionally the motor isn't even able to reach its nominal speed. In this paper, a fuzzy controller is designed such that by considering id≠0 the flux can be controlled appropriately and the motor has a good performance in a wide range of speed.

4. FLC SCHEME

To design the fuzzy logic controller proposed in this paper, at first controller inputs and outputs have to be selected. Controller lingual variables inputs are speed error ($\Delta\omega_r$), speed error variation (Δe), motor speed (ω_r), respectively, and lingual variables outputs are currents of axes d and q. As mentioned before, the first controller input is speed error used to follow reference speed by reducing the difference of reference and motor speeds. Another input of the fuzzy controller presented is speed error variation. This input is $\Delta e_{(n)} = \Delta\omega_{r(n)} - \Delta\omega_{r(n-1)}$ actually the difference between the present time speed $\Delta\omega_{r(n)} = \omega^*_{r(n)} - \omega_{r(n)}$ and speed error immediately before sampling. Speed error variation is used to reduce overshoot and undershoot. To reduce calculations complexity, vector control theory and fuzzy logic are used simultaneously in designing the motor controller so that flux and torque are controlled by axes d and q. Thus fuzzy controller outputs are considered reference currents of axes i^*_d, i^*_q so that current of axis d is for controlling motor flux and current of axis q controls motor torque.

The next step in implementing fuzzy logic controller design is determining membership functions for lingual variables inputs ($\Delta\omega_r$, Δe, ω_r) and outputs (i^*_d, i^*_q) consisting one of the main parts of fuzzy controller. Figure 1 shows membership functions used for input and output of fuzzy sets. There are different options for selecting membership functions of fuzzy sets; in this paper only triangular and trapezoid types are used for simplicity and reducing calculations size. In inputs all fuzzy sets are trapezoid except (*ZE*) and for (*ZE*) and all fuzzy sets related to outputs, triangular membership function is used. As seen in Figure.1, fuzzy sets selected in designing fuzzy logic controller are normalized so that the main structure of the controller is independent of Now by considering values known as scaling factors for each input and output and adjusting them, the suggested controller can be used for any interior permanent magnet synchronous motor. In the next step, fuzzy rules are determined based on fuzzy sets as follow:

1. if Δω is PH(positive high), then iq is PH(positive high)and id is PH(positive high)
2. if Δω is PL(positive low), then iq is PL(positive low)and id is PL(positive low)
3. if Δω is NL(negative low), then iq is NL(negative low)and id is NL(negative low)
4. if Δω is NH(negative high), then iq is NH(negative high)and id is NH(negative high)
5. if Δω is ZE(zero)and ωr is WR, then iq is NC(not change)and id is NC(not change)
6. if ωr is NAR(negative above rated), then iq is NL(negative low)and id is AR(above rated)
7. if ωr is PAR(positive above rated), then iq is NL(negative low)and id is AR(above rated)
8. if Δω is ZE and Δe is PI(positive),then iq is PL(positive low)and id is PL(positive low)
9. if Δω is ZE and Δe is NI(negative),then iq is NL(negative low)and id is NL(negative low)

Values related to constants (scaling factors) and membership functions of fuzzy sets for input and output lingual variables are selected by trial and error to optimize the drive performance. Fuzzy inference used in the research is Mamdani fuzzy inference and gravity center defuzzifiction method was used to convert fuzzy values to numeral ones.

5. SIMULATION RESULTS

To evaluate the suggested controller performance and examine efficiency of fuzzy logic design, several tests were performed on interior permanent magnet synchronous motor drive in different conditions. Simulations on a full drive were conducted using software package Matlab/ Simulink. Using integral-proportional controller, tests in the same condition were performed on an interior permanent magnet synchronous drive system to examine and demonstrate good performance of the fuzzy logic controller and the results were compared in all cases. Motor parameters used in simulation are presented in Table1. In the first test, drive system started to work in the constant load 133 N.m and the speed 272.2 rad/sec. As seen in Figure 2a, when using fuzzy logic controller, actual motor speed converges to reference speed quickly in 0.05s and without any overshoot and undershoot while using integral-proportional controller, the motor reaches to its permanent state after 0.1s and an overshoot and undershoot (Figure 2b).

