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Performance Evaluation of an Indirect Vector Controlled Drive Using Synchronous Current Controller

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ABSTRACT

Ever since its development, the induction motor has been mainly used for constant speed application. Three phase squirrel cage induction motors have been widely preferred due to simplicity, robustness and maintenance free operation. However, in variable speed applications, preference is always given to dc motors. The reason for using separately exited dc motor as a variable speed drives is the simplicity in control as the field and the armature current are electrically decoupled from each other. However the main problem with dc motor is the maintenance of commutators, brushes and brush holders. The rapid developments in power electronics and powerful digital signal processor (DSPs) have made the implementation of new control schemes possible to realize in variable speed induction motor drives. Different control approach such as scalar control, vector control, direct torque control etc. have been used to realize adjustable speed drives through variable frequency control of squirrel cage induction motors.

In the present paper, indirect vector control technique in synchronous reference frame has been used to realize variable speed induction motor drives. The voltage source inverter (VSI) is used to feed an induction motor in current control (CC) mode due to its merits over other variable frequency converters. A comprehensive mathematical modeling of vector controlled induction motor drive (VCIMD) system has been carried out to analyze the drive system. The dynamic response of the VCIMD under various operating condition such as starting, speed reversal and load perturbation is simulated in MATLAB environment using Simulink and power system block set (PSB) toolbox. Both base speed region and field weakening region of the drive system is considered.

Keywords - Indirect vector control, MATLAB, Synchronous current controller, vector controlled induction motor drive (VCIMD), Voltage source inverter.

I. INTRODUCTION

Although the induction motor is superior to the dc motor with respect to size, weight, rotor inertia, efficiency, reliability, cost etc. but because of its non-linear nature, the required control become complex[1-2]. In case of scalar control technique only the magnitude (scalar quantity) for the control variable is used.

The type of control may be open loop control or may be a feedback control. In scalar control, the air gap flux is maintained constant to achieve the maximum torque at a constant level. Constant flux is achieved through maintaining the ratio of voltage to frequency constant with a boost at low frequencies for resistive effects. During steady state operation, the torque is closely related to slip below the peak limit. This forms the basis of simple control. The main disadvantage of scalar control technique is the poor dynamic response. The main reason is that the flux control and torque control is not independent of each other [1], [5]. The vector control is better solution so that control on flux and torque become independent of each other and the induction motor is transformed from non-linear to liner control plant. As a result, the three phase squirrel cage induction motor can replace a separately exited dc motor for variable speed drives. In this manner, using vector control technique all the advantage of induction motor are made use of and the disadvantages of it are eliminated [1], [4].

Rapid devolvement in power electronics have the availability of improved semiconductor devices (especially self-commutating device with high switching speeds, high current and voltage ratings) and compact circuit in modular form. Powerful digital signal processors have made possible the implementation of new control schemes for variable speed ac motor drives. Such processors now provide an economical option as the amount of hardware has reduced drastically. As a result, complex control schemes for ac motor drives are possible to implement employing induction motors [4].

II. VECTOR CONTROL OF INDUCTION MOTOR

Vector control is basically a control technique through which the induction motor can be controlled to behave similar to a separately exited compensated dc motor. The technique is also referred to as field oriented control. Decoupled component of the stator current space vector are taken as control variables and are expressed in two-phase rotating frame of reference, which is aligned to either the stator mmf space vector or the air gap mmf space vector. Such a rotating frame of reference is referred as the synchronously rotating reference frame (SRRF) [1]. In this work, SRRF is aligned with the rotor mmf space vector. In the SRRF, the stator current is split into two decoupled components, one control the flux and the other controls the torque respectively. An induction motor is said to be in vector control mode, if the decoupled component of stator current space vector and the reference decoupled components defined by vector controller in the SRRF match each other respectively. Alternatively, instead of matching the two-phase currents (reference and actual) in the SRRF, the close match can also be made in three phase currents (reference and actual) in the stationary reference frame.

Figure1 shows the basic block diagram of the induction motor in vector control mode. The motor speed is used as feedback signal in the controller. The controller as a first step computes reference values of the decoupled components of stator current space vector in the SRRF namely iqs* and ids* for the control of torque and flux respectively. The components of current are transformed into three phase currents (ias*, ibs*,ics*) in the stationary frame of reference. Three phase induction motor being a balance load, two of the three currents (ias, ibs and ics) are sensed and the third current is computed from the sensed currents. The current controller controls the reference currents closed to the sensed three phase currents in the stationary frame of reference and operate the voltage source inverter to feed the three phase induction motor. Therefore, the motor currents are controlled instantaneously thus ensuring a high level of performance of vector controlled induction motor drives (VCIMD) [1], [6], [7]. Because of the efficient, smooth and maintenance free operation of VCIMDs, such drives are finding increasing application such as air-conditioning, refrigeration, fans, blowers, pumps, waste water treatment plants, elevators, lift, traction, electric vehicles etc. [6-7].

