Kufa Journal of Engineering
Vol. 8, No. 1, January 2017, P.P.119-137
Received 14 April 2016, accepted 18 July 2016

COMPARATIVE ANALYSIS OF SPEED CONTROL OF MULTIPLE (MASTER/SLAVES) PMSMS USING PI CONTROLLER AND FUZZY LOGIC CONTROLLER

Suroor M. Dawood[1], Samar H. Majeed[2], and Habeeb J. Nekad[3]

[1] Electrical Engineering Dept., College of Oil and Gas Engineering, Basrah University for Oil and Gas, suroor.moaid@buog.edu.iq

[2] Electric Power Dept., Basrah Engineering Technical College, Southern Technical University, samar_alhusaeny@yahoo.com

[3] Electrical Engineering Dept., College of Engineering, University of Basrah, hjnaaa1@yahoo.com

ABSTRACT

This paper presents the use of two different controllers in speed control of multi permanent magnet synchronous motors (PMSMs) master/slaves system. These controllers used to improve the performance of multi PMSMs drive system are conventional PI and PD-like fuzzy + I controllers. For PD-like fuzzy + I speed controller, simulation results clearly show that the response of the system is superior as compared to PI speed controller in terms of rise time, settling time, accuracy, and steady state error. The design and analysis of the system with both controllers have been simulated and studied using MATLAB/Simulink environment. Speed responses obtained under PI and PD-like fuzzy + I controllers are compared for a variety of load conditions.

KEYWORDS: Multi (Master/Slaves); Pd-Like Fuzzy +I Speed Controller; Permanent Magnet Synchronous Motors (Pmsms); Pi Speed Controller

التحليل المقارن للتحكم بسرعة عدد من المحركات التزامنية ذات المغناطيس الدائم(السيد/التوابع) بأستخدام متحكم الكسب التكاملي ومتحكم المنطق المضبب

م.م.سرور مؤيد داود، م.م.سمر حميد مجيد، د.حبيب جابر نكاد

الخلاصة

هذا البحث يستعرض استخدام متحكمين مختلفين للسيطرة على سرعة نظام (السيد/التوابع) لعدد من المحركات التزامنية ذات المغناطيس الدائم. هذين المتحكمين المستخدمين لتحسين أداء منظومة سوق المحركات هما متحكم الكسب التكاملي التقليدي ومتحكم المنطق المضبب المتداخل مع متحكم الكسب التكاملي التفاضلي. نتائج المحاكاة لمتحكم المنطق المضبب المتداخل مع متحكم الكسب التكاملي التفاضلي تؤكد تفوق استجابة النظام مقارنة مع متحكم الكسب التكاملي من حيث زمن الصعود, زمن الاستقرار, الدقة وأخطاء الحالة المستقرة. تم محاكاة ودراسة تصميم وتحليل النظام مع كلا المتحكمين باستخدام بيئة برنامج الماتلاب . استجابات السرعة التي تم الحصول عليها لكلا المتحكمين تمت مقارنتها لمجموعة منوعة من ظروف التحميل.

1. INTRODUCTION

In the last years, AC machine drives are became more popular, specially Induction Motor Drives (IMD) and Permanent Magnet Synchronous Motor drives (PMSM). The PMSM has numerous advantages over other machines because of their small volume, low maintenance costs, the use of the permanent magnet in the rotor of the PMSM that makes it unnecessary to supply magnetizing current through the stator for constant air gap flux, the stator current need only be torque-producing, so the PMSM will operate at a higher power factor and will be more efficient than IM (Bajpai D. et al., 2015).

In 2012 Rajat V. and Gunjan G. presented a comparative analysis of PI control, fuzzy logic control, and ANFIs of one PMSM (Varshney R. et al., 2012). In the same year Bhagyashree S. and Vaishali N. studied the behavior of dual motor drives fed by a single inverter using Matlab/Simulink environment (Shikkewal B. et al., 2012).

In 2013 Naseeb K. and Sajida S. proposed model of a PI controller and fuzzy controller for speed control of field oriented PMSM fed by voltage source inverter under load variations (Khatoon N. et al., 2013). Also Ahmad A. and Shahid I. focus on driving two PMSMs connected in parallel using only one three phase inverter. Both voltage space vector of two motors are average in order to achieve the synchronization between these two motors even their load are different (Abd samat A. et al., 2013).

In 2014 Kada H. , Fatima M., and Abdelkader M. proposed a new sensorless master slave direct torque control of PMSM based on speed model reference adaptive system (MRAS) observer for a multi-machine system in electric vehicle (Hartani K. et al., 2014). In the same year Maurice F. and Ana L. studied power supply in parallel of two PMSM with the same inverter, in order to reduce the mass of embedded system. Three control laws are proposed by setting appropriated criteria. The first law uses the concept of Master-Slave machine, the second is defined with a criterion taking into a count the two machines, and the third uses the concept of virtual vectors which leads to an implementation of space-vector pulse width modulation (Fadel M. et al., 2014).

In 2015 Deepa B. and Ahijit M. presented two different inference systems: namely T-sugeno and Mamdani FLCs for the performance of vector controlled PMSM drive. The performance of the drive has been investigated for a speed control at different loading conditions (Bajpai D. et al., 2015).

Fast and accurate speed responses, quick improvement of speed from load disturbances is some of the important criteria of high performance drive system. The conventional PI controller has been generally used as speed controller in PMSM drives. However, the conventional fixed gain PI controller has difficulties in dealing with dynamic speed tracking and load disturbances.

To overcome these disadvantages, different adaptive controllers have been established. PD-like fuzzy + I controller is used as a substitute for conventional control theory to control the nonlinear complex plants (Khatoon N. et al., 2013). Several applications use more than one motor to bear the high load. This paper is concerned with the study of master/slaves control system of PMSMs responsible for synchronization between these motors.

The master-slave synchronization control for PMSM is an important problem since it is often used in manufacturing and production processes. The synchronization between multi motors directly affects the reliability and control accuracy of the whole system. The traditional PI control method cannot meet the requirements of multi motor speed synchronous control accuracy. This paper prefers PD-like fuzzy + I as control method that can use field work experience. It is used for further improvement of the system’s response .

A comparison between fixed gain PI controller and PD-like fuzzy + I controller is presented by simulating results that verify appropriateness of the approach under various operating situations and provide the fast and robust control.

2. MODELING OF PMSM SYSTEM

2.1. DYNAMIC MODEL

With these assumptions the stator d-q PMSM model equations in the rotor reference frame are given by the following expressions (Varshney R. et al., 2012; Rajesh K. et al., 2015).

$$V_{ds} = R_d i_{ds} + L_d \frac{di_{ds}}{dt} - \omega_r L_q i_{qs} \quad (1)$$

$$V_{qs} = R_q i_{qs} + L_q \frac{di_{qs}}{dt} + \omega_r (L_d i_{ds} + \psi) \quad (2)$$

$$T_e = \frac{3}{2} P(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}) \quad (3)$$

$$J \frac{d\omega_m}{dt} = T_e - T_L - b\omega_m \quad (4)$$

$$\psi_{ds} = L_{ds} i_{ds} + \psi \quad (5)$$

$$\psi_{qs} = L_{qs} i_{qs} \quad (6)$$

Where Ψ_{ds}, Ψ_{qs}, V_{ds}, V_{qs}, i_{ds}, and i_{qs} are respectively the motor fluxes, voltages and currents in d-q coordinates; ωr is the electrical angular speed and T_e is the electromagnetic torque. Ψ is the flux of the permanent magnet which is named pm in all simulink model blocks, P is the number of pole, R_d, R_q are the stator resistances and the stator inductance can be divided into two different components L_d and L_q due to the particularities of the PMSM. J is the inertia of the motor, T_L is the load torque, b is the friction coefficient, and ω_m is the mechanical angular speed.

2.2. VOLTAGE SOURCE PWM INVERTER

To produce the required voltage to feed the PMSM, Pulse width modulation (PWM) technique is used. This method is gradually more used for AC drives with the condition that the harmonic current is as small as possible. In general, the PWM schemes generate the switching position patterns by comparing the three phase sinusoidal wave forms with a triangular carrier wave. The inverter model is represented by the relationship between output phase voltages (V_a, V_b, and V_c) and the control logic signals (S_a, S_b, and S_c) to produce the output voltage as shown below (Khatoon N. et al., 2013).

$$\begin{aligned} V_a &= V_{dc}.(S_a - (S_a + S_b + S_c)/3) \\ V_b &= V_{dc}.(S_b - (S_a + S_b + S_c)/3) \\ V_c &= V_{dc}.(S_c - (S_a + S_b + S_c)/3) \end{aligned} \quad (7)$$

2.3. MASTER/SLAVES MOTORS SYSTEM

In a multi or master-slave motors synchronization control system, one of motors is selected as master, and the rest motors are slaves motors. The master motor output speed will be as the speed reference value for the slave motor. So it was concluded that any speed change or load disturbance added to the master motor will be reflected and tracked by the slave motor, but any oscillations from slave motor cannot feedback to the master motor. Multi permanent magnet synchronous motors synchronization control system are shown in Fig. 1 (Ahmed A.M. Emam et al., 2013).