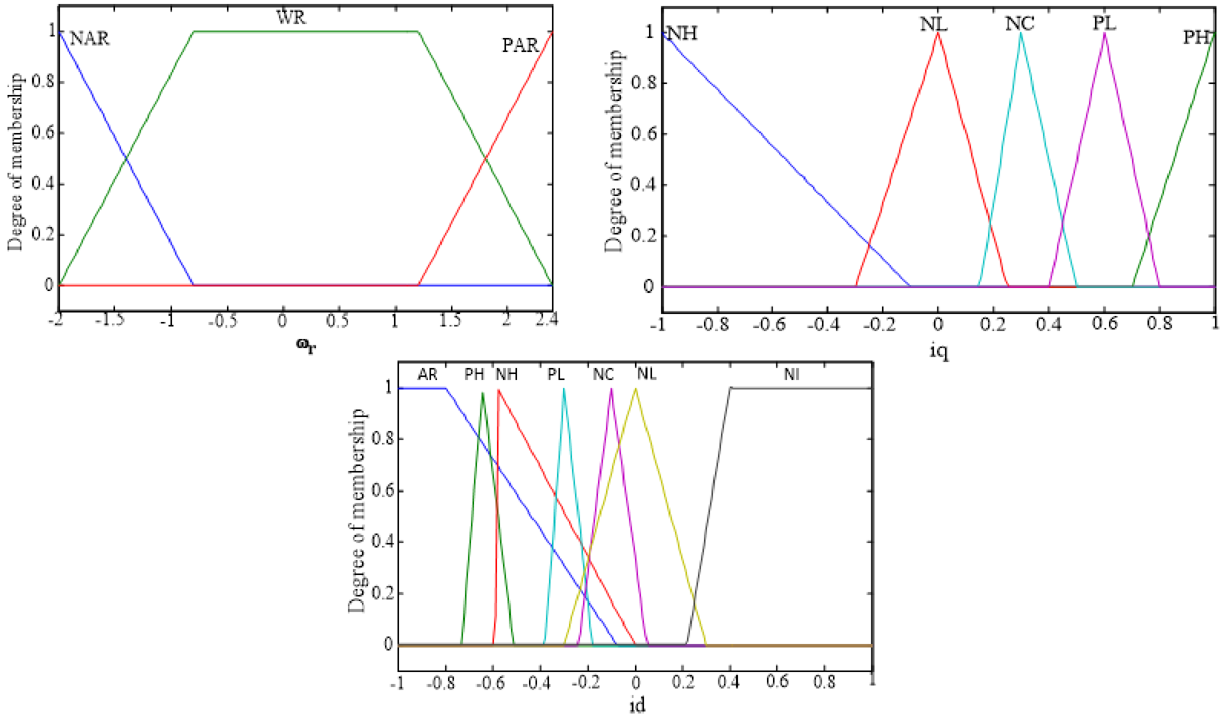

Fig. 1. Membership functions of fuzzy logic controller inputs and outputs

Table 1. Parameters of IPMSM

Rated power (P_n)	40 Kw
Number of pole pairs(P)	3
Reted torque(T_n)	133 N.M
Rated voltage(V_n)	240 V
Rated speed(ω_n)	2600 rpm
Stator resistance(R_S)	29.5 mΩ
d-axis inductance(L_d)	375 μH
q-axis inductance(L_q)	835 μH
Moment of inertia of motor (J)	0.011Kgm^2
Friction coefficient(B_m)	0.0019Nm/rad/s
Permanent magnet flux(λ_f)	0.07 vol/rad/s

