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MASTER-SLAVES SPEED SYNCHRONIZATION OF TRIPLE 3-PHASE INDUCTION MOTORS USING PI AND PID CONTROL METHODS

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ABSTRACT

This paper presents two methods used for three closed loop speed controller of Variable-Voltage Variable-Frequency (VVVF) triple 3-phase Induction Motors (IMs) master/slaves system. A dynamic d-q model of a 3- phase IM in state space form and its computer simulation in MATLAB/SIMULINK software package are described. The two different methods of speed control which are used to improve the performance of three IMs drive system are named as conventional PI controller and PID controller. For PID speed controller, simulation results clearly show that the response of the system is superior compared to PI speed controller in terms of rise time, settling time, accuracy and steady state error.

The design, analysis, and speed responses of the system obtained under both controllers have been simulated, studied and compared using MATLAB/Simulink environment for different operating conditions such as sudden change in reference speed and load torque. The simulation results showed good synchronization between the master and the slave IMs with suitable tracking error.

KEYWORDS: Induction Motors (Ims), (Master/Slave), Pi Speed Controller, Pid Speed Controller, Scalar Control Method.

مزامنة سرعة ثلاث محركات حثية ثلاثية الطور(السيد/التوابع) بأستخدام طريقتي التحكم الكسب التكاملي و الكسب التكاملي التفاضلي

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الخلاصة

هذا البحث استعرض طرقتين استخدمتا للسيطرة على سرعة نظام مغلق الحلقة متغير الجهد والتردد لثلاثة محركات حثية ثلاثية الطور(السيد/التوابع). تم تمثيل النموذج الديناميكي D-Q للمحرك الحثي الثلاثي الطور بشكل فضاء الحالة و نتائج المحاكاة له بأستخدام حزمة البرامجيات MATLAB/SIMULINK. طريقتي التحكم بالسرعة اللتين استخدمتا لتحسين اداء نظام سوق ثلاثة محركات حثية تسميان متحكم الكسب التقليدي التكاملي ومتحكم الكسب التكاملي التفاضلي. بدا واضحا من نتائج المحاكاة ان استجاب النظام لمتحكم السرعة التناسبي التكاملي التفاضلي كانت افضل مقارنة لمتحكم التناسب التكاملي من حيث زمن الصعود, زمن الاستقرار, الدقة وخطأ الحالة المستقرة. تصميم, تحليل, استجابات سرع النظام لكلا المتحكمين تمت محاكاتها, دراستها ومقارنتها بأستخدام بيئة MATLAB/SIMULINK لظروف تشغيل مختلفة مثل التغير المفاجئ في السرعة المرجعية وتحميل عزم الدوران .وأظهرت نتائج المحاكاة مزامنة جيدة بين سيد وتابع المحركات الحثية مع تتبع مناسب للخطأ.

1. INTRODUCTION

Induction Motor is became more popular in motion control field for its advantages of low price, ruggedness, simple construction and high dependability. In modern induction motor industrial applications, a challenging problem is that the movement of multiple motors must be controlled in a synchronous manner. Many reasons such as oscillations, incompatible dynamics, and changing of parameters can be damaged the multiple motors system synchronization performance (Dezong Zhao et al. 2009).

Fast and accurate speed responses, quick improvement of speed from load disturbances are some of the important criteria of high performance drive system. The core of algorithm conventional control for induction motor drives were PI/PID control because of the simplicity and stability.

In 2012 Mhaisgawali and Muley presented the simulation result for speed control of one 3-phase induction motor using PID controller (Madhavi L. Mhaisgawali et al.2012).

In 2013 the same authors above compared between the traditional PI and PID controllers at full load condition. MATLAB is used to simulate the system in order to investigate the speed control results of one I.M. with PI, PID controllers and without any controller at full load situation (Madhavi L. Mhaisgawali et al. 2013).

At the same year above, Swati Sikarwar and Amol Barve reviewed the implementation of discrete PI and PID control scheme when applied to model of single I.M. MATLAB environment is used to develop both controllers. A comparison is made between the performance of discrete PI and PID controllers with that of classical controllers in terms of steady state error and rise time (Swati Sikarwar et al. 2013).

At the same year, Ahmed A.M .Emam and the others introduced a new design of a master slave control system. This new design was used for synchronization between the different motors. The principle of the Field Oriented Control (FOC) is explained. PI-FO controllers are designed for two I.Ms. in master slave arrangement (Ahmed A.M .Emam et al. 2013).

In 2014 Vismay Chauhan and Prof. V.P. Patel, proposed several synchronization methods in order for satisfying synchronization speed during deceleration, acceleration and varies in load requires angle and speed synchronization between at least two axes. They are described the Master-Slave, the Relative Coupling Strategy, Bi-axial cross coupled control method and Cross Coupling Technique (Vismay Chauhan et al. 2014).

In this work, one of the induction motors has been used as a master and the others as slaves, the speed of the master motor uses as a reference signal for a close loop control system that controls the speed of the slave motor to follow the speed of the master.

Scalar control method is used for controlling the induction motor to operate it at the steady state, by changing the magnitude and frequency of the supply voltage. This method gives limited speed precision specially in the poor dynamic torque response and small speed range (Ashok Kusagur et al. 2009).

In this work, 3-phase voltage source inverter (VSI) which is carrier based Sinusoidal Pulse Width Modulation (SPWM) is used. SPWM inverter which powered induction motor drive make it possible to control both amplitude and frequency of the voltage applied to the IM under condition of constant V/f ratio. Consequently, PWM inverter is more variable and offer a wide range better efficiency and higher performance when compared to fixed frequency motor drives.

The sinusoidal PWM is better than other PWM techniques because it offers smooth exchange of V/f and removes harmonics in both open and closed loop applications (C.S.Sharma et al. 2013). V/f drives work well on applications in which the load is predictable and does not change quickly, such as fan and pump loads (Frank D. Petruzella 2010).

Several applications used more than one motor to bear the high load (Ahmed A.M. Emam et al. 2013). This paper is concerned with the design of master/slaves control system of three IMs accountable for synchronization between these motors.

The master-slave synchronization control for IM 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 and PID control methods are used for improvement the system’s response.

A comparison between the performance of the multiple IMs system under both controllers is presented by simulation results that verify appropriateness of the approach under various operating situations and provide the fast and robust control.

2. DYNAMIC D-Q MODEL OF 3-PHASE IM

To check the actions of a high performance IM drive, the d-q model of the IM has been used (Aleck W. Leedy, 2013 and Ashish Kamal et al., 2013). The differential equations produced from analysis of the equivalent circuits of the induction motor represented in the rotating reference frame in Fig. 1 can be written as follows:

$$V_{ds} = R_s i_{ds} + \frac{d\lambda_{ds}}{dt} - \omega_e \lambda_{qs} \tag{1}$$

$$V_{qs} = R_s i_{qs} + \frac{d\lambda_{qs}}{dt} + \omega_e \lambda_{ds} \tag{2}$$

$$V_{dr} = 0 = R_r i_{dr} + \frac{d\lambda_{dr}}{dt} - (\omega_e - \omega_r)\lambda_{qr} \tag{3}$$

$$V_{qr} = 0 = R_r i_{qr} + \frac{d\lambda_{qr}}{dt} + (\omega_e - \omega_r)\lambda_{dr} \tag{4}$$

For 3-ph squirrel cage IM, $V_{qr}= V_{dr}= 0$, sub this in rotor voltages eqs. (3) and (4) as shown above.

Where,

d is the direct axis, q is the quadrature axis, V_{ds} is the d-axis stator voltage, V_{qs} is the q-axis stator voltage, V_{dr} is d-axis rotor voltage, V_{qr} is q-axis rotor voltage, ids is the d-axis stator current, iqs is the q-axis stator current, i_{dr} is d-axis rotor current, i_{qr} is q-axis rotor current, R_s is the stator resistance, R_r is the rotor resistance, ω_e is the angular velocity of the reference frame, ω_r is the angular velocity of the rotor, λ_{ds} , λ_{dr}, λ_{qs}, and λ_{qr} are flux linkages.