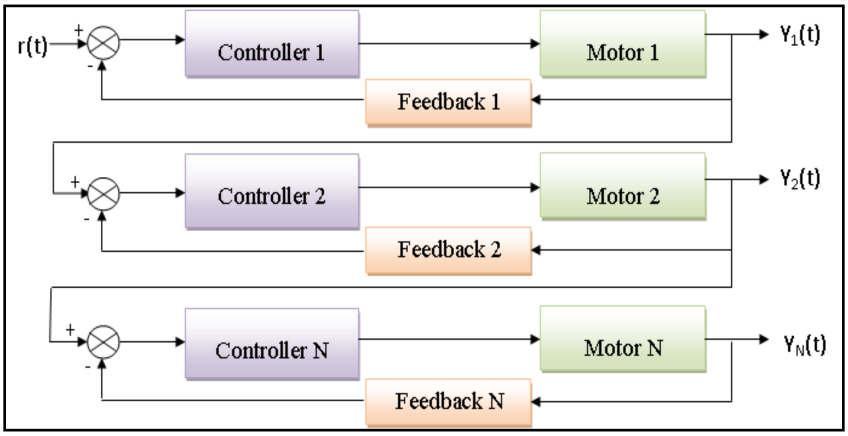

Fig. 1. Multi PMSM synchronization control system.

2.4. PI SPEED CONTROL OF PMSM

The PI controller is the most generally selected in manufacturing applications because of its simple construction, easy to design, and inexpensive. In spite of these advantages, the PI controller fails when the controlled object is extremely nonlinear and uncertain. Fig. 2 shows the block diagram of PI controller. It produces an output signal u (t) consisting of two terms one proportional to input signal e (t) and other proportional to the integral of the input signal e (t) according to the following expression given by (8) (Smriti Rao K. et al., 2014).

$$u(t) = K_p \times e(t) + K_i \times \int e(t)dt \tag{8}$$

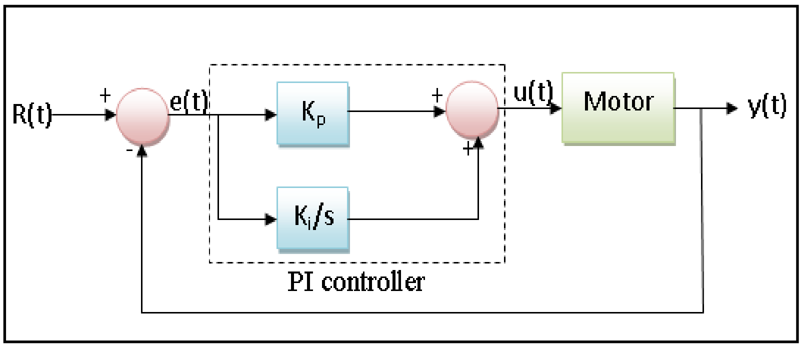

Fig. 2. Closed loop system with PI controller.

2.5. FUZZY LOGIC CONTROLLER

The concept of fuzzy logic control (FLC) is to utilize the qualitative knowledge of a system to design a practical controller. The control doesn't need accurate mathematical model of a system, and therefore it suits well to a process where the model is unknown or ill-defined and particularly to systems with uncertain or complex dynamics. The fuzzy controller block diagram is given in Fig. 3, where a fuzzy controller is embedded in a closed loop control system. The system output is denoted by y (t), its input is denoted by u (t), and the reference input to the fuzzy controller is denoted by r (t). The FLC consists of three stages: the fuzzification, rule execution, and defuzzification. In the first stage, the crisp variables are converted into fuzzy variables using the triangular membership functions.

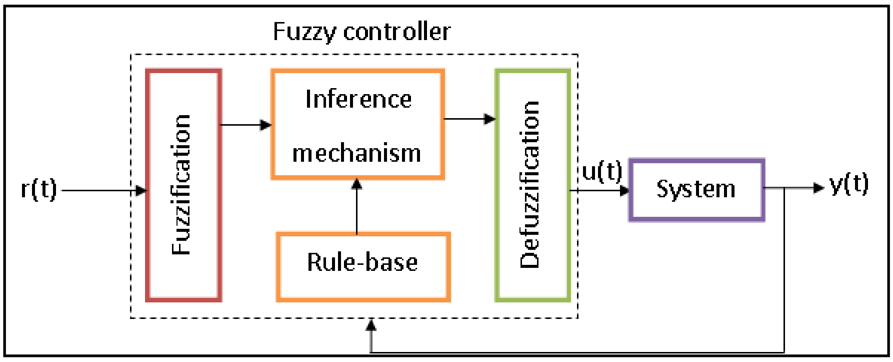

Fig. 3. Block diagram of FLC.

In the second stage, the fuzzy variables are processed by an inference engine that executes a set of control rules contained in rule bases. The control rules are formulated using the knowledge of the PMSM behavior. The inference engine output variable is converted into a crisp value in the defuzzification stage (Patil N. et al., 2010).

3. SIMULATION USING MATLAB/SIMULINK SOFTWARE PROGRAM

3.1. SIMULATION OF PMSM DRIVE INCORPORATED WITH PI CONTROLLER

Simulink block diagram of PMSM drive with PI controller is shown in Fig.4. It consists of PI speed controller, 3-phase voltage source inverter, park transformation to converting the three phase input voltage into dqo variables, and PMSM model. The PMSM mathematical model is described in (1-6) above which is implemented using Matlab/Simulink software as shown in Fig. 5. Converting the phase voltages variables V_a, V_b, and V_c to V_d, V_q, and V_o variables in rotor reference frame using park transformation from the following Eqs.

$$\begin{bmatrix} V_q \\ V_d \\ V_o \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta_r & \cos(\theta_r - 120) & \cos(\theta_r + 120) \\ \sin\theta_r & \sin(\theta_r - 120) & \sin(\theta_r + 120) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (9)$$

The simulink model of this inverter using eq. (7) is shown in Fig. 6. The simulink model of park transformation using the Matlab/Simulink software is shown in Fig. 7. Pulse width modulation (PWM) inverter technique is used to generate the three phase required voltage to feed the PMSM. The speed of the motor is compared with its reference value, and the speed error is processed in PI speed controller as shown in Fig. 8.

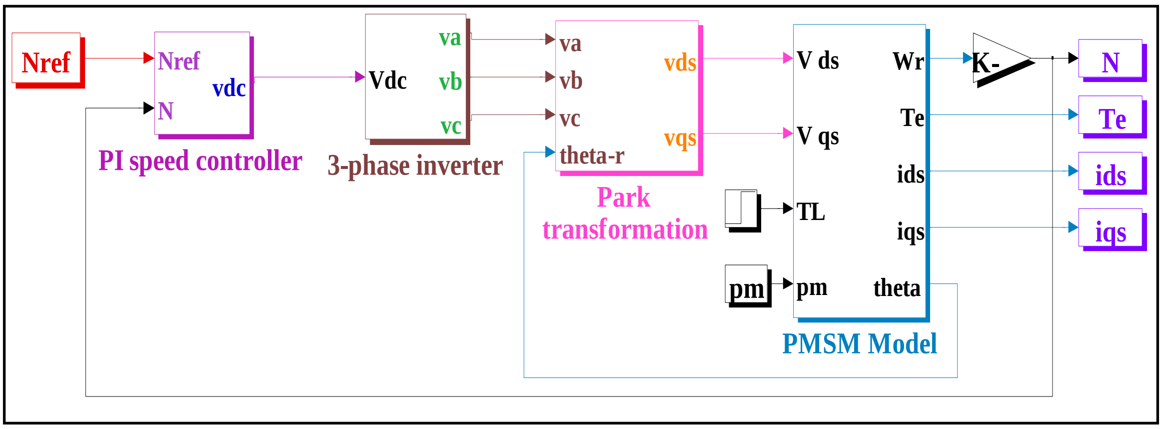

Fig. 4. Implemented simulink model of PMSM with PI controller.