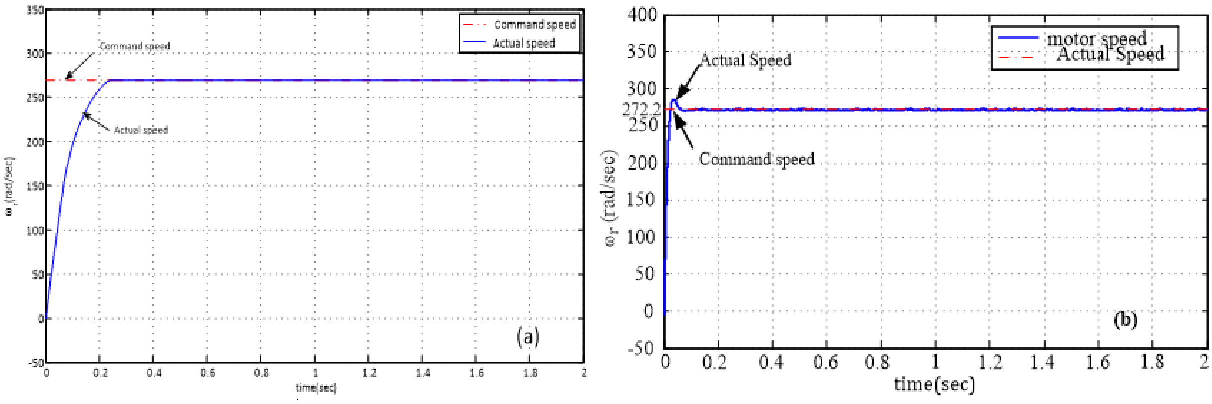

Fig. 2. Motor speed variation to time curve in rated load and speed a) fuzzy logic controller b) PI controller

As simulation shown in Figure 3(a) and (b), a load is applied as stepping from 100 N.m to 133 N.m in t=1 on the motor shaft. As seen with the suggested controller, real motor speed doesn't change in spite of disturbances while stator current reaches to a new value which is related to the applied load.

Effect of changing the torque on the drive using integral–proportional controller to control motor speed is shown in Figure 4a and b. As seen in Figure.4 (a), the motor has a marked undershoot in t=1 affected by the change in torque and after 0.055s converges to its reference value. Its current wave form is shown in Figure.4 (b). It is found that by applying stepping variation in load torque, the current is changed by a great difference compared to the similar state in fuzzy controller (Figure.3 (b)) and reaches to a new value corresponding to the load 133 N.m. It is necessary in a high performance drive that actual motor speed is able to follow new reference value if a stepping variation in reference speed is generated. A stepping variation in t=0.99s was considered in order to study this property in the suggested drive. Thus, first a reference speed 200rad/sec in constant torque range was determined for the motor and then in t=0.99s, speed changed to 400rad/sec as stepping in constant power range.

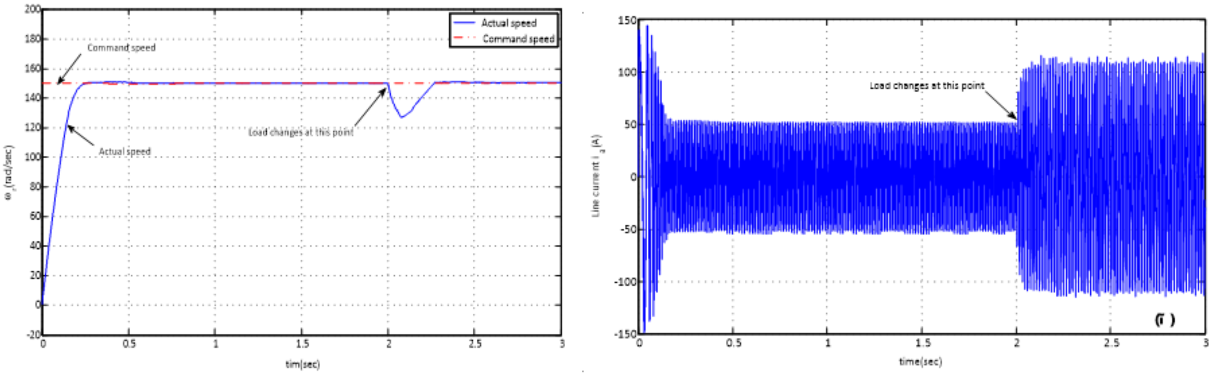

Fig. 3. a) Motor speed variation to time curve by applying stepping torque with FLC. b) The current of stator phase a curve by stepping variation in load torque with FLC.