The d-q stator and rotor currents can be expressed in terms of flux linkages as follows:

$$i_{ds} = \frac{L_r}{L_s L_r - L_m^2}\lambda_{ds} - \frac{L_m}{L_s L_r - L_m^2}\lambda_{dr} \tag{5}$$

$$i_{qs} = \frac{L_r}{L_s L_r - L_m^2}\lambda_{qs} - \frac{L_m}{L_s L_r - L_m^2}\lambda_{qr} \tag{6}$$

$$i_{dr} = \frac{L_s}{L_s L_r - L_m^2}\lambda_{dr} - \frac{L_m}{L_s L_r - L_m^2}\lambda_{ds} \tag{7}$$

$$i_{qr} = \frac{L_s}{L_s L_r - L_m^2}\lambda_{qr} - \frac{L_m}{L_s L_r - L_m^2}\lambda_{qs} \tag{8}$$

where L_r is the rotor self inductance, L_s is the stator self inductance, L_m is the magnetizing inductance. The axis transformation is applied to transfer the 3-phase parameters (voltage, current and flux) to two axis frame called (d-q axis frame). The development torque produced in d-q components can be established as:

$$T_e = \frac{3}{2}\frac{P}{2}(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \tag{9}$$

The torque and rotor speed are related by:

$$T_e = T_L + (\frac{2}{P})J\frac{d\omega_r}{dt} \tag{10}$$

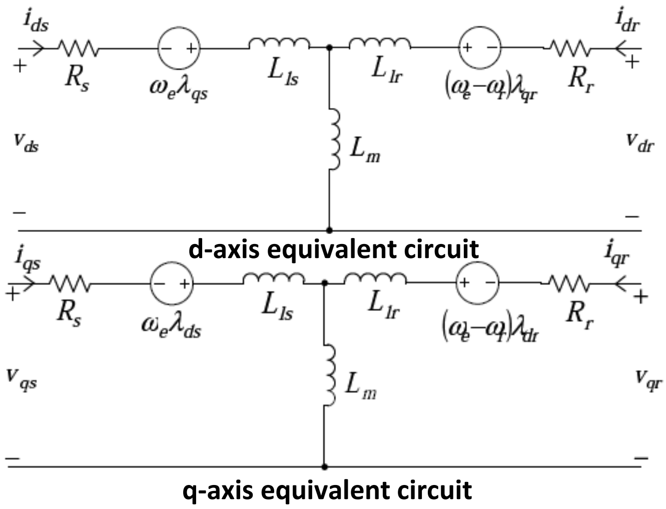

Fig. 1. d-q equivalent circuits of 3-Ph IM.

Where P: no. of poles; J= rotor inertia; T_L= load torque.

The self inductances can be expressed as:

$$L_s = L_m + L_{ls} \tag{9}$$

and

$$L_r = L_m + L_{lr} \tag{10}$$

Where L_{lr} is the rotor leakage inductance, and L_{ls} is the stator leakage inductance (Aleck W. Leedy, 2013).

The Simulink model of 3-ph IM can be constructed by creating Simulink subsystems using eqs. (1-4), (9&10) and (13-16) below.

The Matlab/Simulink implemented model IM illustrated in Fig. 2. Six main subsystems block contained in IM subsystem block see Figs. 3-8.

Equations (5-8) can be more simplified to (13-16) and simulated in Matlab software as shown in Figs. 4 and 5.

$$i_{ds} = \frac{1}{(L_s - (L_m^2 / L_r))}(\lambda_{ds} - \frac{L_m}{L_r}\lambda_{dr}) \tag{13}$$

$$i_{dr} = \frac{1}{(L_r - (L_m^2 / L_s))}(\lambda_{dr} - \frac{L_m}{L_s}\lambda_{ds}) \tag{14}$$

$$i_{qs} = \frac{1}{(L_s - (L_m^2 / L_r))}(\lambda_{qs} - \frac{L_m}{L_r}\lambda_{qr}) \tag{15}$$

$$i_{qr} = \frac{1}{(L_r - (L_m^2 / L_s))}(\lambda_{qr} - \frac{L_m}{L_s}\lambda_{qs}) \tag{16}$$

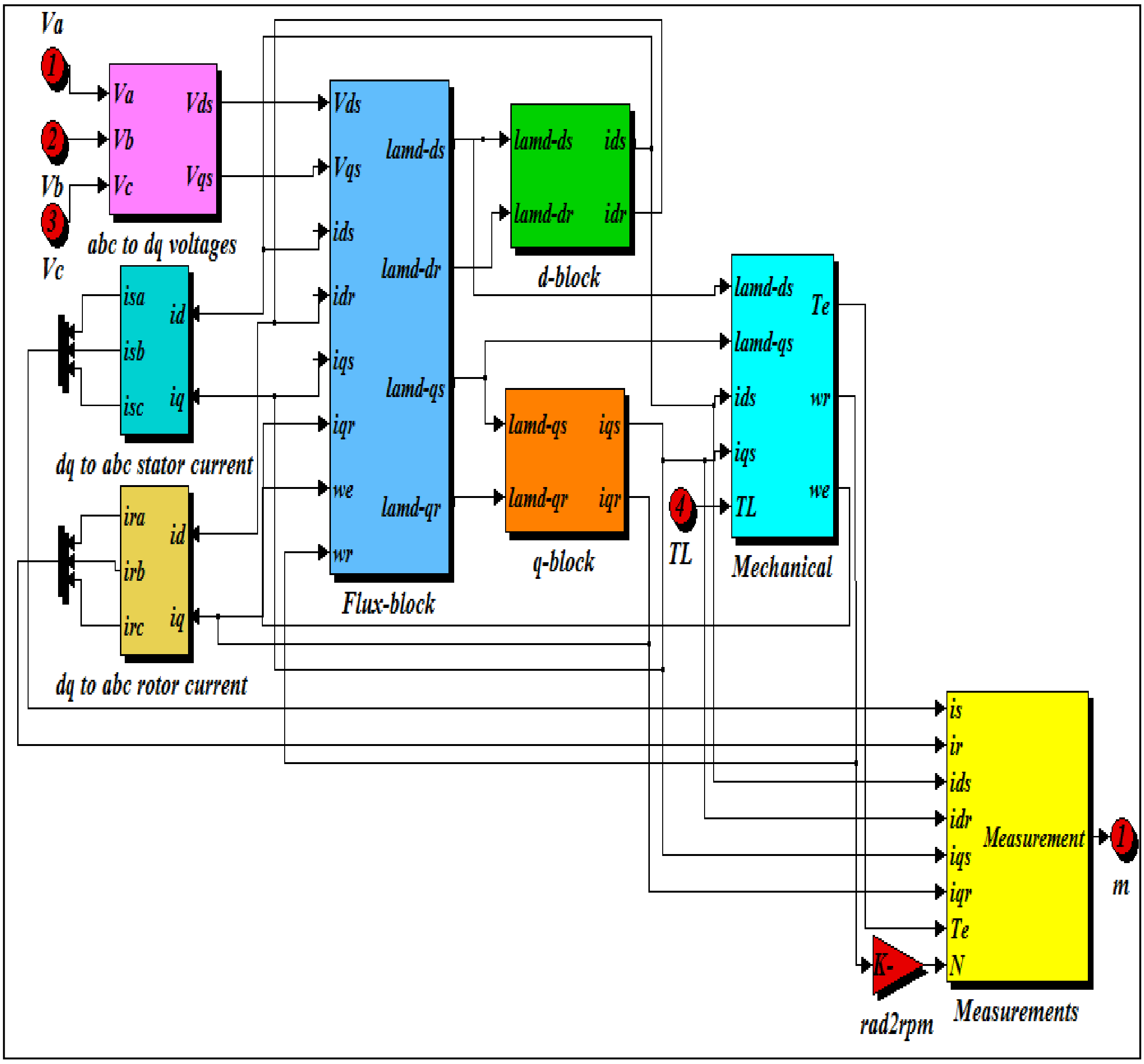

Fig. 2. Implemented simulink model of 3-Ph I.M.

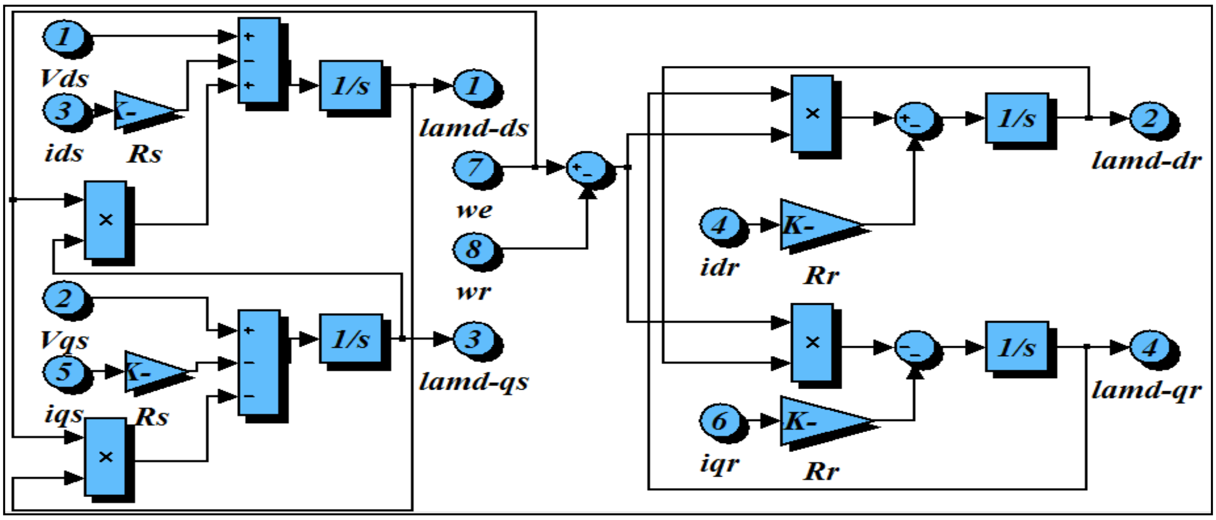

Fig. 3. Simulink model of flux block.