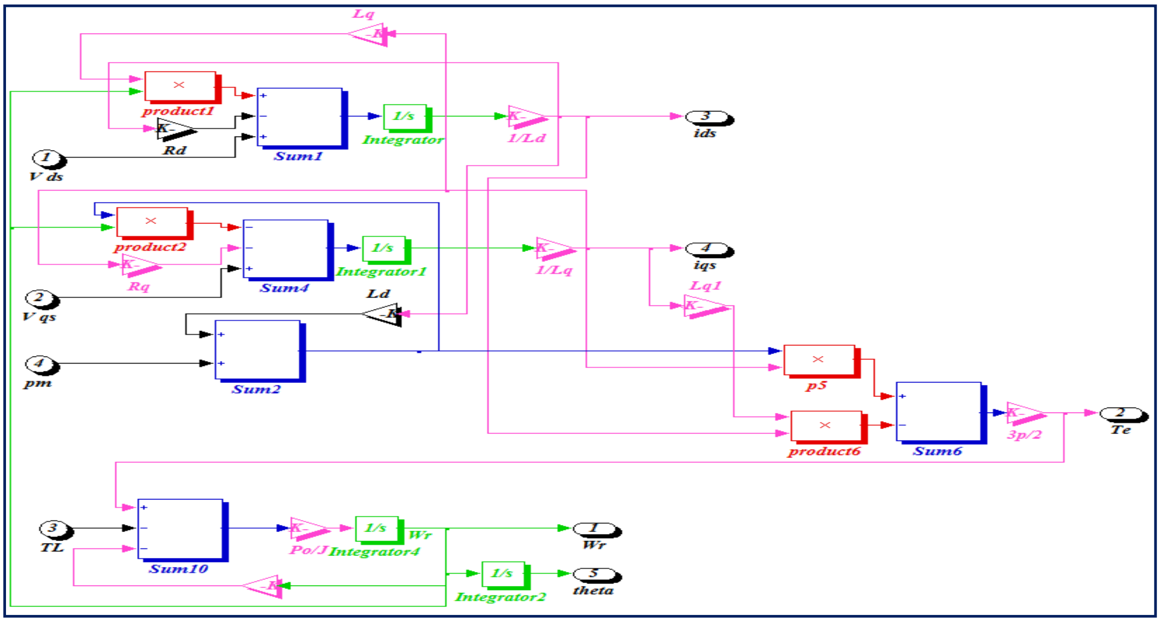

Fig. 5. Implemented simulink model of PMSM

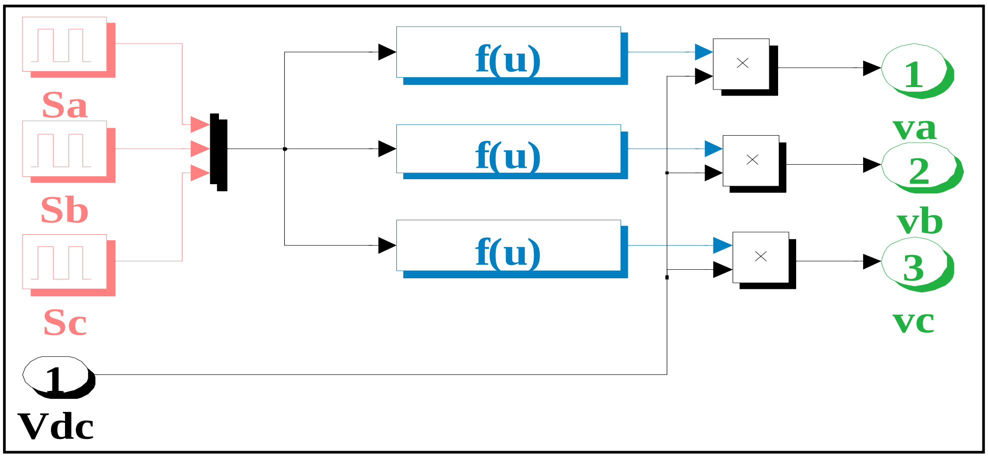

Fig. 6. Implemented simulink model of 3-ph inverter.

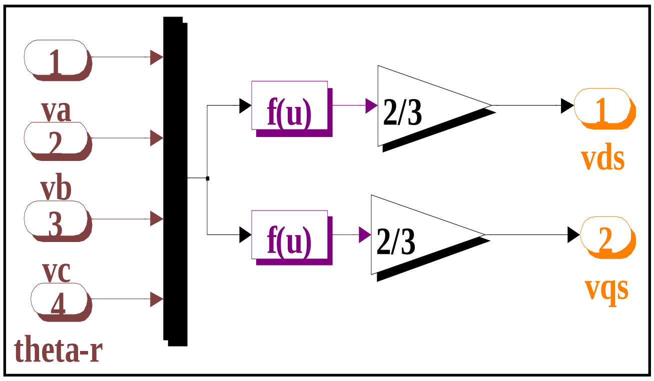

Fig. 7. Simulink model of park transformation block.

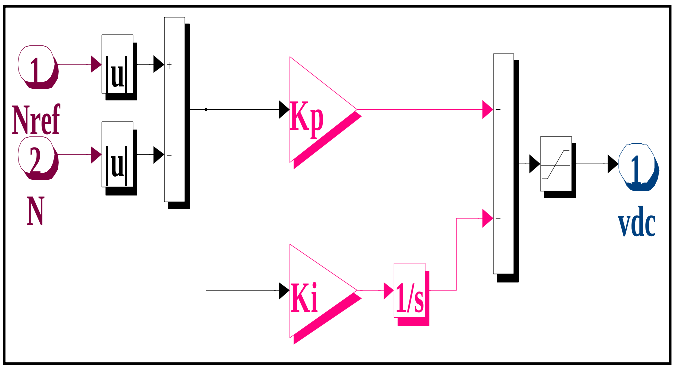

Fig. 8. Simulink model of PI speed controller.

3.2. SIMULATION OF PMSM DRIVE USING FUZZY-PID CONTROLLER

Fuzzy controller is a nonlinear PD controller, it cannot keep away from steady-state error when the system does not have integrating component, so it is an uncertain controller. To overcome this disadvantage, fuzzy-PID compound controller is proposed. It has been shown that it is not straightforward to write rules regarding integral action. Furthermore, the rule based involving three control actions (proportional, derivative, and integral) simultaneously become very large. To avoid these difficulties, one can separate the integral action from the other two actions, resulting a PD like fuzzy + I controller (Liu W. et al., 2006). A complete PD-like fuzzy + I based speed control for PMSM is shown in Fig. 9. A simulink model of PD like fuzzy + I controller block using Matlab/Simulink software package is shown in Fig. 10. The gains Kp, Kd, and Ki in this block can be adjusted by using trial and error method. The fuzzy editor of fuzzy block is shown in Fig. 11. Its input are speed error and change of speed error. Triangular membership function and COG deffuzification algorithms are adapted in the proposed PD like fuzzy + I type controller.

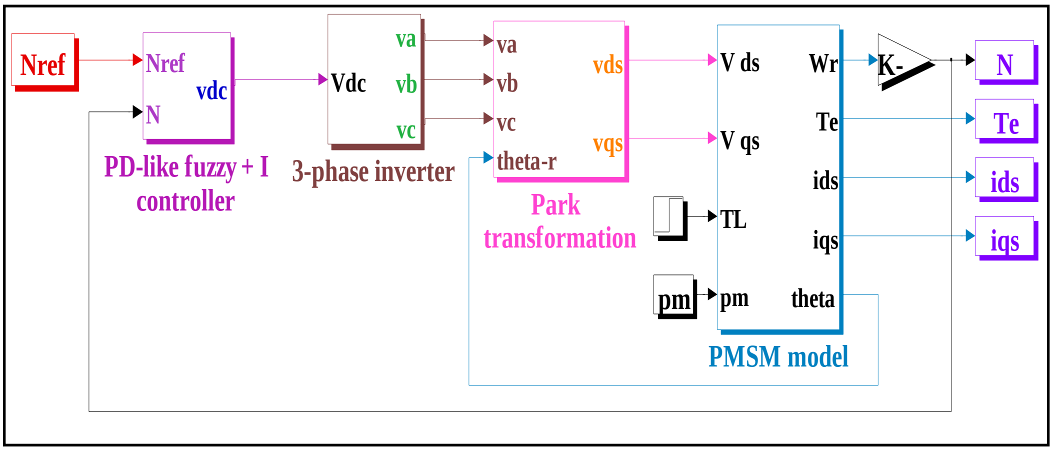

Fig. 9. Implemented simulink model of PMSM with fuzzy controller.

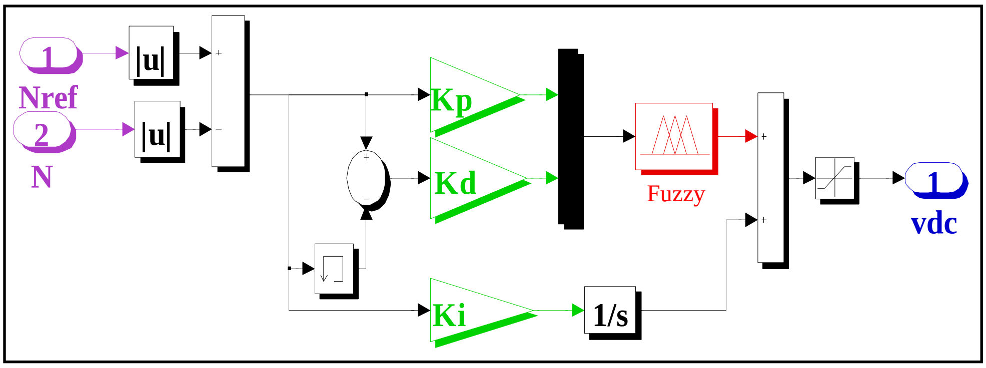

Fig. 10. Simulink model of PD-like fuzzy + I speed controller for PMSM.

The membership functions of the speed error and speed change error and output of this controller are shown in Figs. 12-14, respectively. The rule base, which is represented as a set of rules, is shown in Table 1. The proposed controller uses the following linguistic labels for the input and output membership functions (negative big (NB), negative (N), zero (Z), positive (P), and positive big (PB)). Fig. 15 represents the surface plot of fuzzy controller, where it is a mesh plot of a relationship between error of speed e (t) named (SE) in FLC block and change of error speed Δe(t) named (CSE) in FLC block on the input side and controller output.

