PID Controller Based Multiple (Master/Slaves) Permanent Magnet Synchronous Motors Speed Control

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Abstract: *This paper suggests the use of the traditional proportional-integral-derivative (PID) controller to control the speed of multi Permanent Magnet Synchronous Motors (PMSMs). The PMSMs are commonly used in industrial applications due to their high steady state torque, high power, high efficiency, low inertia and simple control of their drives compared to the other motors drives. In the present study a mathematical model of three phase four poles PMSM is given and simulated. The closed loop speed control for this type of motors with voltage source inverter and abc to dq blocks are designed. The multi (Master/Slaves approach) method is proposed for PMSMs. Mathwork's Matlab/Simulink software package is selected to implement this model. The simulation results have illustrated that this control method can control the multi PMSMs successfully and give better performance.*

***Index Terms*—Multi (Master/Slave), PMSMs, PID speed controller, VSI.**

I. INTRODUCTION

Permanent magnet (PM) motor drives have been attracted of interest for the last twenty years due to its suitability for many applications like in automotive, mechatronics, green energy applications, and machine drives, PM motor drives are classified them into two types such as permanent magnet synchronous motor drives (PMSM) and brushless dc motor (BDCM) drives [1].

PMSM has numerous advantages over other machines that are conventionally used for ac servo drives. PMSM drives are widely used for high-performance servo applications like robotics and aerospace actuators since no external excitation is given to rotor therefore the losses are reduced and make PMSM highly efficient. Also absence of rotor winding renders slip rings and brushes obsolete and thus reduces maintenance cost [2].

This paper obtains mathematical model of PMSM, and achieves simulation of the model obtained in Matlab/Simulink program. PID controller has been compared feedback speed of each AC motor with its reference speed to produce an "error" value which is the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process control inputs. Voltage source inverter-fed PMSMs are most preferred for variable speed drive applications which used with Pulse Width Modulation (PWM) technique to drive the motors.

PID controller for speed control with graphical analysis was made. The main objective of this research paper is to develop the multi PID-speed controller for PMSM using classical master/ slave approach. Rise time, settling time, overshoot and steady-state error analyses of controllers for master and slaves motors are obtained and compared.

II. Modeling of PMSM Drives System

A PMSM drive system includes different components such as PMSM, inverter, and PID controller. The components are connected as shown in Fig.1.
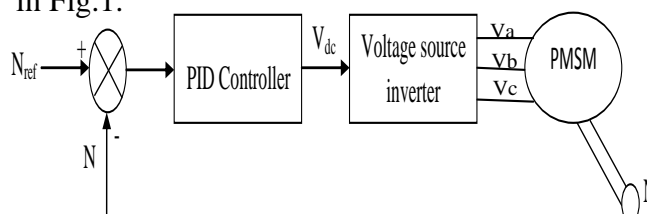

Fig.1 Block diagram of PID controlled PMSM

A. Dynamic Model of PMSM

The mathematical model of the PMSM is generally presented in a rotating d-q frame fixed to the rotor. The resulting model is described by the following equations:

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

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

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

$$J \frac{d\omega_m}{dt} = T_e - T_L - b\omega_m \tag{4}$$

Where:-

$$\psi_{ds} = L_{ds} i_{ds} + \psi \tag{5}$$

$$\psi_{qs} = L_{qs} i_{qs} \tag{6}$$

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; ω_r is the electrical angular speed and T_e is the electromagnetic torque. Ψ is the flux of the permanent magnet (denoted by **pm** in simulink model), 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 [3-6].

The dynamic d-q modeling is used for the study of PMSM. It is done by converting the three phase voltages to dqo variables by using Park transformation. Converting the phase voltages variables V_{abc} to V_{dqo} variables in rotor reference frame the following equations are obtained [7].

$$\begin{bmatrix} V_q \\ V_d \\ V_o \end{bmatrix} = \frac{2}{3} \begin{bmatrix} cos\theta_r & cos(\theta_r - 120) & cos(\theta_r + 120) \\ sin\theta_r & sin(\theta_r - 120) & sin(\theta_r + 120) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{7}$$

B. Voltage Source Inverter Model

Pulse width modulation (PWM) technique is used to generate the required voltage to feed the motor. This method is increasingly used for AC drives with the condition that the harmonic voltage is as small as possible. Consider the equivalent circuit of system inverter motor as in Fig. 2.
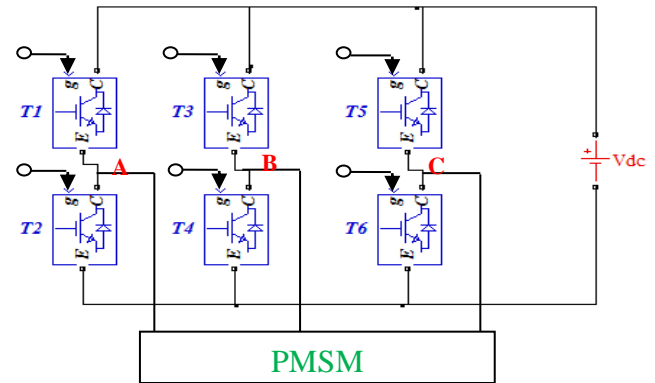

Fig.2 Inverter-motor equivalent circuit.

The motor phase voltage will have the expression:

$$\begin{aligned} V_{ao}(t) &= V_{an}(t) - V_{on}(t) \\ V_{bo}(t) &= V_{bn}(t) - V_{on}(t) \\ V_{co}(t) &= V_{cn}(t) - V_{on}(t) \end{aligned} \tag{8}$$

Being a star connected, then at every time instant the following relation is satisfied.

$$V_{ao} + V_{bo} + V_{co} = 0 \tag{9}$$

then the null voltage is derived as:-

$$V_{on} = \frac{(V_{an} + V_{bn} + V_{cn})}{3} \tag{10}$$

If consider a pulses for each inverter leg (Sa, Sb, Sc), the inverter's leg voltage can be found as:-

$$\begin{aligned} V_{an} &= V_{dc}.S_a \\ V_{bn} &= V_{dc}.S_b \\ V_{cn} &= V_{dc}.S_c \end{aligned} \tag{11}$$

from the above voltage the phase voltage can be found as the following:-

$$\begin{aligned} V_a &= V_{dc}.(S_a - (S_a + S_b + S_c)/3) \\ V_b &= V_{dc}.(S_b - (S_a + S_b + S_c)/3) \\ V_c &= V_{dc}.(S_c - (S_a + S_b + S_c)/3) \end{aligned} \tag{12}$$

The structure of the inverter simulink model is presented later[8].