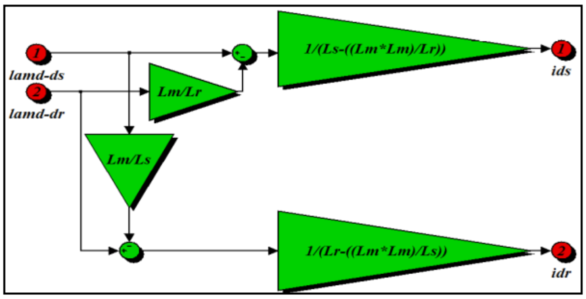

Fig. 4. Simulink model of d- axis currents block.

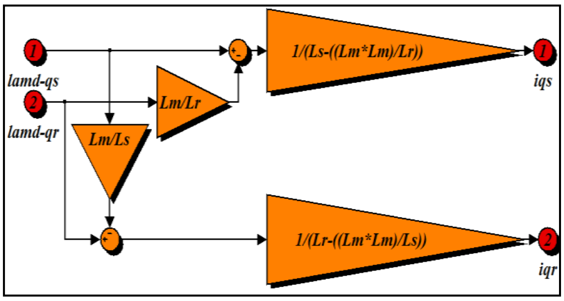

Fig. 5. Simulink model of q-axis currents block.

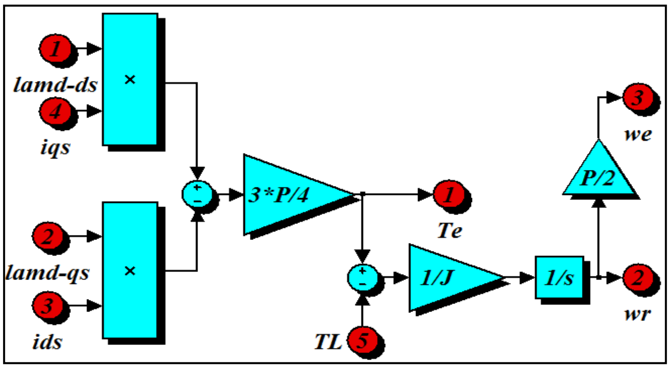

Fig. 6. Simulink model of mechanical block.

The current variables can be found as eqn. (17) below:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -0.5 & -\dfrac{\sqrt{3}}{2} \\ -0.5 & \dfrac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} \tag{17}$$

Figs. 7 and 8 show the stator and rotor currents converting from two to three phase according eqn.(17).

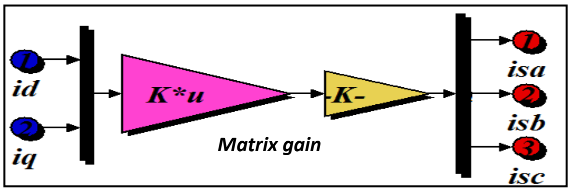

Fig. 7. Simulink model of dq2abc stator current block.

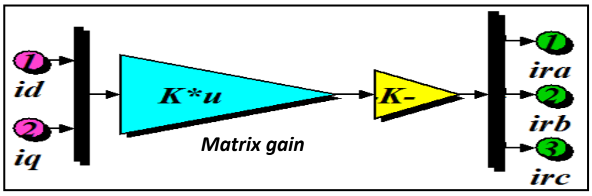

Fig. 8. Simulink model of dq2abc rotor current block.

3. VOLTAGE SOURCE SPWM INVERTER

PMW technology used for reducing the inverter's size and harmonics restricted in the output voltage. To produce the required voltage to feed the IM, Sinusoidal Pulse Width Modulation (SPWM) technique is used. This method is gradually more used for AC drives. In general, the gating signals of SPWM three output legs generated by comparing a constant amplitude and frequency triangular carrier signal, with 3-phase sinusoidal signals called "reference signals", which has variable amplitude and frequency to get the desired output voltage, this comparison leads to generate a sequence of variable width pulses used to gating 3-Ph VSI (C.S.Sharma et al., 2013). Fig. 9. illustrates the principles of SPWM.

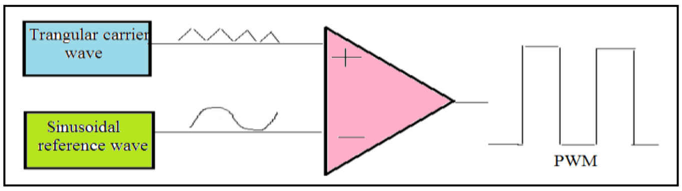

Fig. 9. Sinusoidal Pulse Width Modulation Technique.

The inverter model is represented by the relationship between the control logic signals (S_a, S_b, S_c) and output phase voltages (V_a, V_b, V_c) to create the output voltage as the following eqns. (Naseeb Khatoon et al., 2013 and A. El Shahat et al., 2010).

$$
\begin{aligned}
V_a &= V_{dc}.(2S_a - S_b - S_c)/3) \\
V_b &= V_{dc}.(2S_b - S_a - S_c)/3) \\
V_c &= V_{dc}.(2S_c - S_a - S_b)/3)
\end{aligned}
\tag{18}
$$

The simulink model of this VSI using eqns. (18) which feeding by SPWM signals is shown in Fig. 10.

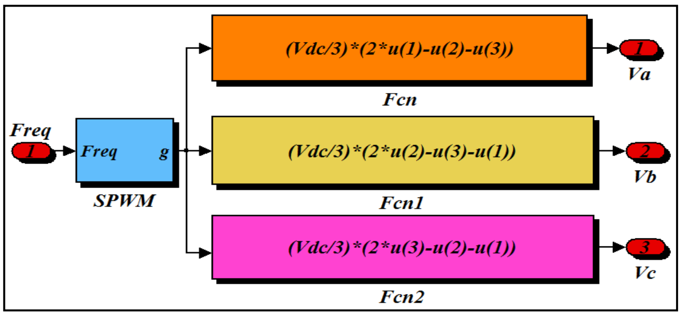

Fig.10 Simulink model of 3-ph SPWM VSI block.

4. SCALAR CONTROL METHOD

The Volt/Hertz control is basically a scalar control technique where only the magnitudes of the control variables are varied simultaneously (in this case, voltage and frequency of stator supply voltage). This technology is the most economical and popular method used in industrial applications as shown in Fig. 11. In variable-speed applications in which a small variation of motor speed with loading is permissible, scalar control scheme can produce satisfactory performance. Scalar control strategy controls shaft speed by changing the voltage and frequency of the signal powering 3-Ph VSI which feed the induction motor. Volts per hertz control in its easiest form takes a speed reference command from an external source and varies the voltage and frequency applied to the motor. The voltage and frequency are changed in the same ratio to keep the air gap flux approximately constant according to eqn. (19).

$$\phi = \frac{V_m}{K\omega} = \frac{V_m}{K' f} \tag{19}$$

This type of control may be executed either in open loop or in closed loop (Lina J., 2012 and Pabitra K. Behera et a1., 2014).

Where:

V_m is the induced EMF, ω is the speed, K and K' are constants, and f is the frequency. In this paper an open loop V/f control method has been used. For this strategy, feedback signals are not required. This type of motor control has the advantages of simple implementation, inexpensive and protection against errors of feedback signals.

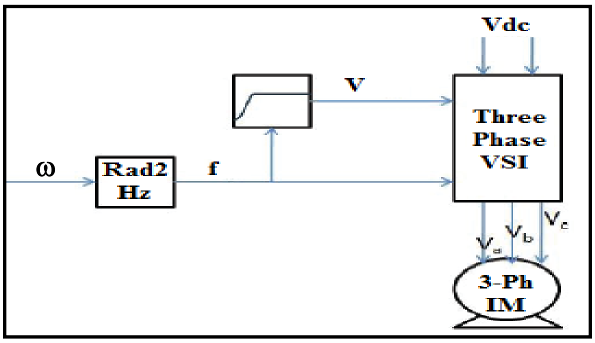

Fig. 11. Block diagram of the open loop V/f control for I.M.

The simulation structure of the open loop V/f control method and SPWM are represented in Fig. 12.