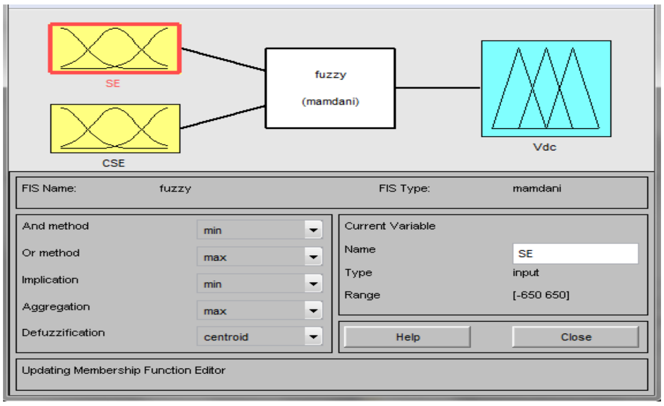

Fig. 11. Fuzzy editor of fuzzy controller.

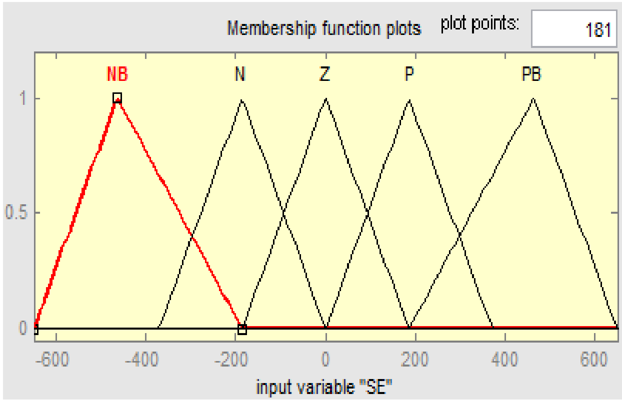

Fig. 12. Membership functions of the speed-error input of fuzzy controller.

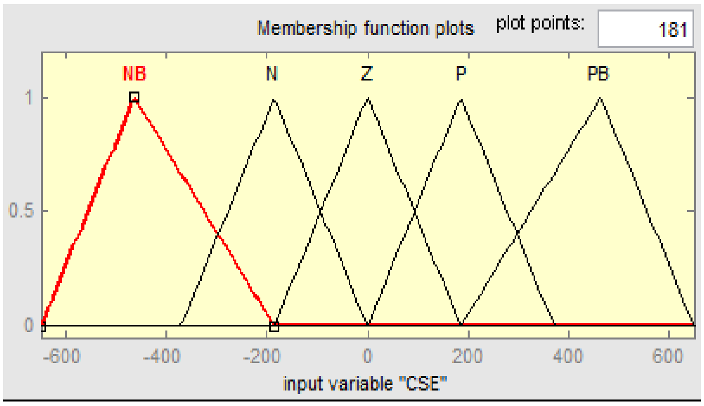

Fig. 13. Membership functions of speed change error input of fuzzy controller.

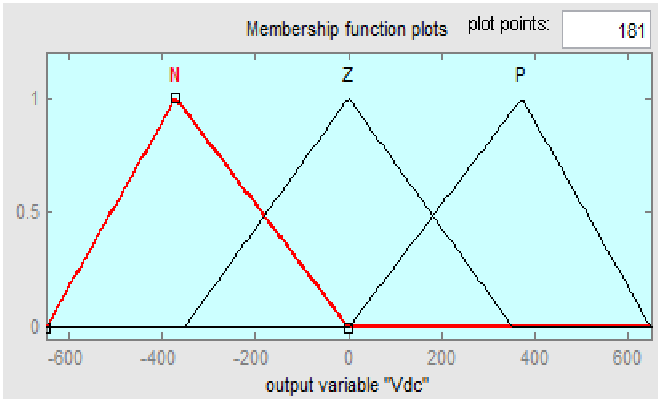

Fig. 14. Membership functions fuzzy controller output.

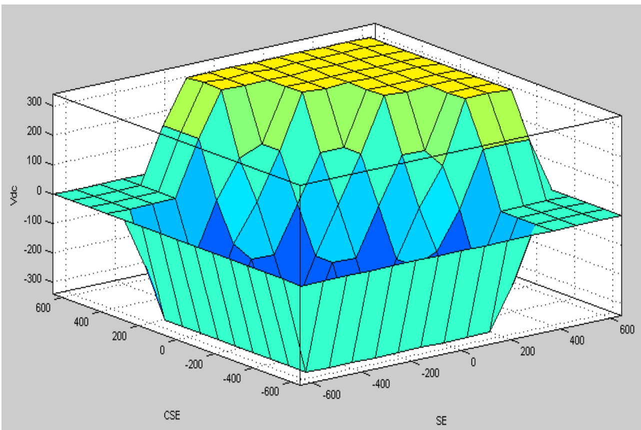

Fig. 15 surface plot of fuzzy controller

Table 1. Fuzzy Rules Matrix For Pmsm Controller

CSE \ SE	NB	N	Z	P	PB
NB	N	N	N	N	Z
N	N	N	N	Z	P
Z	N	N	Z	P	P
P	N	Z	P	P	P
PB	Z	P	P	P	P

3.3. SPEED CONTROLLER OF MASTER/SLAVES PMSM SIMULATION MODEL

In order to study the effect of the permanent magnet synchronous motor synchronization control system, a system including two PMSMs is built for simulation. One motor is selected as master motor, and other motor is as slave motor. The Simulink model of master-slave control system of PMSM is shown in Fig. 16. In Fig. 17 three PMSMs (first master and others slaves) are shown. The master motor is the reference motor to which one or more of the slave motors are synchronized.

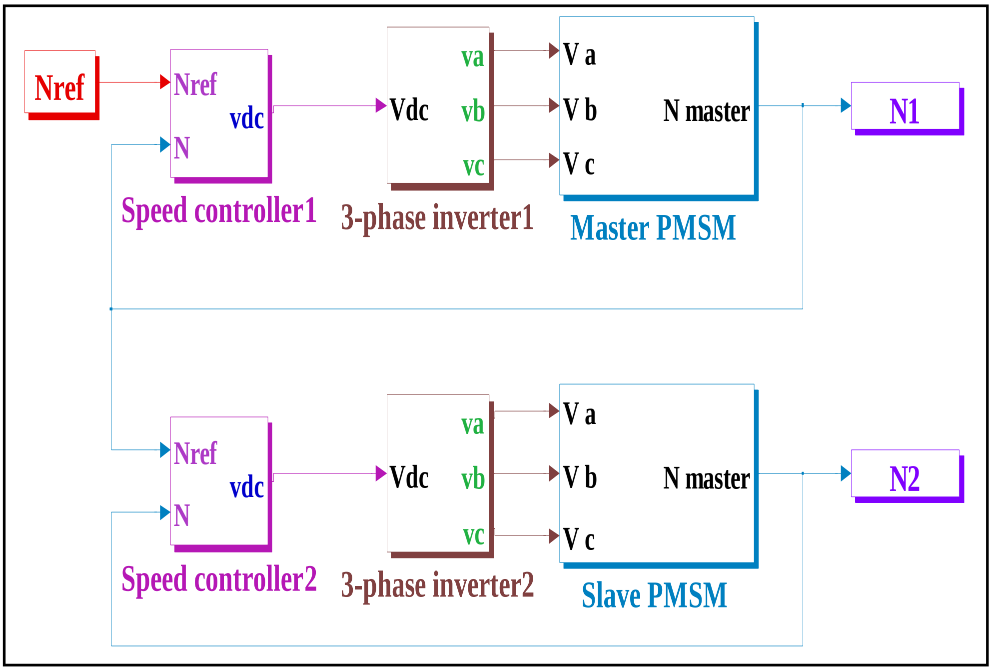

Fig. 16. Simulink model of master-slave control system of PMSM.