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C. PID Controller Modeling

A PID controller involves three terms: the proportional term designated as K_p, the integral term designated as K_i/S, and the derivative term designated as SK_d. In the PID speed controller the motor speed is compared with the reference speed and the output of the speed controller gives to the motor [9].

II. Master-Slave Control Method

In this paper, the master (slave or slaves) control is applied in synchronous controller of double then triple PMSMs. In double motor method one motor is chosen as the master motor, the output speed of the master motor will be the reference value of the slave motor, the slave motor follows any change in the motion of the master motor but not the opposite. The simple structure of this control method is shown in Fig.3[10].
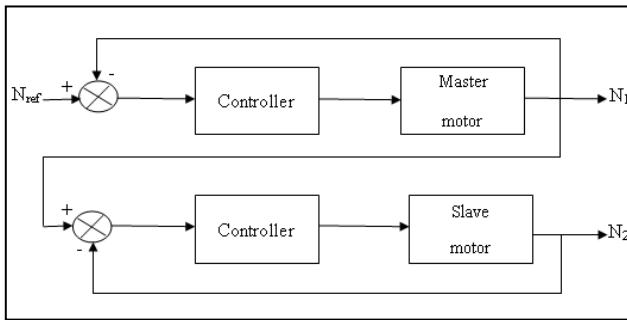
Fig.3 Simple structure of master-slave control method.

III. PMSM Drive Circuit Simulation Model

The implemented simulink model of PMSM with drive circuit using Matlab/Simulink software is shown in Fig.4, this circuit contains three major blocks: PMSM circuit block, abc to dq transformation system block, and three phase inverter circuit block. The PMSM model described through equations (1) to (6) is implemented as shown in Fig.5. The implemented simulink model of abc to dq system block is constructed using equation (7) as shown in Fig. 6. The simulink model of the 3-phase inverter circuit block using equations (12) is shown in Fig.7.
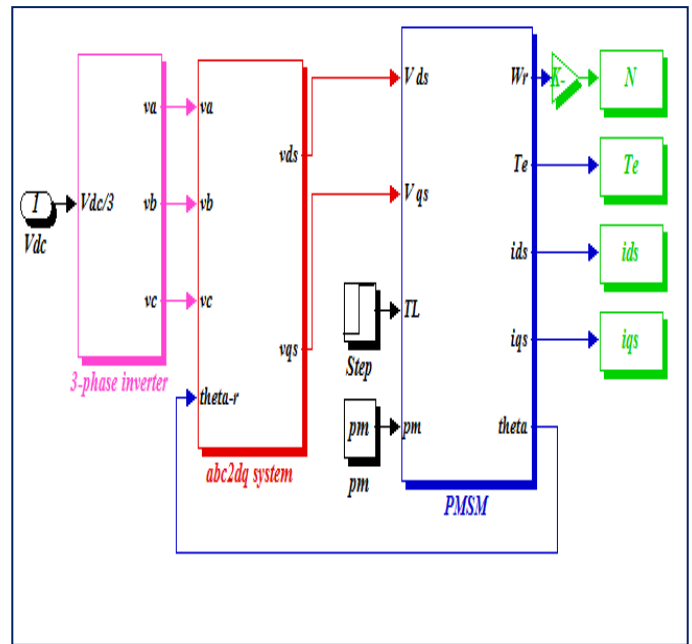
Fig.4 Implemented simulink model of PMSM drive circuit.
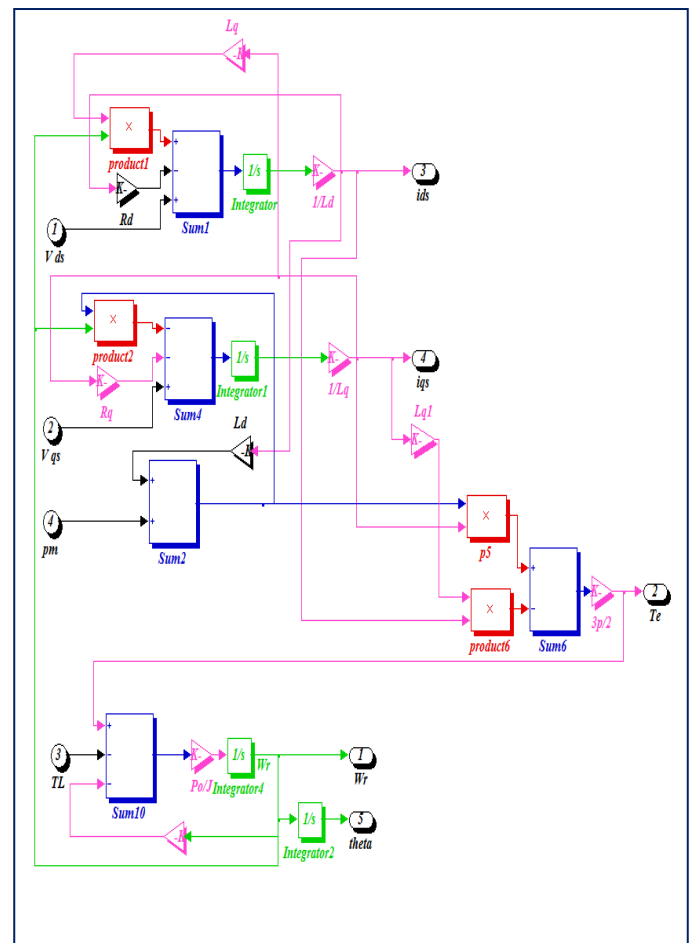
Fig.5 Simulink model PMSM model.

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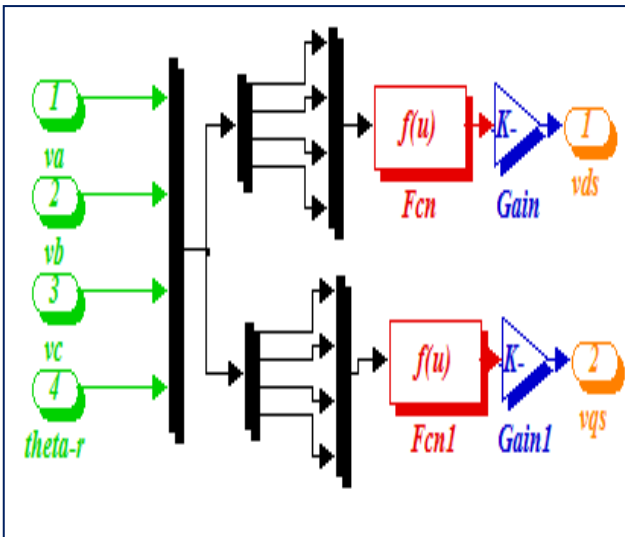
Fig.6 Simulink model of abc2dq system block.