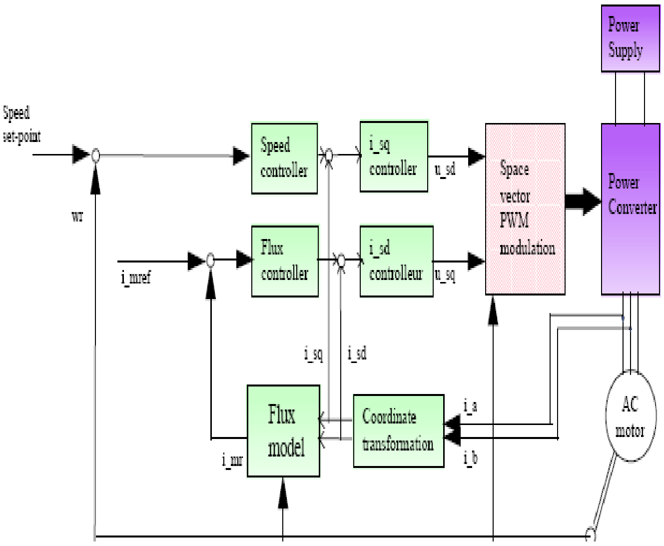

Fig1: Block Diagram of a Three Phase Induction Motor Drive Using an IFOC Structure

III. CLASSIFICATION OF VECTOR CONTROL TECHNIQUES OF INDUCTION MOTOR

For realizing vector control technique, the SRRF can be aligned with the stator flux or the magnetizing flux (field flux) space vector respectively. Accordingly, vector control is also known as stator flux oriented control, rotor flux oriented control or magnetizing flux oriented control. Generally, in induction motor, the rotor flux oriented control is preferred. This is due to the fact that by aligning the SRRF with the rotor flux, the vector control structure becomes simple and the dynamic response of the drive is observed to be better than any other alignment of the SRRF [1], [6].

On a broad basis, vector control technique can be classified into (a) direct vector control and (b) indirect vector control. Direct vector control also called as flux feedback control, is a method in which the required information regarding the rotor flux vector (magnitude and alignment) is obtained by means of direct flux measurement of estimation. Direct flux measurement is achieved using Hall Effect sensor, search coil, tapped stator winding of the machine etc [1]. Alternatively, rotor flux can also be achieved by use of flux model, which is based on motor parameter and the electrical input variables. The major disadvantage of the method is the need of a number of sensors. This prevents the scheme from being used in motors, which is already in use and add to the manufacturing cost of new motor. Moreover, fixing up of flux sensors becomes a tedious job. Problems such as drift because of temperature, poor flux sensing at lower speed also persist. Existence of related problems in case of direct vector control leads to the use of indirect vector control. In indirect vector control technique, the rotor flux vector position is computed from the speed feedback signal of the motor. The difference between the reference speed and the rotor speed is fed to the controller. The controller computes the slip speed that on addition to feedback motor speed provides the speed of rotor flux vector from which the angle of inclination of the rotor flux is computed. Therefore using indirect vector control technique eliminates most of the problems, which are associated with the flux sensors as the controller is now free from rotor flux sensing [1], [4], [6].

The method adopted in this investigation is indirect vector control or indirect flux oriented control. The in phase component of stator current space vector in the SRRF is aligned with the excitation current of rotor flux (rotor m.m.f vector). This component of the stator current vector is responsible for the production of flux. Similarly, the quadrature component of the stator current space vector is responsible for the production of torque. Hence, such a control technique provides a substitute for the separately exited dc motor.

IV. CURRENT CONTROLLER

Motors and other ac loads which are usually fed by converters exhibit, in general, better performance and faster response if they are current fed rather than voltage fed [1], [4]. In ac motors, current control (CC) reduces the dependence on stator parameters and allows an immediate action on the flux and torque developed by the machine [5]. In other ac loads, such as in the cases of uninterruptible power supplies (UPS's) and ac power supplies, Current Control results in an increased stability of the control loop and in intrinsic short-circuit and overload protection [4-5]. These requirements can be fulfilled, while keeping the advantages of the VSC (voltage source control) power structure (typically, three phase bridge topology), by a closed-loop regulation of the ac-side currents produced by the converter. This solution ensures several additional advantages. Among them, it gives the control of the current waveform within the ac period, which also compensates for load transients and nonlinearities and for commutation delays. The feedback loop also results in some limitations, in that fast-response voltage modulation techniques must be employed, such as pulse-width modulation (PWM) or discrete pulse modulation (DPM). Optimal techniques, which use pre-calculated switching patterns within the ac period, cannot be used, as they are not oriented to ensure current waveform control [7].