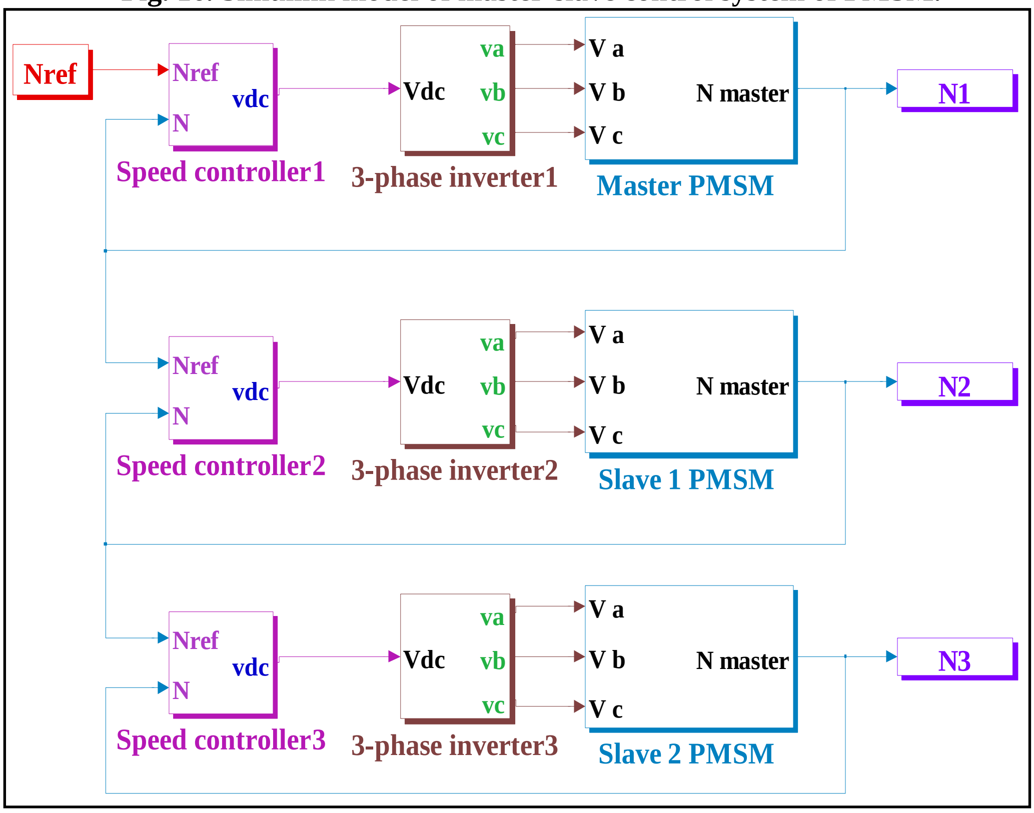

Fig. 17. Simulink model of multi PMSMs system.

4. SIMULATION RESULTS

In this paper a PI controller and PD-like fuzzy + I controller are used to improve the multi PMSMs speed profile. The PMSM parameters are listed in Table 2:

Table 2. PMSM Parameters

Parameter	Value
q-axis stator resistance (R_q)	2.875 Ω
d-axis stator resistance (R_d)	2.875 Ω
q-axis inductance (L_q)	2.8 mH
d-axis inductance (L_d)	1.4 mH
Combined Viscous Friction(b)	0.0014 Nm/rad/s.
Moment of Inertia (J)	.0011 Kg.m^2 0
DC link voltage (V_{dc})	90V.
pm)(Rotor magnetic flux	0.12 wb.
Number of poles(p)	4

The system was subjected to different load conditions. The PMSMs were operated for a reference speed of 3000 rpm under no-load condition and change in load condition for master and slaves motors. The values of the controller gains are obtained by using trial and error method. Figs. 18-20 show the output of the three phase voltage source inverter, PMSM speed, and electromagnetic torque without applied load and without any controller.

Figs. 21-23 show the output of inverter, PMSM speed and electromagnetic torque with step change applied load from 0 to 3 Nm at 2 sec and without any controller.

The system was run, while motor shaft was under no load condition; graphs of speed and electromagnetic torque response of the PMSM are obtained in Figs. 24 and 25 when using PI controller. The controller gains used are K_P=0.02 and K_I=2. It can be seen from the speed profile that the oscillation in the starting is omitted and the starting improved by using closed loop PI controller.

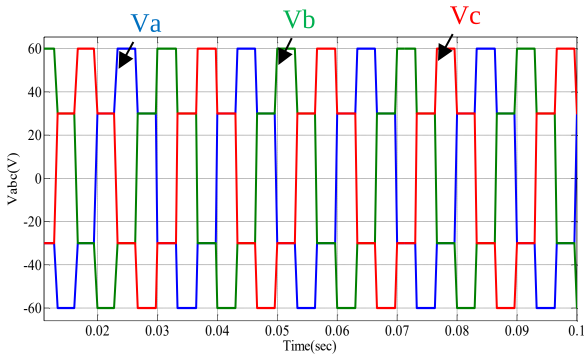

Fig. 18. Three-phase output voltages of the inverter.

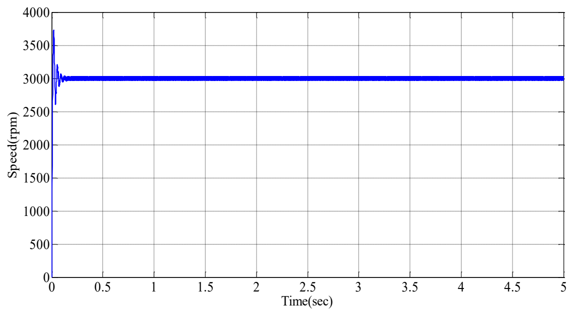

Fig. 19. PMSM speed without load and controller.

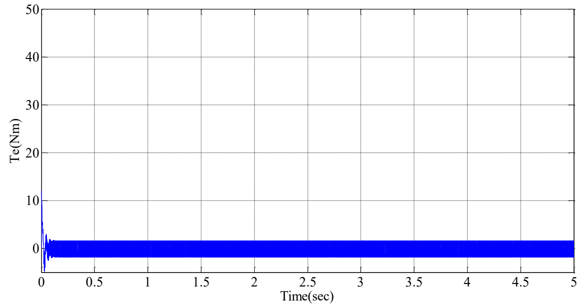

Fig. 20. PMSM Electromagnetic Torque.

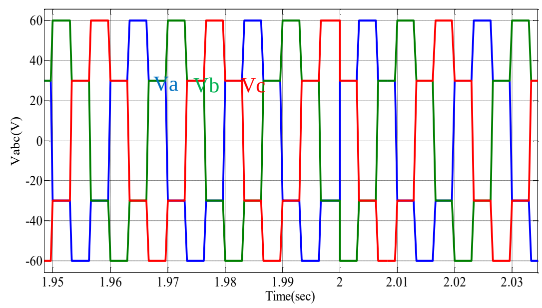

Fig. 21. Three-ph output voltages of the inverter with load applied on 2sec.

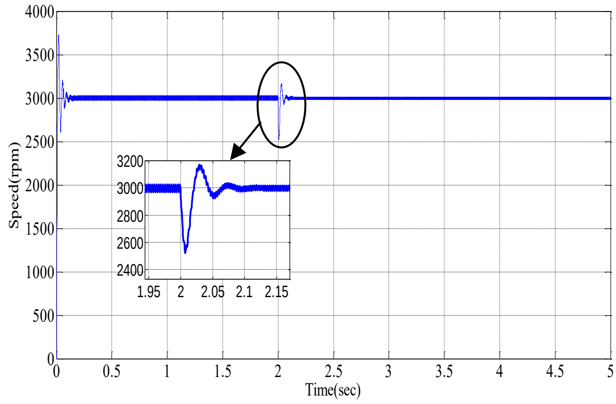

Fig. 22. PMSM speed without any controller but with load applied at 2sec.

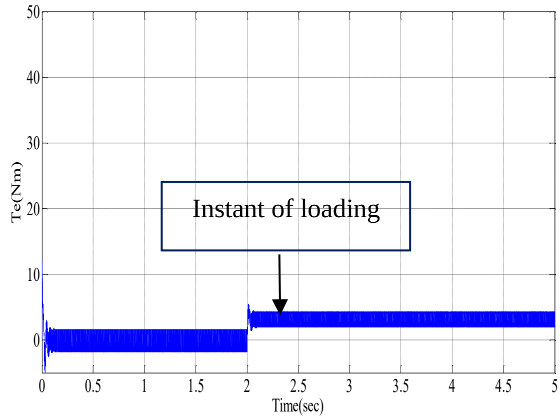

Fig. 23. PMSM torque profile without controller with load change of T_L= 3 Nm

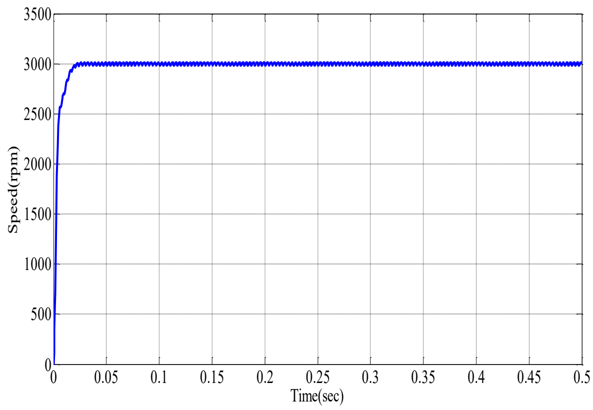

Fig. 24. Motor speed profile with PI controller but with no load.

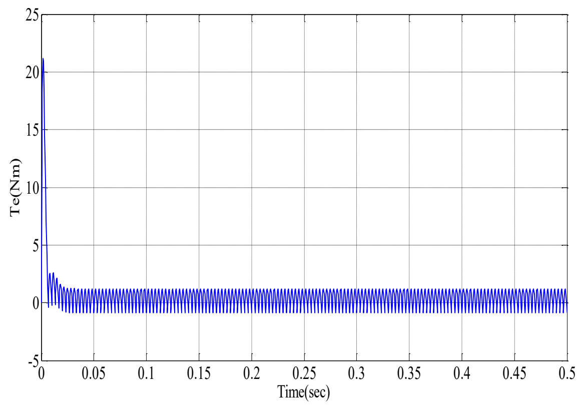

Fig. 25. Motor torque profile with PI controller and with no load.