As seen in Figure.5(a), when using fuzzy controller, the motor actual speed reaches to 400rad/sec in 0.07s after this sudden change however according to Figure. 5(b), when the same change is applied on the drive with integral-proportional controller, the motor speed converges to the reference value 400rad/sec in 0.12s after this change.

Since a high performance drive should have the ability to work in a wide range of speed, so a reference route involving all speeds was considered for the respective drive in additional test performed on the motor drive. In addition to previous cases, the route is shown in Figure. 6(a),(b) for very low speeds (near to zero speed) as well as negative speeds. In Figure. 6(a), fuzzy controller is designed for all speeds so that it can follow reference speed without marked overshoot and undershoot. However, as seen in Figure. 6(b) , integral-proportional controller isn't able to follow reference trajectory and remove disturbances effects in times when sudden stepping variation in speed and torque is applied because it is not robust to speed and load variations in different times. Additional test was performed on interior Permanent magnet motor in which sensitivity of fuzzy logic and integral-proportional controllers to changes in motor parameters was studied. To this purpose, first in t=0.4s motor inertial moment coefficient (J) was decreased from nominal value to its 25% and then in t=0.6s friction factor (Bm) was increased from nominal value to its two times of nominal value. The results of the simulation performed on the drive system with two controllers are shown in Figure. 7(a),(b). As seen in Figure. 7(a),(b), when parameters are changed, the motor speed of fuzzy logic controller has less oscillation than integral-proportional controller in the same condition. One of the main features of smart controllers is their ability to maintain motor stability when a phase interruption occurs. Hence in another test, this situation and interruption of a motor phase were considered. As seen in Figure. 8(a) , (b), motor operates in three phases until t=1.2s, and at this time motor phase is interrupted. As seen in Figure. 8(a) , (b), due to good designing fuzzy controller continues to control speed by applying overcurrent on the two other phase when the motor phase current is interrupted. However, as seen in Figure. 8(b), since integral-proportional controller in t=1.2s removes a phase and isn't able to supply load torque exerted to motor with the other two phases, so motor drive system becomes instable and speed isn't controlled after phase interruption.

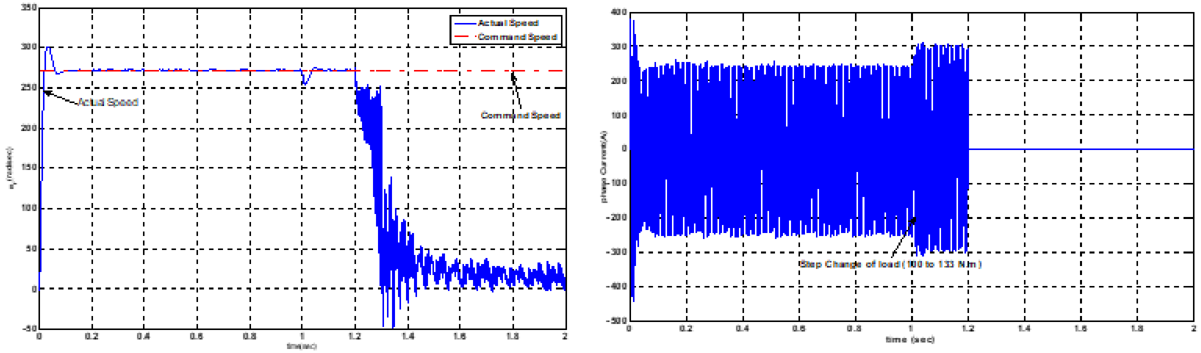

Fig. 4. a) motor speed variation to time curve by applying stepping torque with PI controller. b) The current of stator phase a curve by stepping variation in load torque with PI controller.