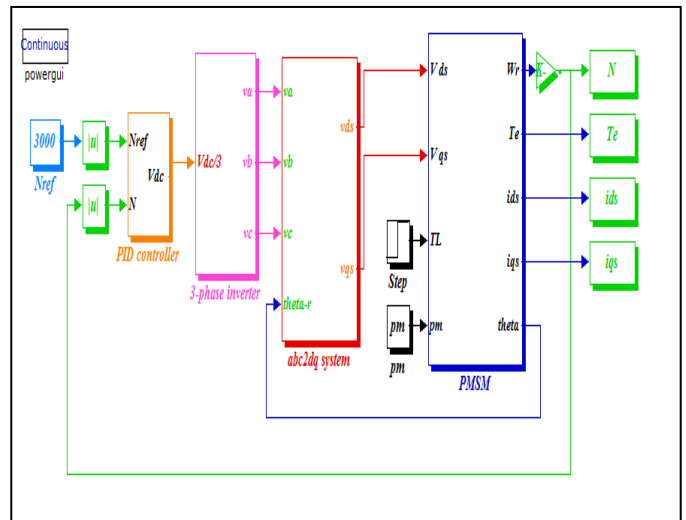
Fig.8 Simulink model of PMSM with PID controller.

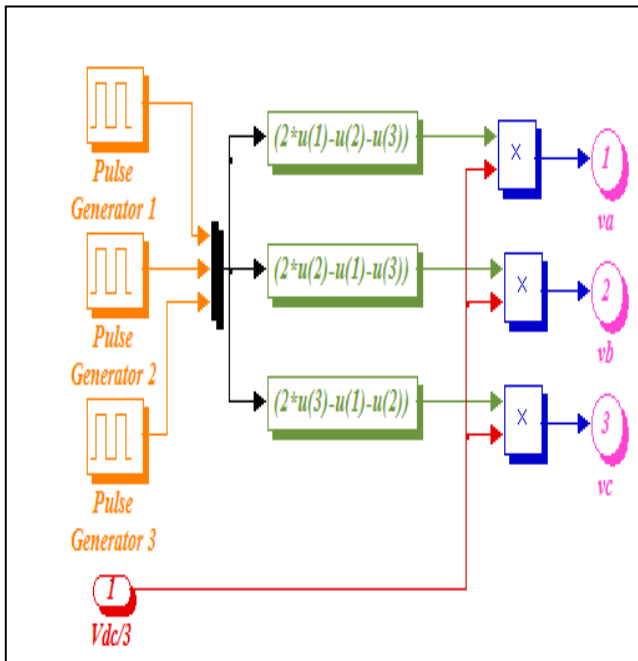Fig.7 Simulink model of 3-phase inverter block.

Fig.9 Simulink model of PID controller block.

IV. PID Based Controller for PMSM

The reference speed N_{ref} compared with the rotor speed N to produce the speed error. The speed error signal is processed though PID controller to yield the motor input voltage. The appropriate values of the parameters K_p, K_i, and K_d of the PID controller have been chosen by trial and error method. A complete PID speed control based PMSM drive circuit is shown in Fig.8. The simulink model of PID controller block is shown in Fig.9.
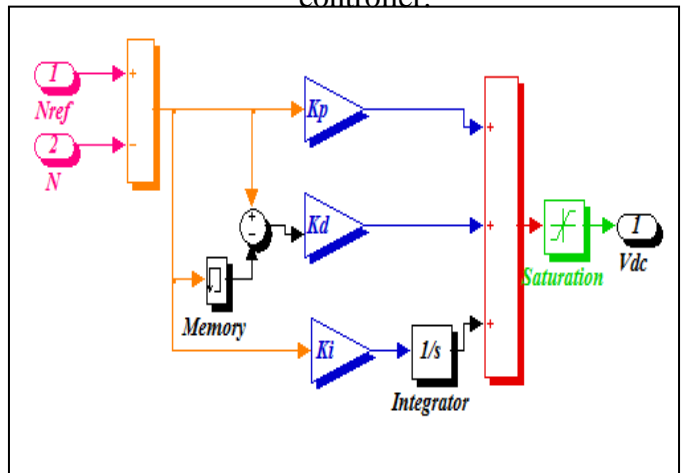
V. PID Controller of Master/Slave PMSM Simulation Model

Figure 10 shows the Matlab/Simulink model of two PMSM. One motor is the master and other motor is the slave.