The PMSM speed and torque waveforms computer simulation results with a sudden load T_L=5 Nm applied at t =0.1sec and lifted at t =0.3 sec are shown in Figs. 26 and 27 for the PI controller which proves that the PMSM speed and motor torque profiles have been improved (i.e. transient is omitted) during starting and during sudden load change applying and removing.

When a single motor operated under the PD-like fuzzy + I controller, the values of the PD-like fuzzy +I (PD-LF+I) gains are obtained using trial and error method and are found to be (K_P=10, K_I=3.12, and K_d=0.12) for operating speed of 3000 rpm. The PMSM speed profile is tested with a sudden load change (T_L= 10 Nm at t= 0.3 sec.) as shown in Fig. 28.

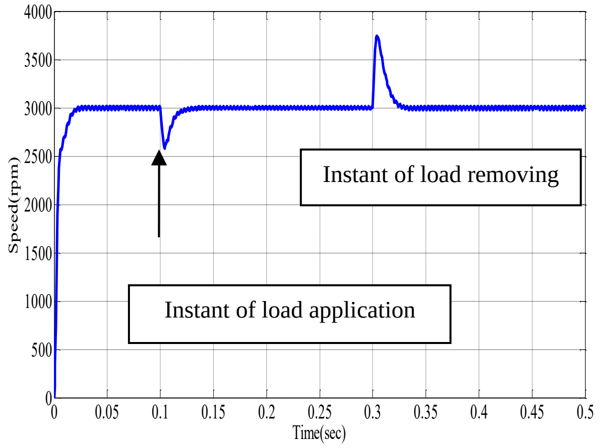

Fig. 26. PMSM Speed profile with PI controller and with sudden load change of TL= 5 Nm

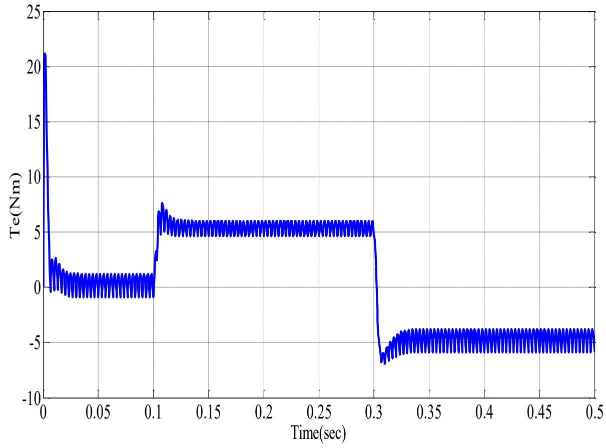

Fig. 27. PMSM Torque profile with PI controller and with sudden load change of TL= 5 Nm.

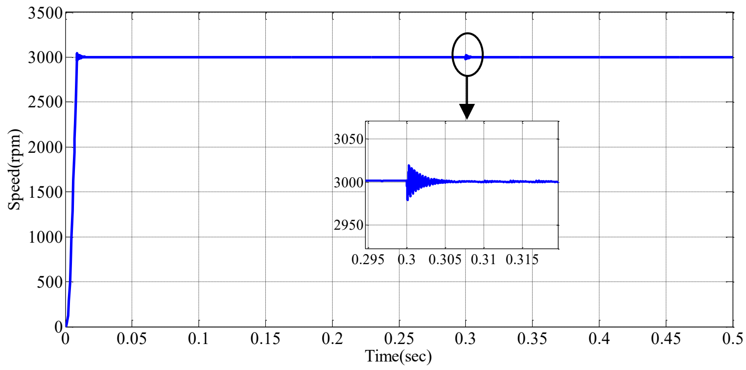

Fig. 28. Motor speed profile with PD-like fuzzy + I controller with sudden load change of T_L=10 Nm at t=0.3sec.

In Figs. 29 and 30, the PMSM speed and torque responses under PI and PD-like fuzzy + I controllers are compared with sudden load conditions. It is seen that in rise and settling times of angular speed and steady-state error the PD-like fuzzy + I controller exhibit the best performance. The results show that the PD-like fuzzy +I controller is superior than the conventional PI one because it reduced the speed and torque oscillations.

In these figures, the PMSM speed and torque profiles with PI and PD-like fuzzy + I controllers that is tested with a sudden load applied on both motors, for PMSM with PI controller (T_L= 1Nm applied at t=1 sec. and removed at t=2 sec.). For PMSM with PD-like fuzzy + I controller (T_L= 10Nm applied and removed at the same instants above).

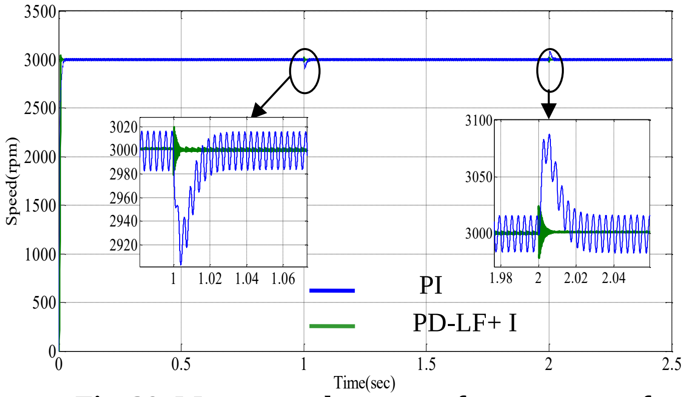

Fig. 29. Motor speed response for two types of controllers with load applied on and removed from both PMSMs.

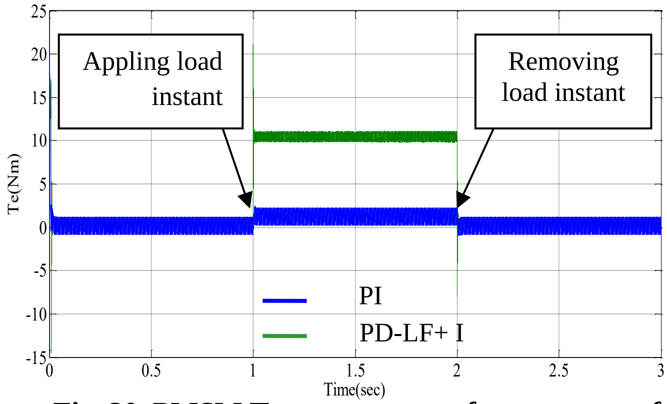

Fig. 30. PMSM Torque response for two types of controllers with load applied and removed from both PMSMs.

In Fig. 31 The PMSM speed profile with PI and PD-like fuzzy + I controllers is tested again with a sudden load applied on both motors, for PMSM with PI controller (T_L= 1 Nm applied at t=(0.1 and 0.6)sec. and removed at t=0.3 sec.). For PMSM with PD-like fuzzy + I controller (T_L= 10 Nm applied and removed at the same instants for PMSM under PI controller). As shown in speed and torque graphs, controller obtained with PD-like fuzzy + I control reached to the desired reference speed in a very short time while controller obtained with PI control reached to reference speed after much longer period of time both under load change conditions.

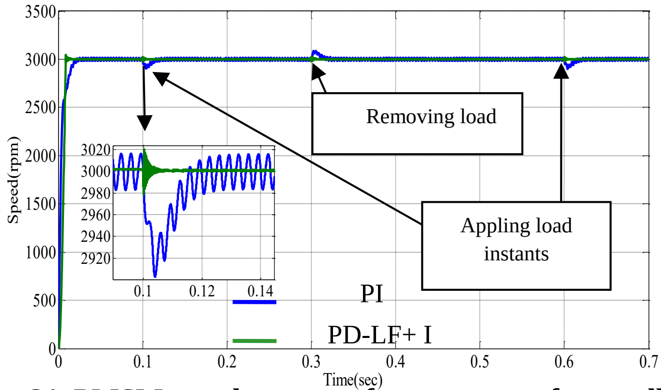

Fig. 31. PMSM speed response for two types of controllers with load applied and removed on both PMSMs.

Figs. 32 and 33 show the speed of two (master/slave) PMSMs under PI controller. For Fig. 32, at the time of starting master motor running with zero load torque so it is called no load operation but at t=0.2sec step changed in load from no load 0Nm to a torque of 1Nm is applied on master motor. From this figure, it can be see that any input signal or disturbance on the master motor speed can be reflected and tracked by the slave motor speed due to load change. For Fig. 33, the slave motor running at sudden step change in load torque at t=0.2sec from 0Nm to a torque of 5Nm. The controller gains used for controlling the two PMSMs are K_P=0.2 and K_I=1.4 for master motor and K_P=2 and K_I=8 for slave motor.

From this figure, it can be shown that the disturbance on the slave motor speed never affect the master motor.