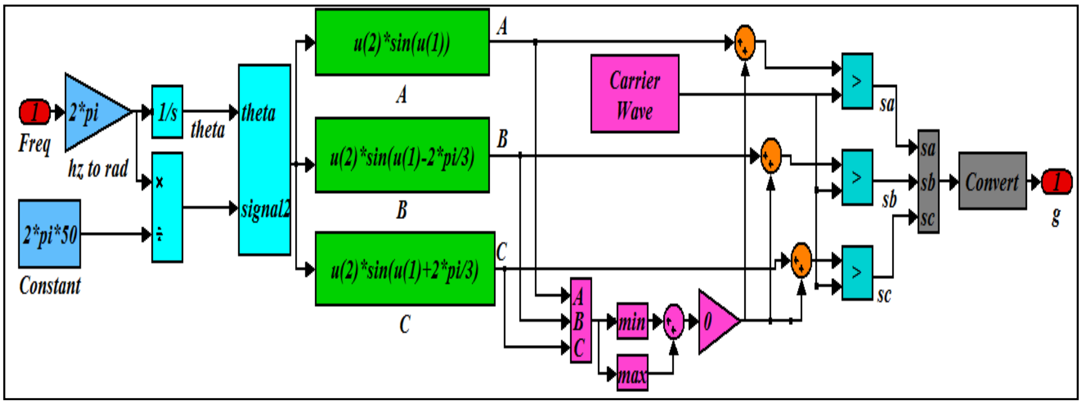

Fig. 12. Internal of SPWM simulink model block.

5. CLASSICAL MASTER/SLAVES MOTORS SYSTEM

For master-slaves motors synchronization control system, one of induction motors is selected as a master motor, the other motors are selected as slaves motors, the master I.M. output speed will be as the speed reference value for the slave I.M. So it has been concluded that any speed change or load variation added to the master motor will be reflected on the slave motor, but any disturbances from slave motor cannot feedback to the master motor. Multi induction motors synchronization control system is shown in Fig. 13 (Ahmed A.M. Emam et al. 2013).

Where: N_r is the reference speed and N_m is the motor actual speed.

To make the synchronization error as small as possible, the master-slave technique is used by assuming that the slaves motors are tracked the master one immediately. Electronic synchronization is recommended recently, because it provides certain merits in terms of reliability and flexibility (Pratiksha Shingade et al. 2014).

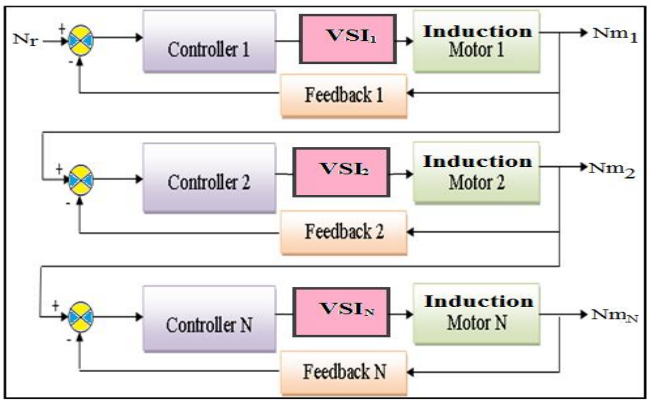

Fig. 13. Master-slaves I.M. synchronization control system.

6. PI SPEED CONTROL OF I.M.

(Proportional Integral) PI controllers are the feedback controller which reduces the system sensitivity to changes in the surrounding environment and small changes in the system. They offer the easiest and yet most efficient solution to many real-world control problem. It is a type of feedback controller whose output, that is a control variable (CV), is generally based on the error e(t), between user reference speed (N_{ref}) and measured actual speed (N) after converting both of them into frequencies. Each element of the PI controller refers to the particular action taken on the error. The PI controller 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 (Jeyalakshmi et al. 2010).

$$u(t) = K_p \times e(t) + K_i \times \int e(t)dt \quad (20)$$

Where,

K_P is a proportional gain

K_i is an integral constant.

Fig. 14 shows the simulink model of PI controller. A complete PI speed control based 3-ph I.M. drive circuit is shown in Fig. 15.

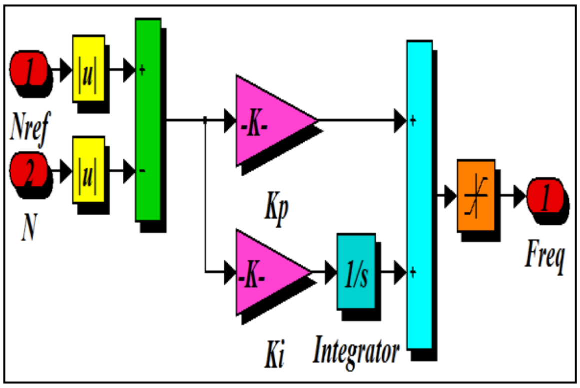

Fig. 14. Simulink model of PI Controller.

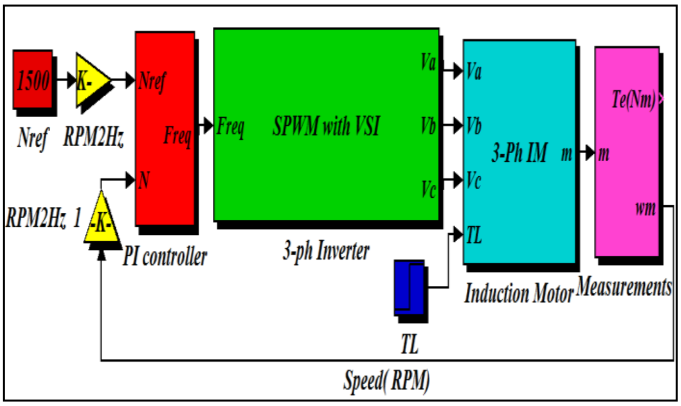

Fig. 15. Simulink model of I.M. with PI controller.

7. PID SPEED CONTROL OF I.M.

The classical Proportional-Integral-Derivative, PID, controller is widely used in manufacturing control system. PID controller has all the essential dynamics: (P) controller gain is used for removing oscillations, (I) controller gain is used for raising in control signal to lead error towards zero (D) controller gain is used for high-speed response. The output of PID controller consists of three terms the error signal, the error integral and the error derivative according to the following expression.

$$u(t) = K_p \times e(t) + K_i \times \int e(t)dt + K_d \frac{de(t)}{dt} \tag{21}$$

Fig. 16 shows the simulink model PID controller. A complete PID speed control based 3-ph I.M. drive circuit is shown in Fig.17.

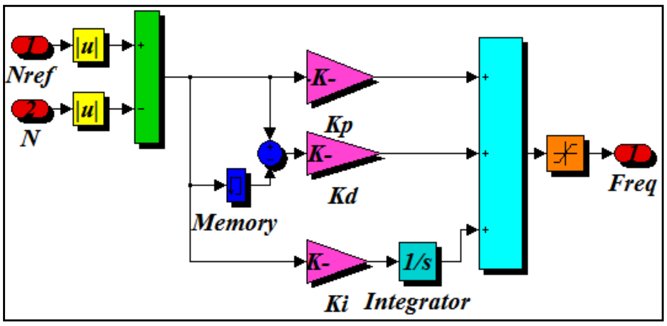

Fig. 16. Simulink model of PID Controller.

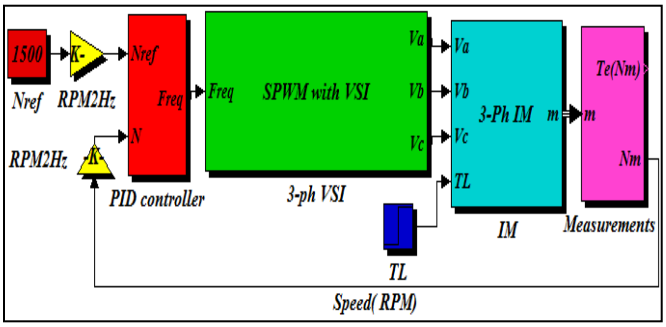

Fig. 17. Simulink model of PID Controller with I.M.

8. SPEED CONTROLLER OF MASTER/SLAVE INDUCTION MOTORS

The model of the speed controlling system as shown in Fig. 18 consists of two induction motors each driving a different load and feeding from separated 3-ph VSI. One motor is the master and the other motor is the slave. The master motor directly executes the desired trajectories. The encoder of the master motor is also used as the master encoder for the parallel slave motor. Thus, in essence, the slave motor simply follows the motion of the master motor.