VI. Simulink Model of PID Control of Multi PMSM

In Fig.11, three PMSMs (first motor is the master and others are slaves) are shown. These motors are drives by separate inverters. The master motor is the reference motor to which one or more of slave motors are synchronized.
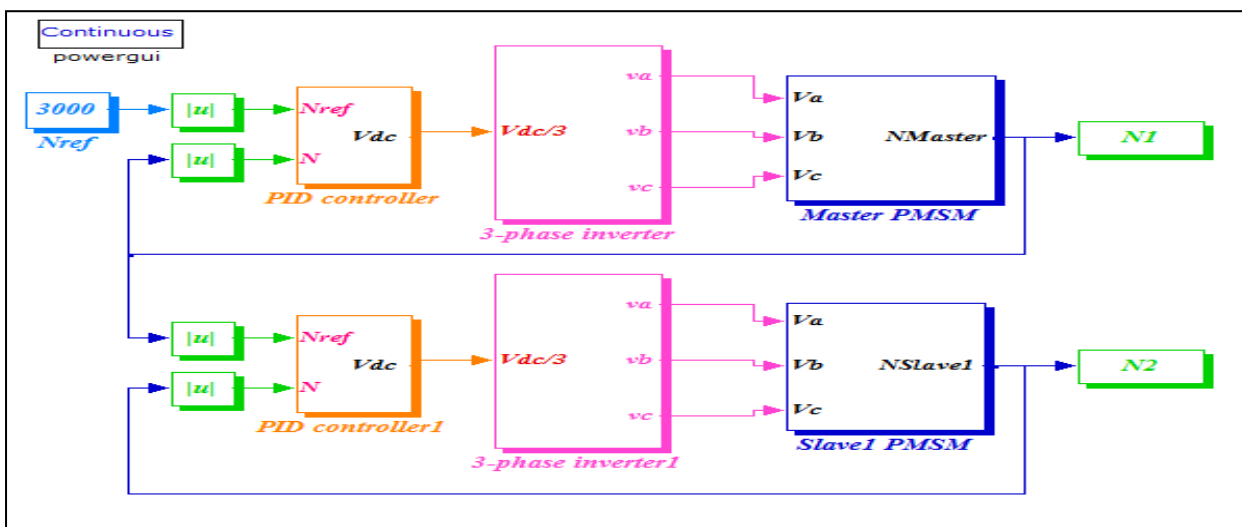
Fig.10 Simulink model of PID controller of master/slave PMSM.
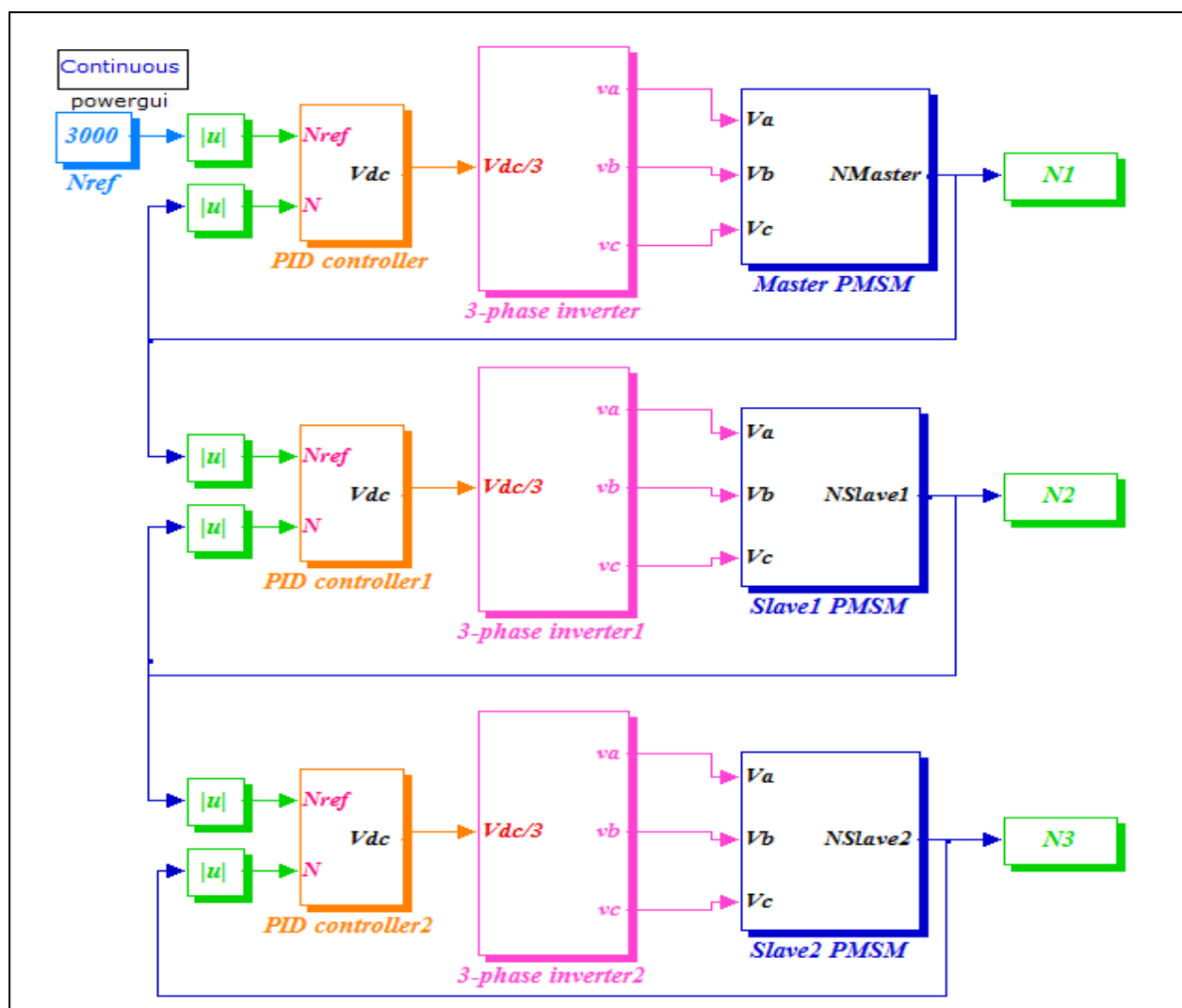
Fig.11 Simulink model of PID controller of Multi PMSM.

VII. Simulation Results

To demonstrate the possibilities of the proposed model of the PID control of multi permanent magnet synchronous motors, a set of tests has been performed.

Figures (12-16) show the output of inverter, PMSM speed , electromagnetic torque and d-q stator currents without applied load and PID controller.
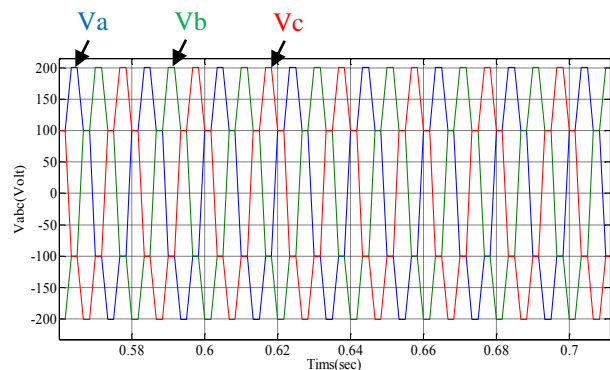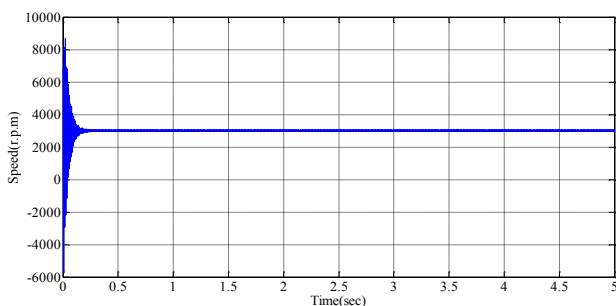

Fig.12 Inverter three-phase output voltages.