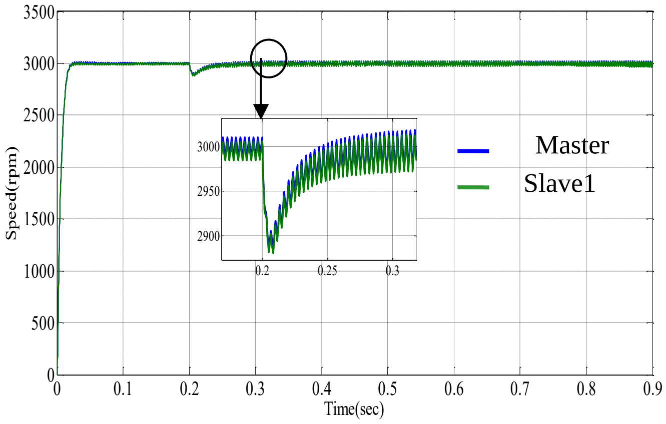

Fig. 32. Speed of multi PMSMs with PI controller and applied load on the master motor only.

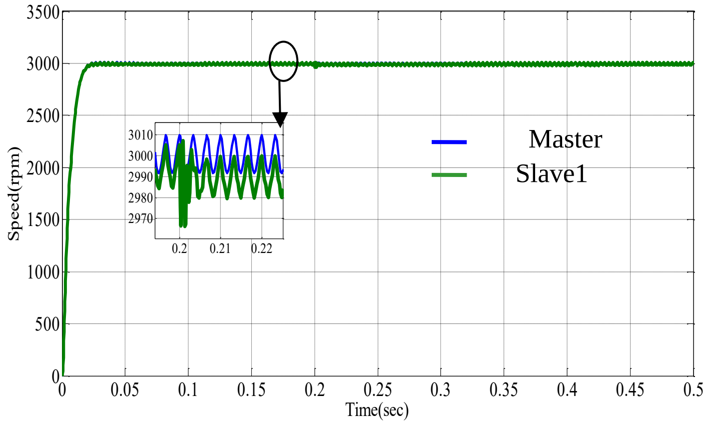

Fig. 33. Speed of multi PMSMs with PI controller and applied load on slave1 motor only.

In Fig. 34 two (master/slave) PMSMs operated with PD-like fuzzy + I controller and with load T_L=10Nm applied on master motor at t=0.3sec and removed at t=0.5sec. It is clear that the slave motor followed the master under a load change condition. This controller gains that are used for controlling two PMSMs are K_P=10, K_d=0.5, and K_I=2 for master motor and K_P=2, K_d=2, and K_I=5.5 for slave motor.

In order to compare the performance of PD-LF+I controller with PI controller in the same test, Fig. 35 shows the simulated results comparison of them for speed control of two master/slave PMSMs under no load variation.

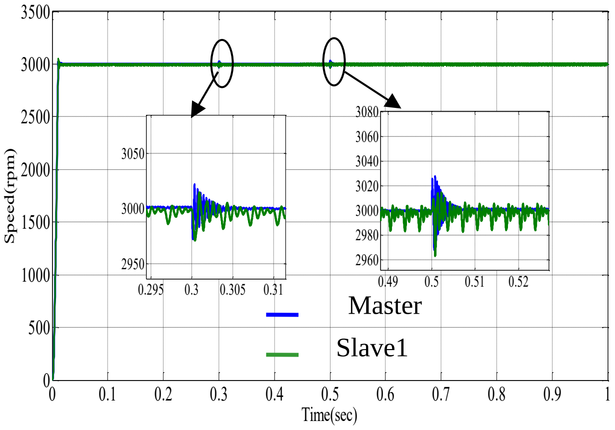

Fig. 34. PMSMs master/slave speed with PD-LF+I controller and with load change applied and removed from master motor only

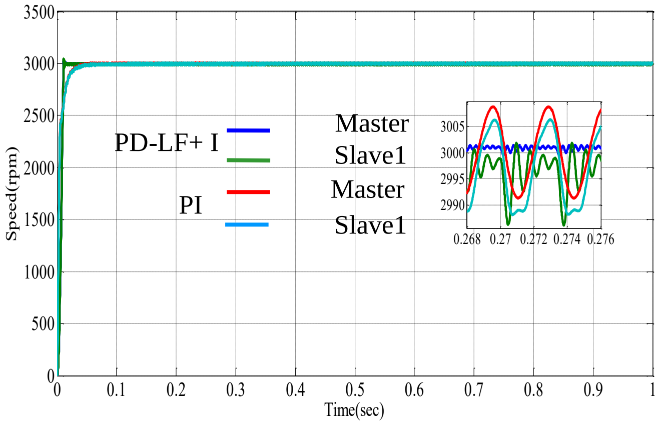

Fig. 35. Speed of multi PMSMs under two controllers and without load.

Fig. 36 shows the speed response curves of master/slave PMSMs under PD-like fuzzy + I controller. The master motor with step change load T_L=10 Nm applied at t=0.3 sec and removed at t=0.5 sec. They indicate that compared to conventional PI controller which its master motor tested under step changed load T_L=2Nm applied at and removed at the same instants above. The PD-like fuzzy + I controller improves the control performance of the system; it has features of small overshoot, short rise time and settles faster than the PI controller.

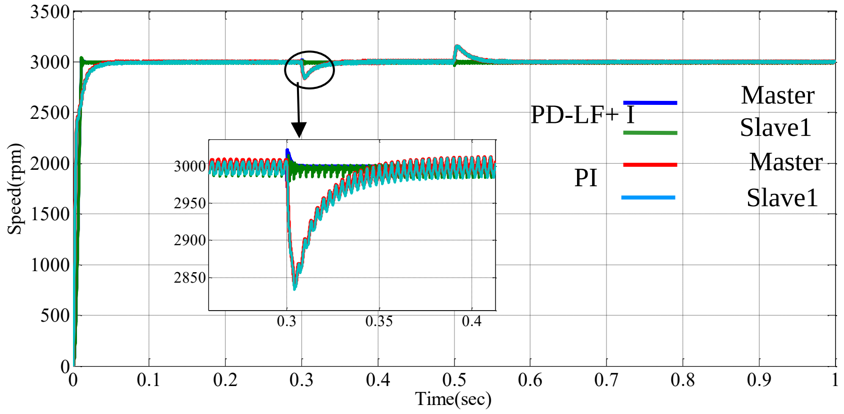

Fig. 36. System speed response of PI vs PD-like fuzzy + I controllers for master/slave PMSMs.

Fig. 37 shows the speed profile for two (master/slave) PMSMs system. They were started with no-load, and a load T_L=10 Nm is added suddenly on the slave motors for the two types of controllers at time 0.1 sec and removed at time 0.3 sec. The difference in response for the PD like fuzzy + I controller and PI controller is clear in these figures.

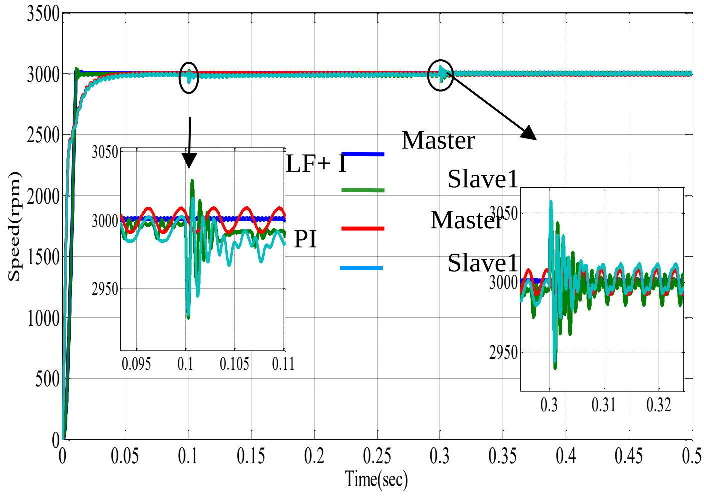

Fig. 37. System speed response of PI vs PD-like fuzzy +I controllers for master/slave PMSMs with load change condition.

Fig. 38 presents multi (master/two slaves) PMSMs system response under PI controller with sudden load change conditions. The controller gains used for controlling three PMSMs are K_P=0.01 and K_I=1.2 for master motor, K_P=7 and K_I=9.5 for slave1 motor, and K_P =200 and K_I=200 for slave2 motor. In this figure, T_L=1 Nm applied on a master motor at t=0.2 sec and removed at t=1sec, simultaneously step change load of T_L=20 Nm applied on slave2 motor at t= 0.8 sec. It is obvious from Fig. 38 that the sudden load change on master PMSM reflected on the two PMSMs slaves, but the sudden load change on the slave2 motor never affect the master motor.