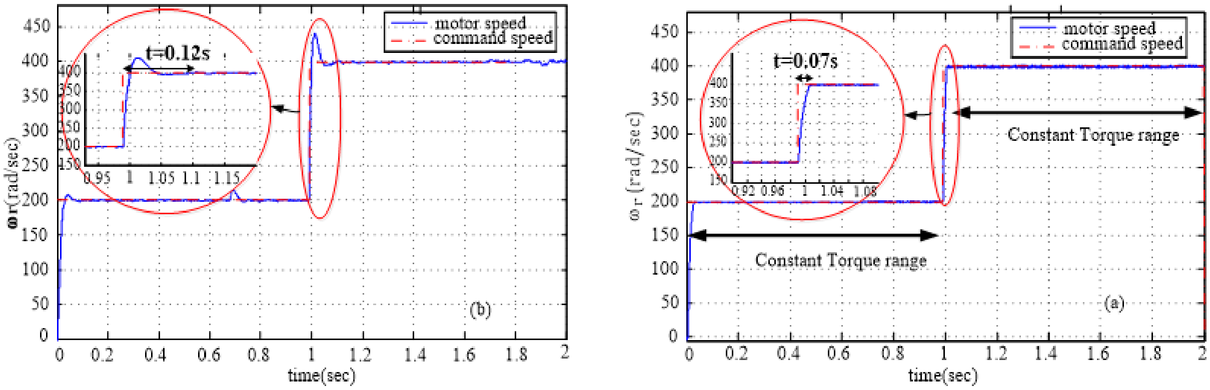

Fig. 5. the curve of interior permanent magnet synchronous motor speed in constant torque and power range a) FLC b) PI controller

6. CONCLUSIONS

In this paper, a fuzzy logic controller proposed to control the speed of interior permanent magnet synchronous motor and its results were successfully simulated on interior permanent magnet synchronous motor drive with the power 40kw in Matlab/Simulink setting. The main feature of this paper is using a fuzzy logic controller to control electromagnetic torque and flux of interior permanent magnet synchronous drive in a wide range of speed. Different conditions were employed for this motor drive such as load torque variation, speed step variation, motor parameters variation and interruption of a motor phase to study efficiency of the suggested fuzzy logic controller and its results

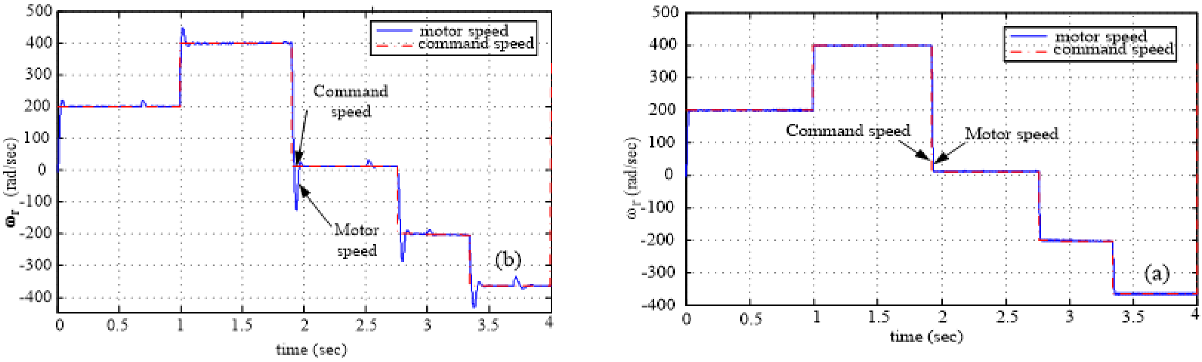

Fig. 6. motor speed variation to time curve in wide range of speed a) FLC b) PI controller