Fig.13 PMSM speed without PID controller.
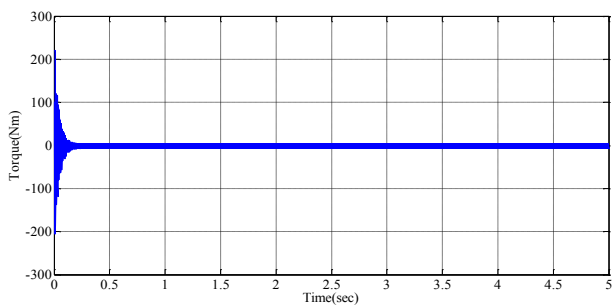
Fig.14 PMSM Torque with no load.
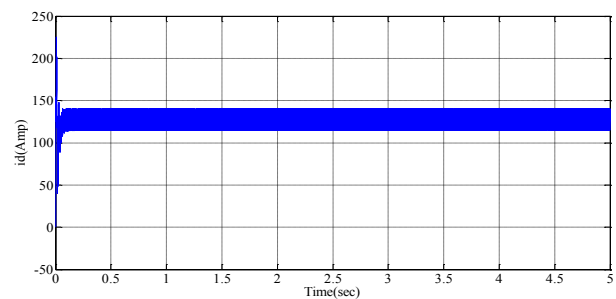
Fig.15 PMSM d- axis current.
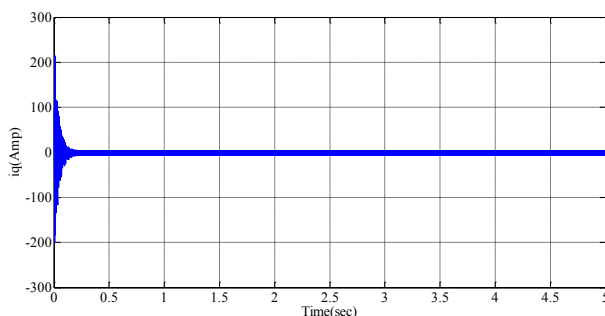
Fig.16 PMSM q- axis current.

Figs.(17-21) show the output of inverter , PMSM speed , electromagnetic torque and q-axis and d-axis components of stator current with step change applied load from 0 to 7Nm at 4 sec. and without PID controller.
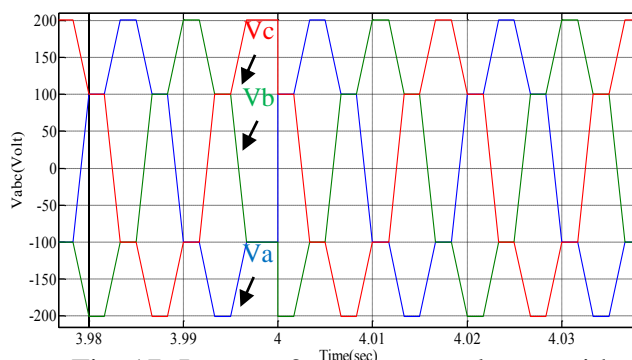

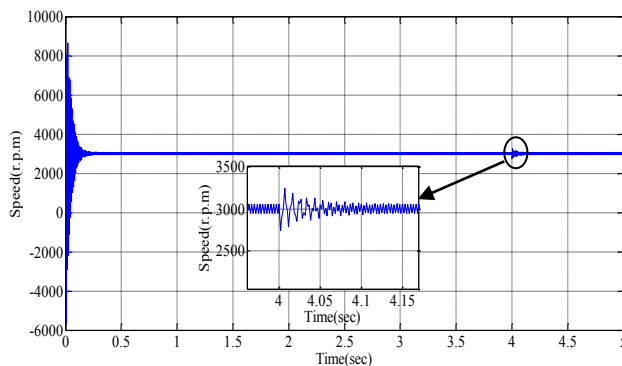Fig. 17 Inverter 3-ph output voltages with load applied on 4sec.

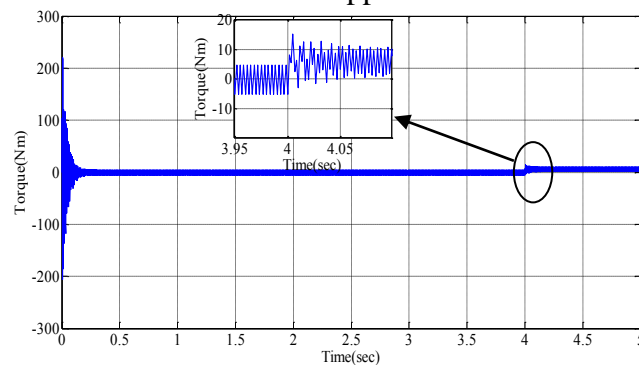Fig.18 PMSM speed without PID controller but with load applied at 4sec.
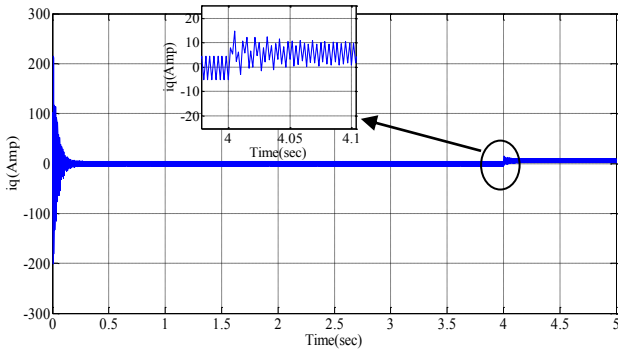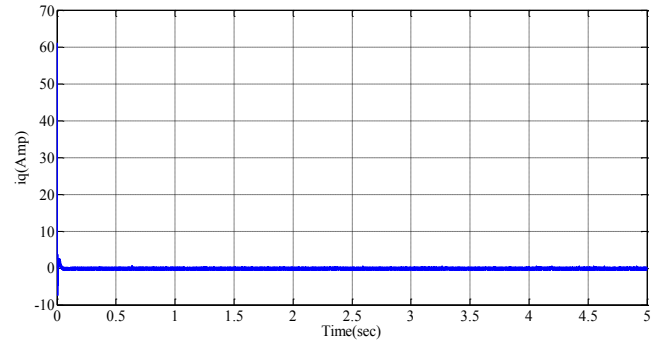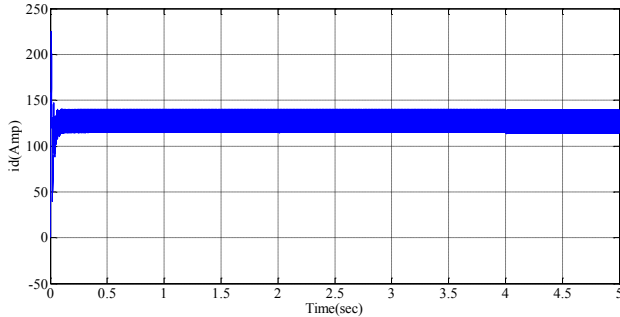