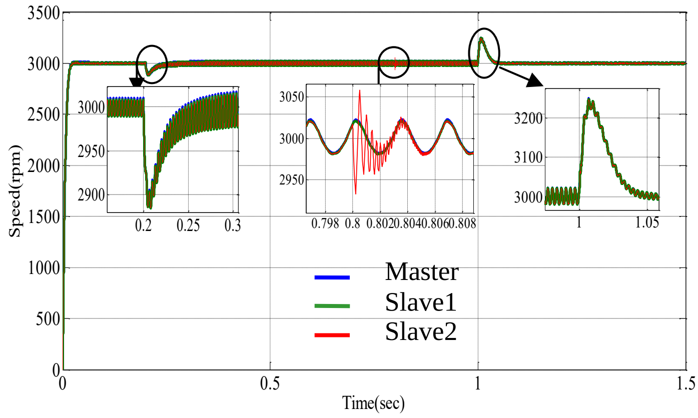

Fig. 38. Speed of three PMSMs under PI controller with load condition.

Fig. 39 shows multi (master/two slaves) PMSMs system characteristics under PD-like fuzzy + I controller. In which at t=0.1 sec a 14 Nm load torque step change is applied on master PMSM, and the same value of load is applied at t=0.3 sec on slave2 motor. This controller gains which are used for controlling three PMSMs are K_P=15, K_d=6, and K_I=3 for master motor, K_P=6, K_d=8, and K_I=7 for slave1 motor, and K_P=4.1, K_d=13, and K_I=0.08 for slave2 motor.

In Fig. 40, a comparison has been done between the speed response of three PMSMs operated with a conventional PI controller under no load condition and with PD-like fuzzy + I controller with a sudden change in the load applied to the master motor from no-load to 16 Nm at 0.038 sec.

In Fig. 41, a second comparison between the speed response of three PMSMs operated with conventional PI controller under sudden load of 1Nm applied on the master motor at t= 0.1 sec and removed at t=0.2 sec, and with PD-like fuzzy + I controller under no load condition.

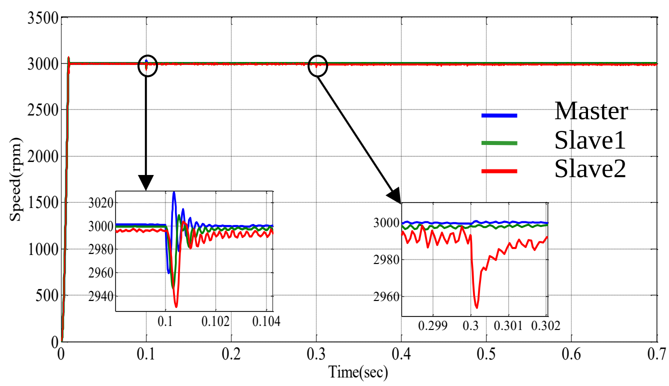

Fig. 39. Speed of three PMSMs under PD-LF+I controller with load condition.

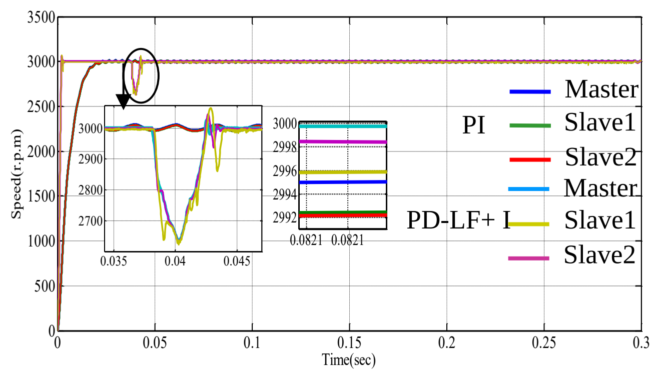

Fig. 40. Difference between speed response of three PMSMs system under PI and PD-LF+I controllers.

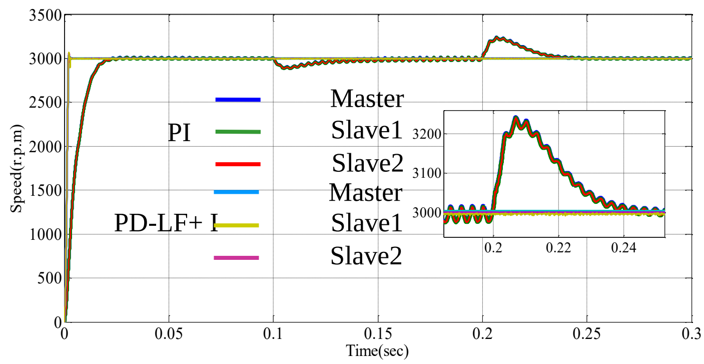

Fig. 41. Comparison between speed response of multi PMSMs system under PI and PD-like fuzzy + I controllers.

5. CONCLUSION

This paper mainly presented a study of multi PMSMs mathematical model and dynamic response. In addition to, two useful controllers used to improve the system speed profiles are offered. The d-q model of the PMSM, the two controllers and the drive circuit have been derived and implemented using Matlab/Simulink software program. Two types of controllers have been used to improve the multi (master/slaves) PMSMs speed profile. The first one is a conventional PI controller, and the second is a PD-like fuzzy + I controller. Each motor speed is the feedback signal to determine the error in speed at instant of starting and loading, and the output of the controller is then fed to the voltage source inverter. When a closed loop conventional PI controller is used to control the multi motors, speed and torque responses were not sufficient to the higher degree of accuracy condition. While using of the PD-like fuzzy + I controller improves the speed and torque responses for high values of sudden load torques for master and slaves motors. The three motors are tested for different load conditions. The results showed that the motors have very high starting torque and their speed curves pass through small durations of variation and disturbance after sudden load application or removal. The performance of the multi PMSMs drive with PI controller and PD-like fuzzy + I controller has been compared in this paper, and it was found that PD- like fuzzy +I speed controller improved the performance of PMSMs.

6. REFERENCES

Abd samat A. , Ishak D. & Iabal S., "Voltage Space Vector Averaging Technique for Two PMSMs Connected in Parallel" International Journal of Electrical Energy, Vol. 1, No. 4, December 2013.

Ahmed A.M. Emam, Eisa B. M. Tayeb, A.Taifour Ali and Musab M.S.A, " Master-Slave Speed Control of Double Induction Motor", International Journal of Computational Engineering Research, May 2013, Vol. 03, Issue, 5.

Bajpai D. and Mandal A. , "Comparative Analysis of T- Sugeno and Mamdani Type Fuzzy Logic Controller for PMSM Drives", International Journal of Engineering Research and General Science Volume 3, Issue 2, March-April, 2015, ISSN 2091-2730.

Chakraborty M., " Comparative Analysis of Speed Control of PMSM using PI-Controller and Fuzzy Controller", International Journal of Scientific & Engineering Research, Volume 4, Issue 7, July-2013, ISSN 2229-5518.

Dogan M. and Dursun M., "Application of speed control of permanent magnet synchronous machine with PID and Fuzzy Logic Controller", Energy Education Science and Technology Part A: Energy Science and Research, 2012 Volume (issues) 28(2): 925-930.

Fadel M. & Llor A., "Comparison of different solutions in predictive control for two PMSM in parallel", Proceedings of the 19th World Congress The International Federation of Automatic Control Cape Town, South Africa. August 24-29, 2014

Gurumurthy G., Kumar P. , and Reddy D., " Design and Simulation of Permanent Magnet Synchronous Motor Drive by Using Fuzzy Logic Controller", International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering, Vol. 3, Issue 5, May 2015.

Hartani K., Maata F. & Merah A., "Sensorless Master-slave Direct Torque Control of Permanent Magnet Synchronous Motors Based on Speed MRAS Observer in Electric Vehicle" Research Journal of Applied Sciences, Engineering and Technology 7(23): 5034-5048, 2014, ISSN: 2040-7459.

Khatoon N. and Shaik S. , "Speed Control Methods for Field Oriented Permanent Magnet Synchronous Motor Drive", International Journal of Advancements in Research & Technology, Volume 2, Issue 12, December-2013, ISSN 2278-7763.

Liu W., Song S., "Application of Fuzzy Control in Switched Reluctance Speed Regulating System", International Conference on Computational Intelligence for Modeling Control and Automation, and International Conference on Intelligent Agents, Web Technologies and Internet Commerce, 2006.

Patil N., Chile R., and Waghmare L., "Fuzzy Adaptive Controllers for Speed Control of PMSM Drive", International Journal of Computer Applications (0975 – 8887) Vol.1, No. 11, 2010.

Rajesh K., Sudarsan M., and Suresh L., "Neuro PID Speed Controller for Permanent Magnet Synchronous Motor", International Journal of Computer Science and Mobile Computing, Vol.4 Issue.5, May- 2015, pg. 887-893.

Shikkewal B. & Nandanwar V., "Fuzzy Logic Controller for PMSM", International Journal of Electrical and Electronics Engineering (IJEEE), Vol-1, Iss-3, 2012, ISSN: 2231 – 5284.

Smriti Rao K. , and Mishra R. , " Comparative study of P, PI and PID controller for speed control of VSI-fed induction motor", International Journal of Engineering Development and Research, Vol. 2, 2014, Issue 2 | ISSN: 2321-9939.

Varshney R. and Gupta G. , "Neuro-Fuzzy Based Speed Controller For Permanent Magnet Synchronous Motor", International Journal of Advanced Research in Computer Science and Software Engineering, Volume 2, Issue 11, November 2012, ISSN: 2277 128X.