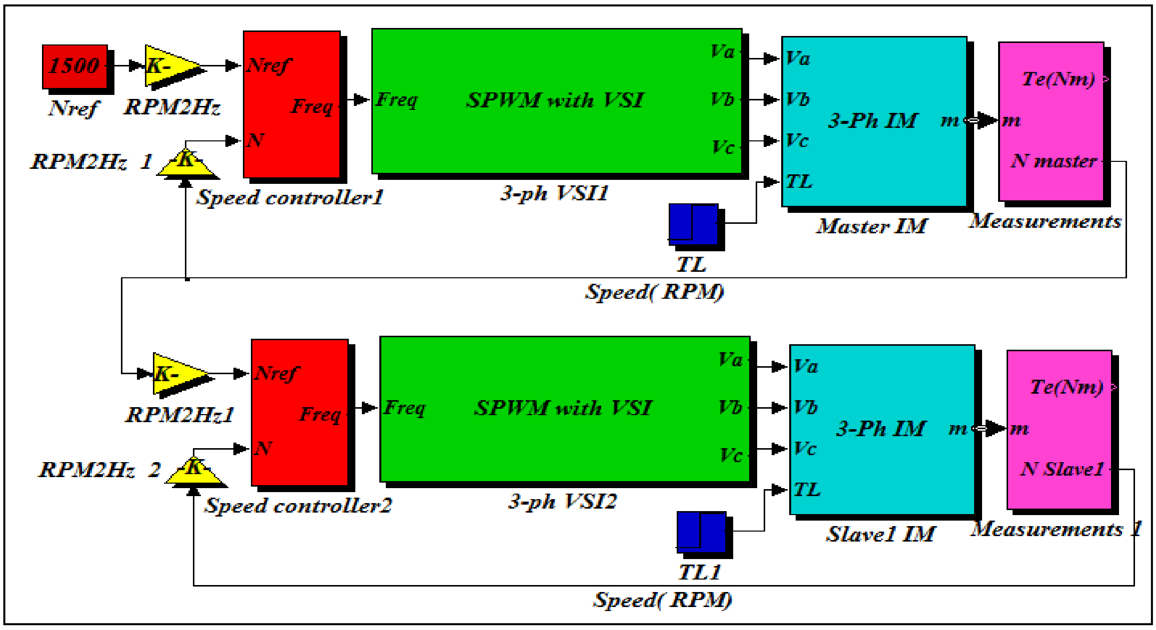

Fig. 18. Simulink model of speed controller of master/slave I.Ms.

9. SPEED CONTROLLER OF MULTI THREE-PHASE INDUCTION MOTORS

Three induction motors (first master and others slaves) are shown in Fig. 19. These motors are powered by separate VSIs. The master motor is the reference motor which followed by one or more slave motors.

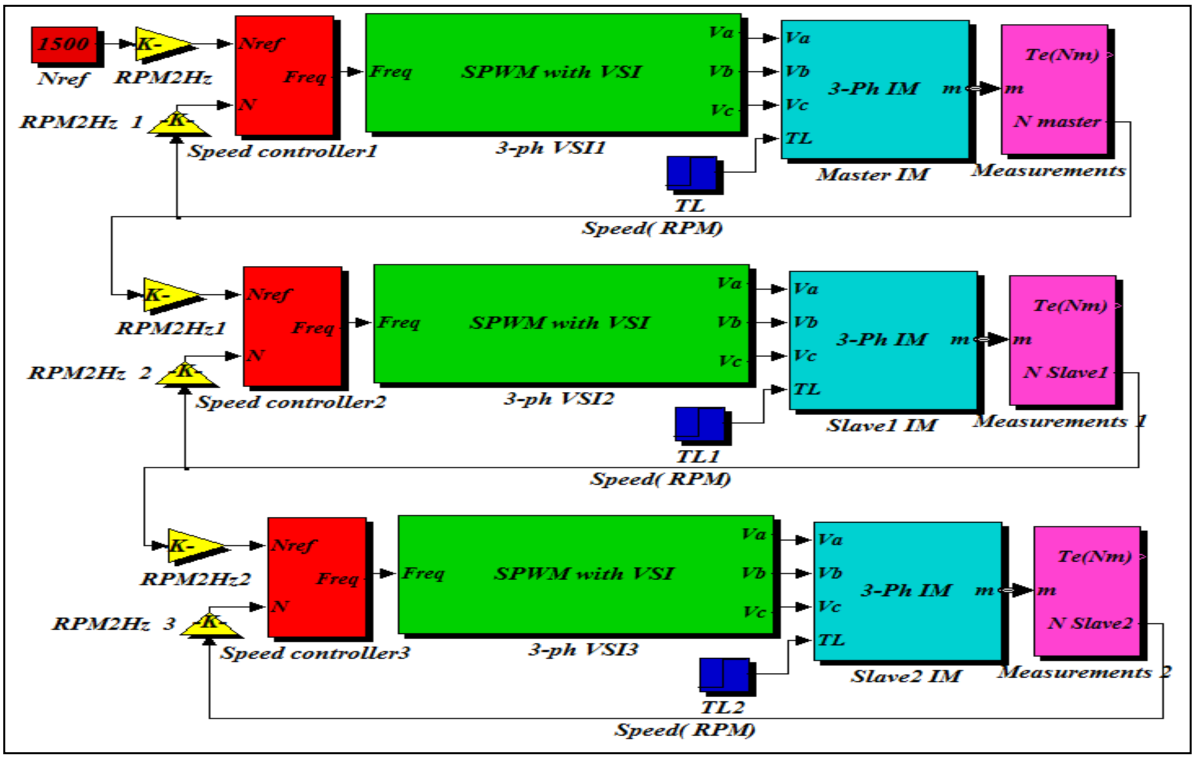

Fig. 19. Implemented simulink model of speed controller of Multi I.Ms.

10. SIMULATION RESULTS AND DISCUSSIONS

In this work a PI controller then PID controller are used to improve the multi I.Ms speed responses. The nominal parameters of the I.M. are listed in Table 1.

The proposed system was subjected to different load conditions. The I.Ms were operated for different values of reference speed under no-load condition and change in load conditions for master and slave motors. The values of the controllers gains are obtained by using trial and error method.

Figs. 20 and 21 show the output of three phase I.M. speed and electromagnetic torque without applied load and without any controller. While Figs. 22 and 23 show the same variables under 2Nm sudden load applied but without controller. When a load is applied on the machine at 5 second, the electromagnetic speed and torque are plotted against time. It can be seen that when the load is applied the speed drops down its rated value 1500 rpm and cannot builds up again to its rated value.

Table 1 I.M. Parameters

Parameter	Value
Stator Resistance R_s	10.1Ω
Rated Voltage V_{dc}	220V
Stator Inductance L_s	0.833 H
Rotor Resistance R_r	9.8546Ω
Rotor Inductance L_r	0.833 H
Rotor Inertia J	0.0098 $Kg.m^2$
Mutual Inductance L_m	0.7827 H
Number of Poles p	4
Frequency f	50 Hz

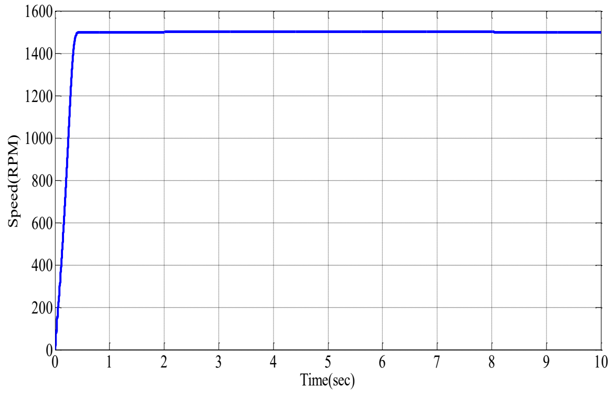

Fig. 20. 3-ph IM speed without load and controller.

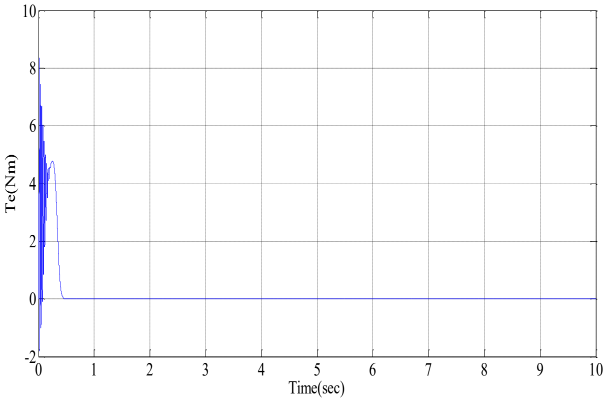

Fig. 21. 3-ph IM Torque without load and controller.