Fig.19 PMSM Torque.
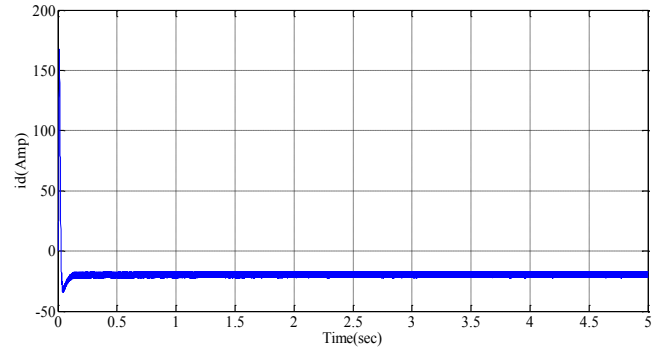
Fig.20 PMSM q- axis current.

Fig.21 PMSM d- axis current.

Figs.(22-25) which show the speed, torque , q-axis and d-axis components of stator current response of the PMSM without applied sudden load when using PID controller and voltage source inverter. The controller gains used are K_P=0.08, K_I=1.2 and K_d=1.1. Its can be shown from speed curves that the transient is omitted and the starting improved by using closed loop PID controller.

Fig.22 PMSM Speed with PID controller.

Fig.23 PMSM Torque.

Fig.24 PMSM q- axis current.

Fig.25 PMSM d- axis current.

The PMSM speed, torque, q-axis and d-axis stator current components waveforms computer simulation results with load torque=9Nm applied at t =0.5sec are shown in Figs.(26-29) for the PID controller which prove that the proposed system can produce very good performance.
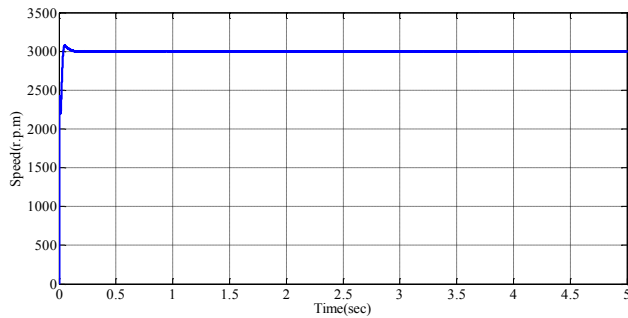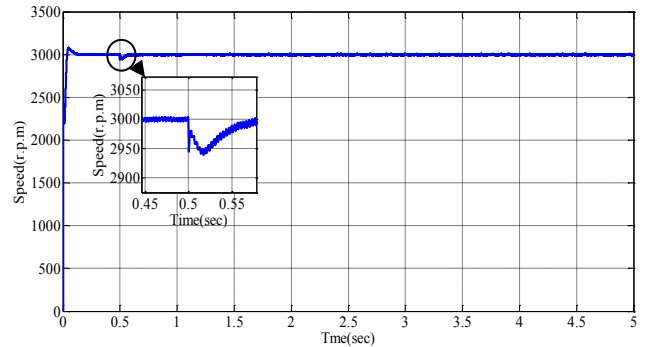

Fig.26 PMSM Speed with PID controller and load applied at 0.5 sec.
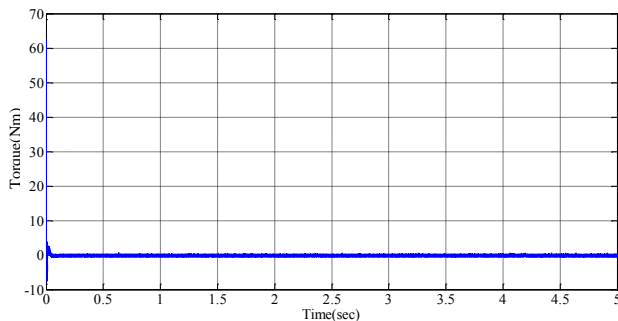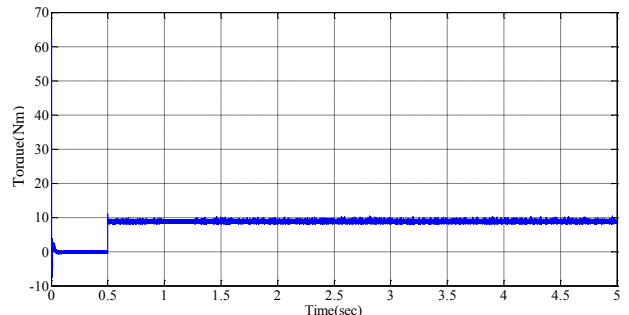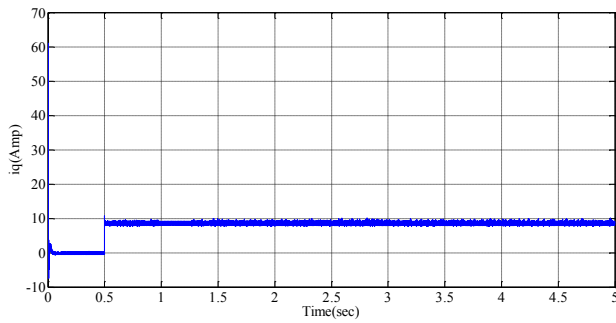

Fig.27 PMSM Torque.
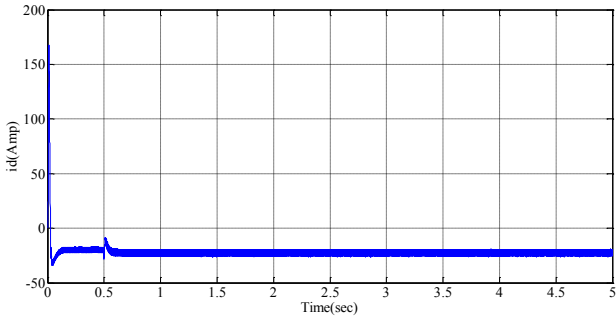
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Fig.28 PMSM q- axis current.