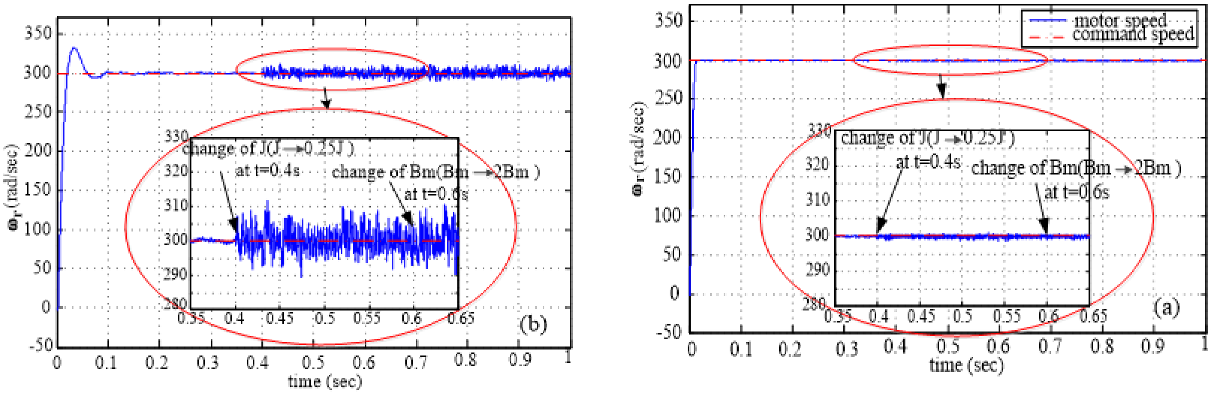

Fig. 7. the curve of motor speed by changing parameters of the moment of inertia and friction factor in the load 100 N.m. a) The proposed fuzzy logic controller b) PI controller

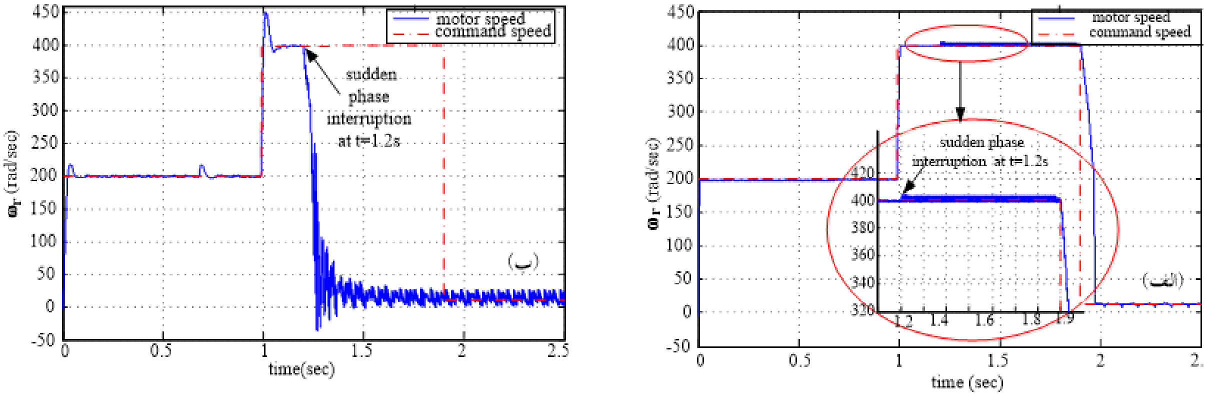

Fig. 8. The curve of motor speed in a phase interruption at t=1.2s a) The proposed FLC b) PI controller

Were compared with a conventional integral-proportional controller. The simulation results indicated that the proposed controller is robust to different conditions and able to remove disturbances effects related to load and motor parameters variation and can maintain motor stability in special conditions such as one phase interruption. So this design is applicable for high performance interior permanent magnet synchronous drives.

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