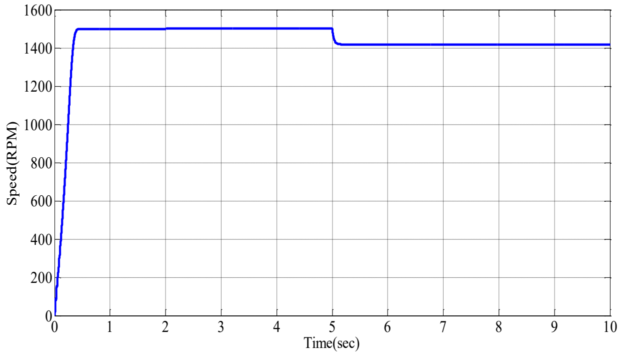

Fig. 22. 3-ph IM speed without load and controller.

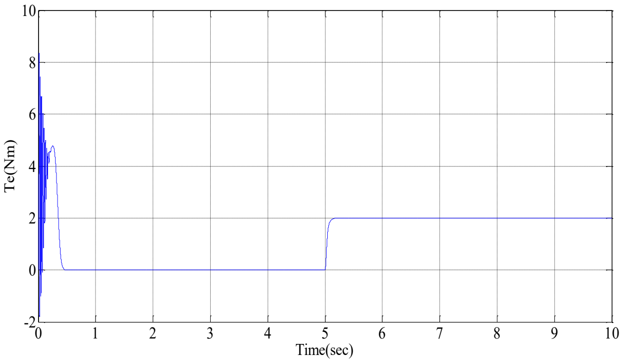

Fig. 23. 3-ph IM torque without load and controller.

In Figs. 24 and 25 the speed and torque response of the 3-ph IM are shown when the motor operated with reference speed 1500 rpm under no load condition when using closed loop PI controller. The controller gains used are K_P=0.1 and K_I=2. Its can be shown from speed curves that the PI controller can control the IM speed and torque. Figs. 24 and 25 prove that the proposed system can produce very good dynamic and static performance.

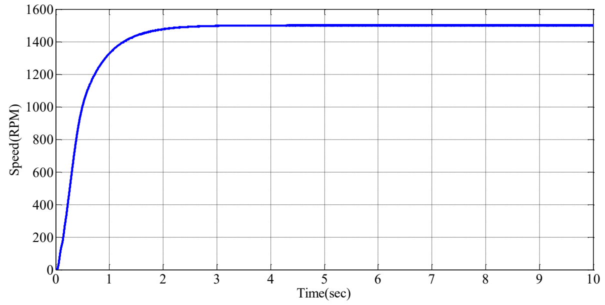

Fig. 24. 3-ph IM speed without applied load but with PI controller.

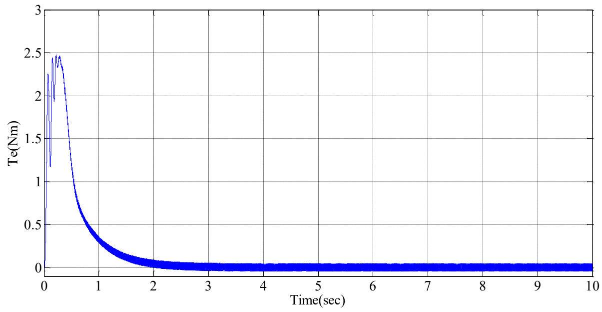

Fig. 25. 3-ph IM torque without applied load but with PI controller.

The developed electromagnetic torque waveform is shown in Fig. 26 for the PI controller and Fig. 27 shows the computer simulation results of the rotor speed with 2Nm load torque applied and removed. The load is applied during t =4sec to t=8sec. The speed response of PI VVVF controller have the little fluctuation slope of rise time**.** An approximately 1.9 sec for rise time. The speed response is robust to variations in load**.** When sudden load applied at 4 second of time the speed response have fall then return to its value 1500 rpm and then rise up above its value when the load is removed at 8 sec.

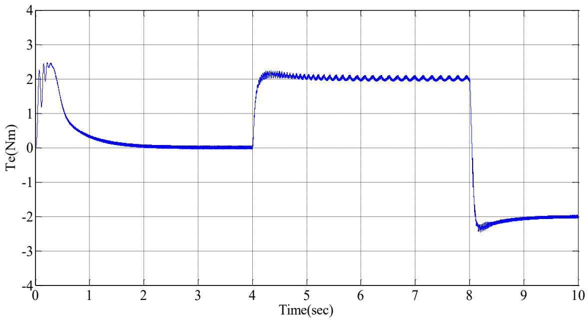

Fig. 26. 3-ph IM torque with sudden load applied and removed under PI controller.

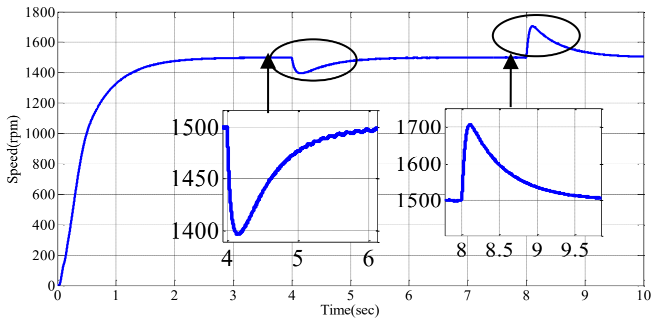

Fig. 27. 3-ph IM rotor speed with sudden load applied and removed under PI controller.

At t=0, the motor is stand still. When the moment supply is given, the motor reaches its nominal speed gradually. The load torque is initially kept zero and then at time t=3sec, the load torque is made 2 Nm. By trial and error method, the PID gains KP, KI and KD selected as (0.08, 3.5 and 1.4) respectively. The operation performance under different reference speed commands;

800 rpm then 1100 rpm at 5 sec are shown in Fig. 28. From this figure, it can be noticed that the rotor speed decreases the command value under the sudden load 2Nm applied at 3sec by an overshoot value. Then, it returns to its value due to the PID controller because of the control signal went up to compensate the loss of speed. The rise time of the rotor speeds until reaches the steady state approximately equal to (0.5 sec.). There is a small deviation of air gap flux under speed deviation steps, which causes torque variation as shown in Fig. 29.

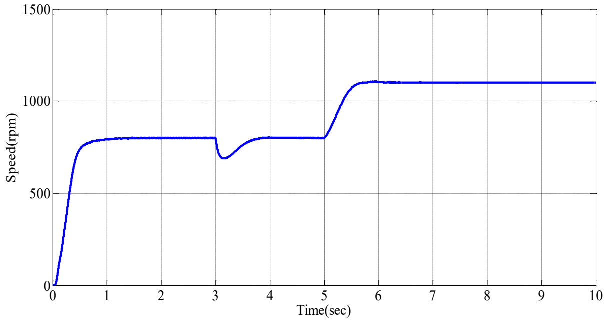

Fig. 28. 3-ph IM rotor speed with different reference speed commands and with sudden load applied under PID controller.

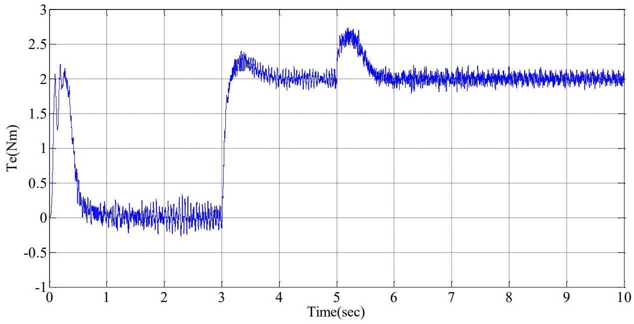

Fig. 29. 3-ph IM torque with different reference speed commands and with sudden load applied under PID controller.

For comparison, the following simulation tests show the speed and torque responses respectively of the system while using PID and PI for various reference speed, applied and removed load.

In Fig. 30, multi reference speeds (700, 1200 and 850 rpm) were used with load applied at time = 3 s and removed at time = 12 s. As noticed in this figure, the actual speed went down after each load applying, while both PI and PID showed a good response to this change. It is clear from the figure that PID showed faster response in both rise time and settling time compared with PI response for multistep speed input. As a result, PID showed better performance compared with PI controller. PID also showed the ability to control speed of the

3-ph IM and provide an accurate and fast response with fairly no overshoot and no steady state error. Fig. 31 shows the IM developed torque under the same conditions above.

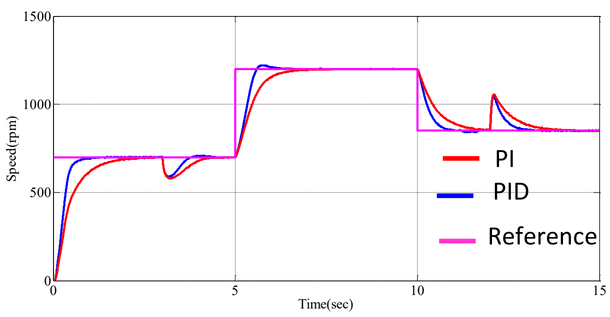

Fig. 30. Speed response comparison for sudden change in load and reference speed for single IM.