Fig.29 PMSM d- axis current.

Figs.(30&31) show the speed and torque responses of two (master/slave) PMSMs without sudden load application. From these figures, it can be seen that the motors (master/slave) reach final speed at the same value 3000 RPM because the slave motor speed has to follow the speed of the master motor. The controller gains used for controlling two PMSMs are K_P=0.1, K_I=1 and K_d=2.2 for master motor and K_P=5, K_I=9 and K_d=2 for slave motor.
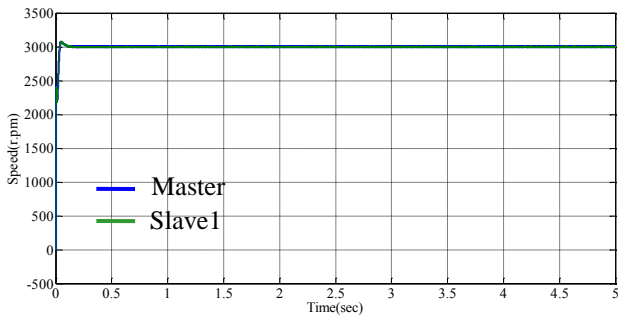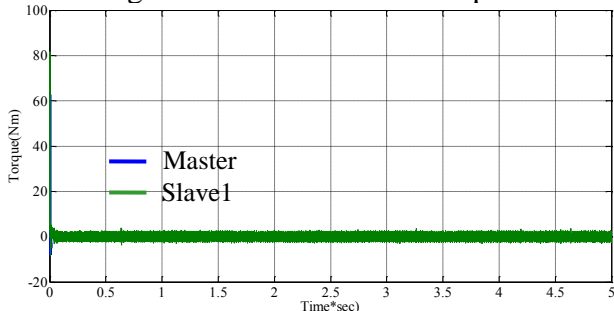

Fig.30 PMSM master/slave speeds

Fig.31 PMSM master/slave torques

Figs.(32&33) show the speed and torque of two (master/slave) PMSMs. At the time of starting master motor running at no load with zero load torque so it is called no load operation but at t=2sec step changed in load from no load 0Nm to a torque of 10Nm is applied on master motor. From these figures, it can be seen that the slave motor tracked any change in master motor speed due to load change.
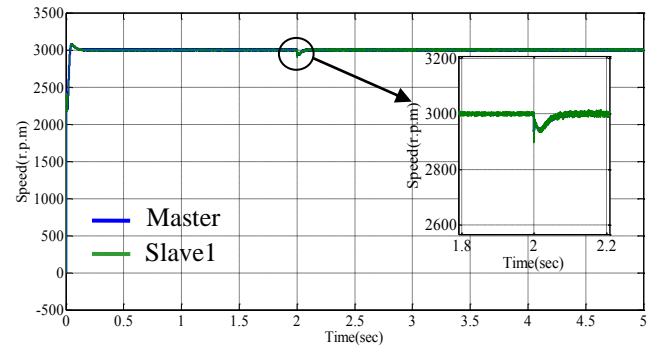
Fig.32 Speed of multi PMSMs with applied load on the master motor only.
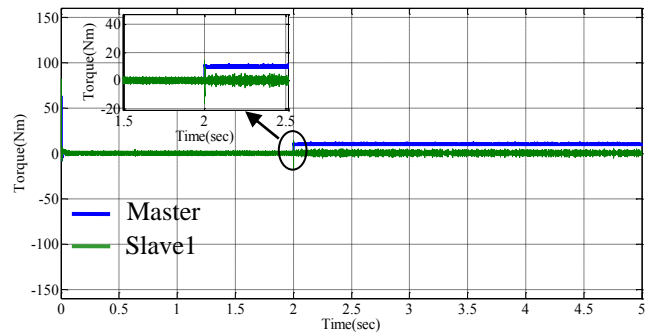
Fig.33 Torque of multi PMSMs with applied load on the master motor.

Figs.(34&35) show the speed and torque waveforms of two (master/slave) PMSMs with 8Nm sudden load applied on master motor at 4sec and another 22Nm sudden load applied on slave motor at 3sec. From fig.23, it can be seen that the slave motor speed recouped its initial speed (master motor speed) with a short period of time (approximately 0.005sec) when sudden load application or removal from slave motor.

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Fig.34 Speed of multi PMSMs with different applied loads on master and slave motors.
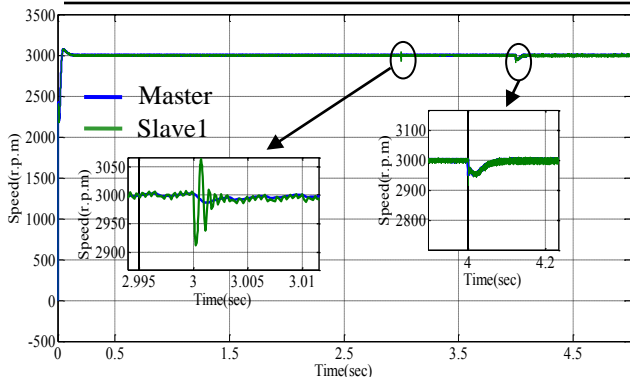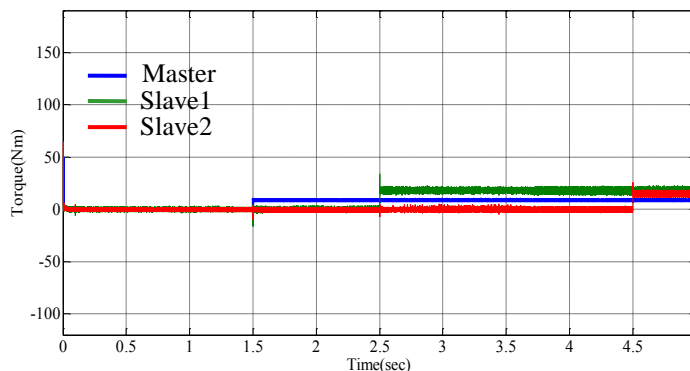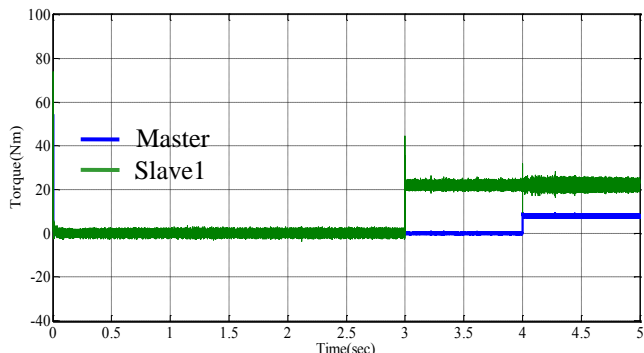

Fig.35 Torque of multi PMSMs with different applied loads on master and slave motors.

Figs.(36&37) show speed and torque characteristics of PID control of multi (master/slaves) PMSMs under different application load values. From fig.36, the sudden load applied on master motor is 9Nm at 1.5sec, on the first slave motor the applied load is 18Nm at 2.5sec and on the second slave the sudden applied load is 16Nm at 4.5sec, it is clear that slaves motors reach their final speed with the load application after very short periods because the slave motors follow the speed of the master motor. The parameters for PID controller of master are K_P=0.07, K_I=0.8,and K_d=2, for slave1 are K_P=5, K_I=8,and K_d=7,and finally for slave2 are K_P=0.8, K_I=13,and K_d=3.

Fig.36 Speed of three PMSMs with different applied loads on master and slaves motors.

Fig.37 Torque of multi PMSMs with different applied loads on master and slaves motors.

Figs.(38&39) present speed and torque characteristics of PID control of three (master/slaves) PMSMs with sudden load 7Nm applied on master motor at 1sec. From fig.38, it is seen that motors (master/slaves) move together to reach the final speed under the load application since the slave motors track the speed of the master motor.
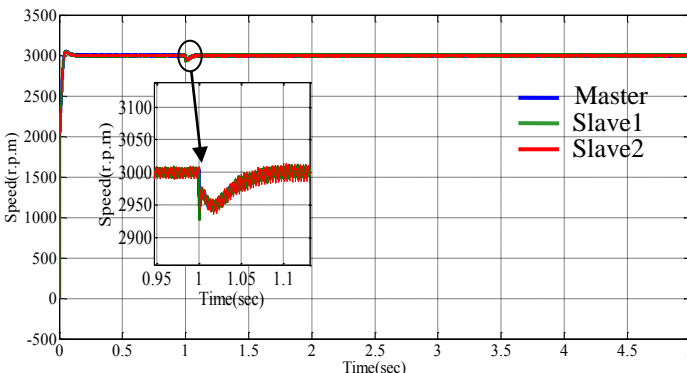

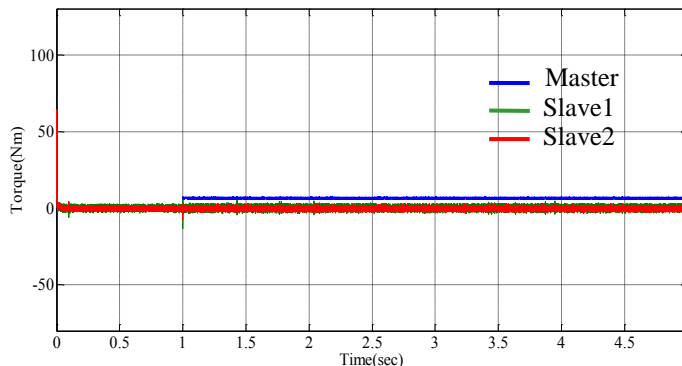Fig.38 Speed of three PMSMs with Load applied on master motor only.

Fig.39 Torque of three PMSMs with Load applied on master motor only.
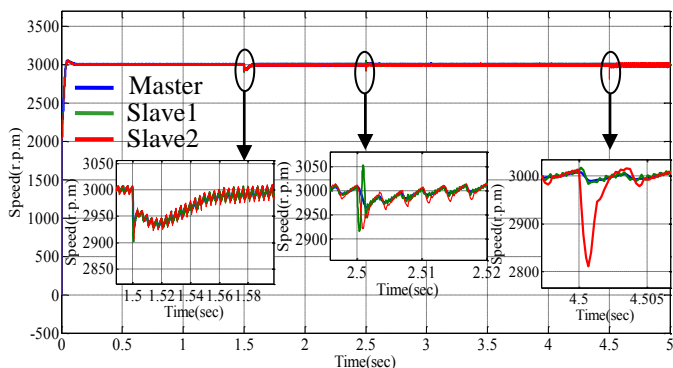
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VIII. CONCLUSION

This paper chiefly proposes simulation dynamic model for closed loop PID controller of multi AC three phase Permanent Magnet Synchronous Motors (PMSMs) (master/slaves) with the aid of MATLAB/Simulink. The model of this proposed system has been presented to control the speed of these motors.

The modeling procedures are described and simulation results are presented.

Also, the voltage source inverter was designed to drive the PMSM. The designed system was tested first for single PMSM, then its tested for multi(master/slaves) PMSMs. For this system, voltage of inverter, torque, speed, d-axis and q-axis of stator current of the PMSM are obtained when the motor is supplied by a three-phase voltage waveforms under different cases of sudden load applications. It is observed from the computer simulation results that the speed responses of master/slave motors are quite good because the PID strategy control the system more effectively with faster dynamic response, shorter setting time, better performance and less steady-state error so this dynamic model able of predicting the machine's behavior for this motor type.

APPENDIX
TABLE I
PMSM parameters

No.	Parameter	Value
1	q-axis stator resistance (R_q)	0.4578Ω
2	d-axis stator resistance (R_d)	0.4578Ω
3	q-axis inductance (L_q)	3.34 mH
4	d-axis inductance (L_d)	3.34 mH
5	Combined Viscous Friction(b)	0Nm/rad/s.
6	Moment of Inertia (J)	$0.001469 Kg.m^2$
7	DC link voltage (V_{dc})	300V.
8	Rotor magnetic flux(pm)	0.171 wb.
9	Number of poles(p)	4

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