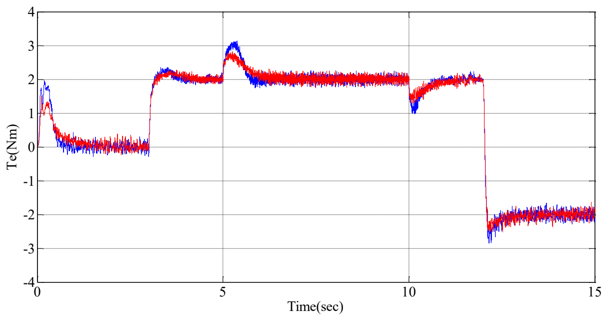

Fig. 31. Torque comparison for sudden change in load and reference speed for single IM.

Fig. 32 shows the speed response of master/slave IMs. From this figure, it can be seen that both motors reach final speed at the same value because that the slave motor speed has to track the speed of the master motor. The controllers gains used for master motor are K_P=0.1 and K_I=2 and for slave motor are K_P=7 and K_I=160. Multi reference speeds (1500, 950 and 1300 rpm) were used with load applied on master motor at time = 2s and on slave motor at time = 5s. The slave speed recouped its initial speed (master motor speed) in load application. The slave motor followed any change in master motor speed due to load change but not vice versa. Fig. 33 shows the torque profile under the same above conditions.

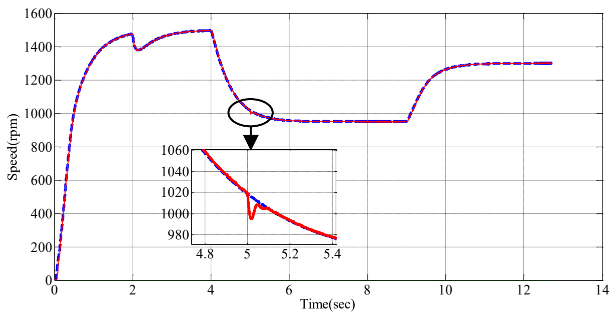

Fig. 32. Rotor speed of multi motors at different reference speed and applied load on the master and slave motors with PI controller.

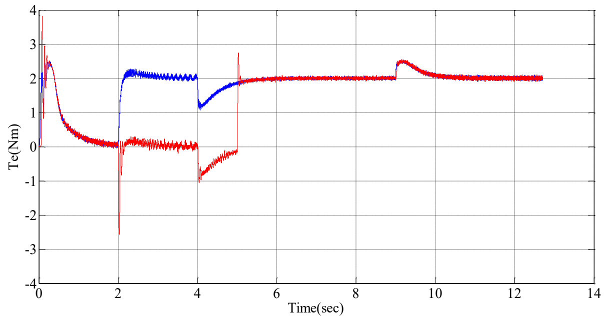

Fig. 33. 3-ph master/slave IMs torques profile.

Fig. 34 shows the computer simulation results with three-step changes in speed command signal under PID controller. The first step change is from 800 r.p.m to 1100 r.p.m. The master and slave speeds move together to final speed with sudden load of 2Nm applied on master motor at 2sec. The second step change is from 1100 r.p.m to 1500 r.p.m with sudden load 2Nm applied on slave motor at 5sec and removed at 7sec. The master/slave speed synchronization is reached after each vary in load application condition. While the third step change at 1500 r.p.m the speed responses of the master/slave motors are identical. The controllers gains used for master motor are K_P=0.08 K_I=3.3 and K_D=1.4 and for slave motor are K_P=15, K_I=60 and K_D=10. Fig. 35 shows both IMs developed torques under the same conditions above.

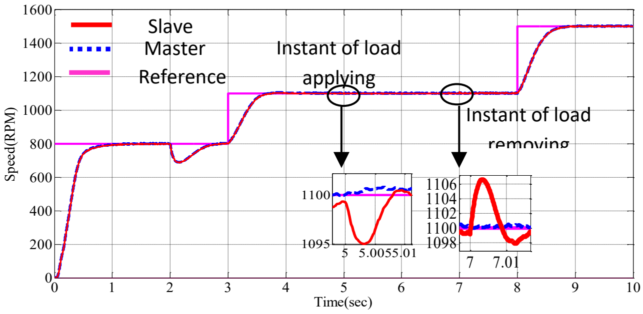

Fig. 34. Rotor speed of multi motors at different reference speed and applied load on the master and slave motors with PID controller.

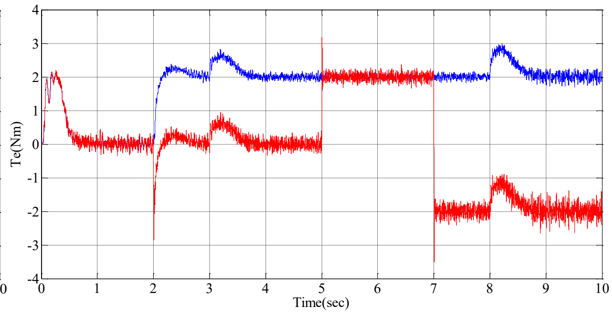

Fig. 35. Master/slave IMs torques profile under PID controllers.

Fig. 36 shows a comparison of two IMs (Master/slave) system behavior operated with reference speed 1500 rpm (with PI and with PID controllers) while applying load T_L=2Nm at time = 2 sec on both master motors under PI and PID controllers and another load 2Nm at time = 5sec on slave motor under PID controller. At 7 sec, a sudden load 2Nm was removed from slave motor under PID controller and applied on slave motor with PI controller.

As noticed in the this figure, the actual speed went down after applying each load, and up after load removing then it's return to the required value so both PI and PID obtained an excellent performance to this change. PID controller provided rapidly reaction in both rise time and settling time compared with PI reaction. So, PID controller has the best response than PI controller because that it's highly improved the speed tracking step response.

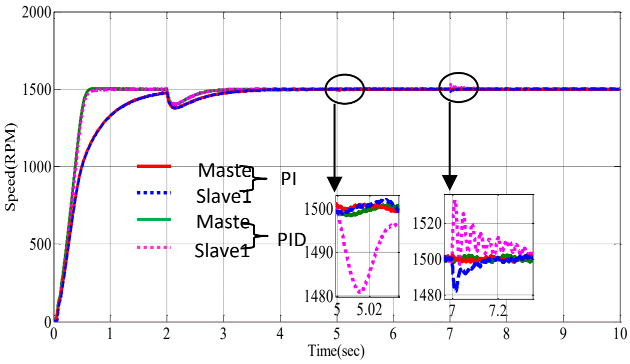

Fig. 36. Speed response comparison for sudden change in load for two IMs.

Fig. 37 shows multi (master/two slaves) IMs system characteristics under PID controller where multi reference speeds (1300, 600 and 1000 rpm) were used. In which, at t=2 seconds, a 2 Nm load torque step change is applied on master IM. The same value of load applied at t=6 sec on slave2 motor and T_L=1Nm applied on slave1 motor. This controller gains which used for controlling three IMs are K_P=0.08, K_D=1.4 and K_I=3.5 for master motor, K_P=250, K_D=20 and

K_I=75 for slave1 motor and K_P=250, K_D=20 and K_I=75 for slave2 motor. It's obvious from this figure that the sudden load change on master IM reflected on the two IMs slaves, but the sudden load change on both slave1 and slave2 motor never affect the master motor.

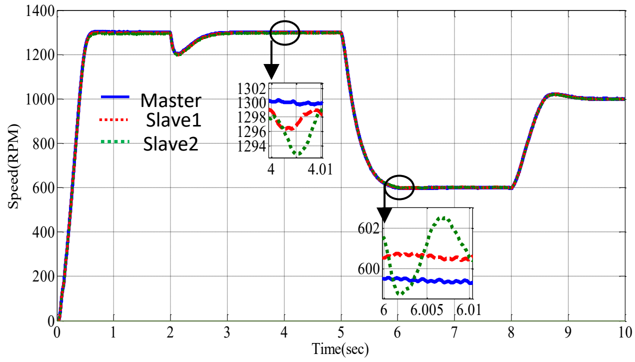

Fig. 37. Speed of three IMs under PID controller with load and reference speed change condition.

Fig. 38 shows speed characteristics for PI control of multi 3-phase IMs. From this figure, it is clear that motors (master/two slaves) move together to reach the final speed since the slave motors track the speed of the master motor. In this figure, the parameters for PI controller of slave1 are KP=0.1, KI=2, slave2 are KP =10, KI=150 and slave3 are KP=7, KI=170. At t=4.5 sec a 2 Nm load torque step change is applied on master IM, it is clear that the two slaves motor followed the master motor, the same value of load applied at t=6.5 sec on slave1 motor so the second slave followed the first one and T_L=2Nm applied on slave2 motor at t=8 sec. It is obvious from Fig. 38 that the sudden load change on master IM reflected on the two IMs slaves, but the sudden load change on the slave motors never affect the master motor.

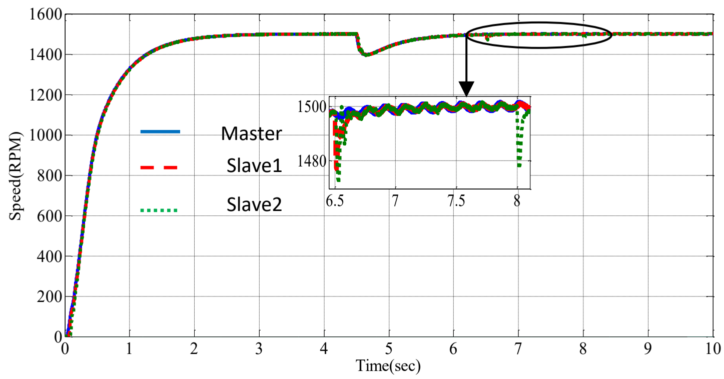

Fig. 38. Speed of three IMs under PI controller with load change condition.

In Fig. 39, a comparison has been done between the speed response of three IMs operated with conventional PI controller under the following load conditions (T_L=2Nm applied on master motor at t=2sec then the same value applied on slave1 at t= 6.5 sec and on slave2 at t=8 sec), and with PID controller with sudden change in load applied to the master motor from no-load to 2 Nm at 2 sec and the same value applied on both slaves at t=5 sec but removed from slave2 at t=7 sec. As shown in speed graph, controller obtained with PID control reached to the desired reference speed 1500 rpm 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.

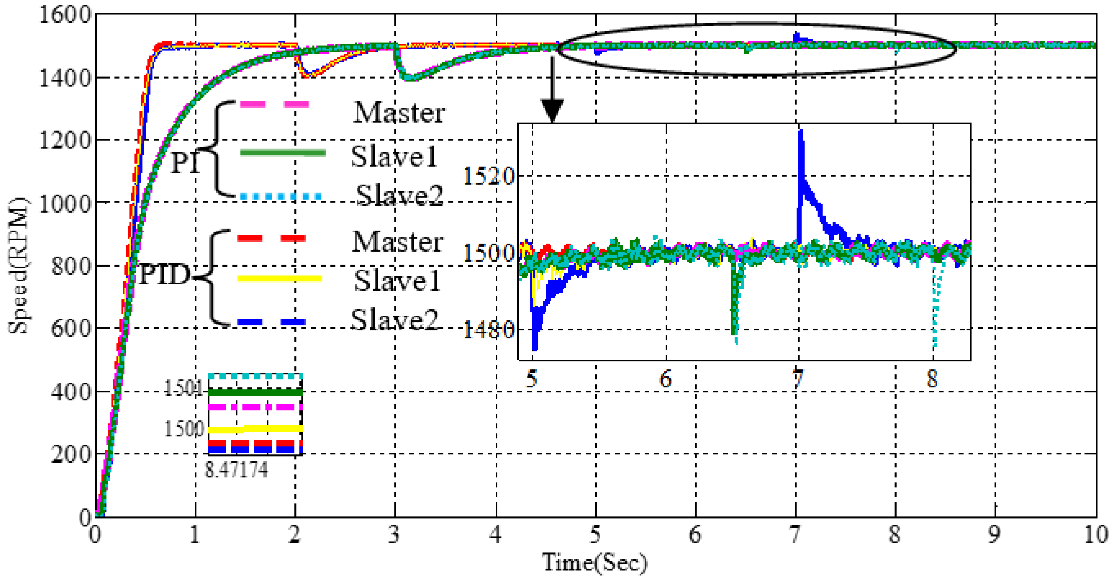

Fig. 39. Difference between speed response of three IMs system under PI and PID controllers.

So in the above Fig. 39, a comparison is shown between three I.Ms under PI and PID controllers. From this one can be noted that PID controller is better than PI controller. The speed of induction motor using PID controller settled early than that of PI controller. The comparative results for rated speed (1500 rpm) under both controllers are reported in Table 2 below.

Table 2. Comparison of speed of three I.Ms. using PI and PID controllers.

Parameters	With PI controller	With PID controller
Speed	1500 rpm	1500 rpm
Settling Time	2.1sec	0.9 sec
Rise Time	1.7 sec	0.75 sec

In Fig. 40, second comparison between the speed response of multiple IMs operated with PI and PID controllers under different reference speeds (1450, 1250 and 950 rpm) with sudden load of 2Nm applied on both master motors at t= 2 sec ,then under PI controller load torque T_L=2 Nm applied on slave1 at t=7 sec and on slave2 at t=2sec, under PID controller, the same value of T_L applied on both slave motors at t=12 and 13 sec respectively and removed from slave2 motor at t=14 sec.

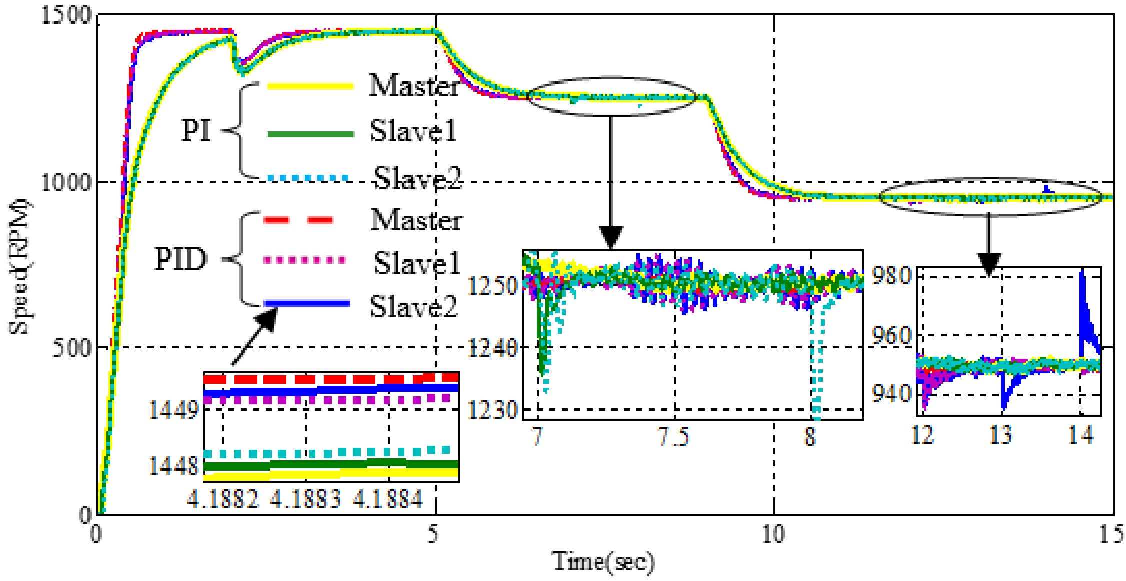

Fig. 40. Comparison between speed response of three IMs system under PI and PID controllers with different conditions of reference speed and load torques.

11. CONCLUSION

In this work, the speed control of triple (master/slaves) induction motors using closed loop conventional PI and PID controllers under unbalanced load condition and different reference speeds is demonstrated. Dynamic d-q Model of a 3-phase induction motor is also presented. A simulation of IM, two controllers and the (SPWM) drive circuit are done in MATLAB/ Simulink software program to accomplish the open loop V/f control method of three induction motors. The effectiveness of the system is analyzed through the speed and torque response profiles achieved from the simulation. The results shows that the PID controller is more effective than PI controller in controlling multi induction motors speed.

When a single IM model is supplied from 3-phase VSI drive and runs without control, its dynamic response has been made by causing sudden step change in load from 0 to 2 Nm at 5sec. The results show that the motor speed cannot returned to its required value due to sudden change in load because of the absence of controlled.

Two types of controllers have been used to improve the multi IMs speed profile. Each motor speed is the feedback signal after converting it to frequency for determining error in frequency at instant of starting and loading. The output of the controller is then fed to the voltage source inverter.

The implementation of PID controller improves the speed and torque responses as settling time and rise time for any values of reference speeds and under sudden load torques for master and slaves motors. This speed controller shows high-speed response, smooth performance and high dynamic response with changing and transient conditions.

The three motors performance under both PI and PID controllers has been checked and compared for different reference speeds and load conditions. The results show 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.

As a future work, the hardware of the project can be implemented and more advanced controller can be used instead of PI and PID controllers

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