The position, speed, torque, DC bus voltage etc. control loops of all the PWM VSI drives generate voltage or current references that must be matched by the inverter. High performance voltage and current regulators are critical parts of an inverter drive that achieve this task. Depending on the performance requirements, the regulator types vary. Constant V/f drives employ voltage feed forward, while all the other high performance drives employ closed loop voltage/current regulators. As an exception the DTC method employs torque and flux regulation and the voltages and currents are not directly controlled. High performance Field Oriented Control (FOC) induction and synchronous motors and PWM-VSC applications employ current regulators. Within two decades the current regulator technology evolved from the simplest on-off principle based AC current regulator to the present day industry standard high performance synchronous frame current regulators.

The three phase current regulators can be grouped into two classes; on-off principle based (memory-less) regulators and linear control principle based regulators employing carrier based PWM methods. The hysteresis and delta current regulators are the two established current regulators, based on-off principle. In the delta current regulators the phase current errors are periodically sampled and the phase current error polarity determines the switch state of the associated inverter leg. If the error is positive the upper device, otherwise the lower device of the inverter leg associated with the regulated phase is turned on. In the hysteresis current regulator the phase current errors are continuously monitored and if the current errors become larger than a predetermined tolerance band, commutation takes place in the same manner as the delta regulator [8]. Hysteresis current regulators can be built for each phase individually (scalar method) or in vector coordinates (vector method) with the latter being superior. In today's practice, VSI's with CC are employed in every application where fast response, high accuracy, and a high level of performance are needed. As these features are required more and more, the interest in cheap, reliable, and high-quality current control techniques is increasing.

The voltage source inverter (VSI) feeding the induction motor is operated in the current controlled (CC) mode. The CC modes of VSI, leads to quick and fast response of the winding currents are regulated in accordance vector control mode of an induction motor. Normally, uncontrolled ac-dc converters are used to feed vector controlled VSI based induction motor drives [1]. The uncontrolled ac-dc converters draw non-sinusoidal current from the ac mains and behave as nonlinear loads. Operation of such non-linear loads results in power quality problem, and several other standards such as IEEE-519 are being enforced on the users. Recently, a number of techniques in ac dc converters have been proposed for improving power qualities at ac main.

V. MODELING & SIMULATION OF VECTOR CONTROLLED THREE PHASE INDUCTION MOTOR

Step by step development of Matlab/Simulink model of IRFOC is presented. Dynamic model of induction machine in d-q reference frame is reviewed. Ideal three-phase voltage source inverter is considered. Current control of phase current is exercised in synchronous rotating reference frame. Matlab/simulink model of the complete system is provided. The simulation results are presented.

VI. VECTOR CONTROLLER

The vector controller model is presented in Fig.2. The speed controller is anti-windup PI (analogue) type. The d-q axis current generated by the vector controller is then transformed into three-phase sinusoidal references. Thus the input to the vector controller is the actual speed of the motor and the outputs are the three-phase current references.

In vector controller reference speed of motor is given as input and compared with the desired speed. The reference speed and desired speed is fed to an anti-windup PI controller, it gives the required value of torque to run the motor at the reference speed. Also as shown in the figure the actual and command values of current i_d and i_q are compared and precisely controlled using PID (having $K_P = 20$, $K_I = 2500000$, $K_D = 0$) controller. From figure it is clear that:

Channel 1 provides d-axis current.

Channel 2 provides q-axis current.

Channel 3 provides rotor flux position.

These information are fed to a MUX and consequently to vector rotator block which then transfer i_d and i_q into stationary reference frame. These currents are transferred to three axis (a-b-c) current using Two/Three transfer block. Speed reference is provided for acceleration and reversal from a subsystem. Rotor flux reference is provided as a ramp step function. The rate limiter limits the rate of rise of rotor flux reference, so that a step reference flux is not applied, but a ramp step type reference flux is applied. The flux weakening phenomena above base speed is provided by Embedded MATLAB Function as shown in Figure 5.

A. Anti-Windup Controller

An anti-windup PI controller consists of a nominal (most often linear) controller appended with anti-windup compensation as shown in figure 3. An important property of anti-windup controller is that it leaves the loop unaffected as long as saturation does not occur. Consequently, the control action provided by the anti-windup controller is identical to that of the nominal controller, as long as the control signals operate within the saturation limits. The design can be split into two parts where the first part concerns the linear controller and the second the anti-windup modification. Hence, when designing anti-windup controllers in this way, input saturations are taken into account. Anti-windup was originally used for preventing the integrator state in PID controllers from growing large and cause overshoots and limit cycles.

B. Three To Two Phase Transformer

Three to two phase transformation blocks are used as shown in Figure 4.The transformation from three to two phase voltage is implemented using function blocks from Simulink library. The first block is used to calculate V_d and V_q voltages which has to be fed to the d-q model of three phase induction motor. The second block is used to convert the 3- phase stator current of induction motor model into V_α and V_β voltages to be fed to the rotator block.

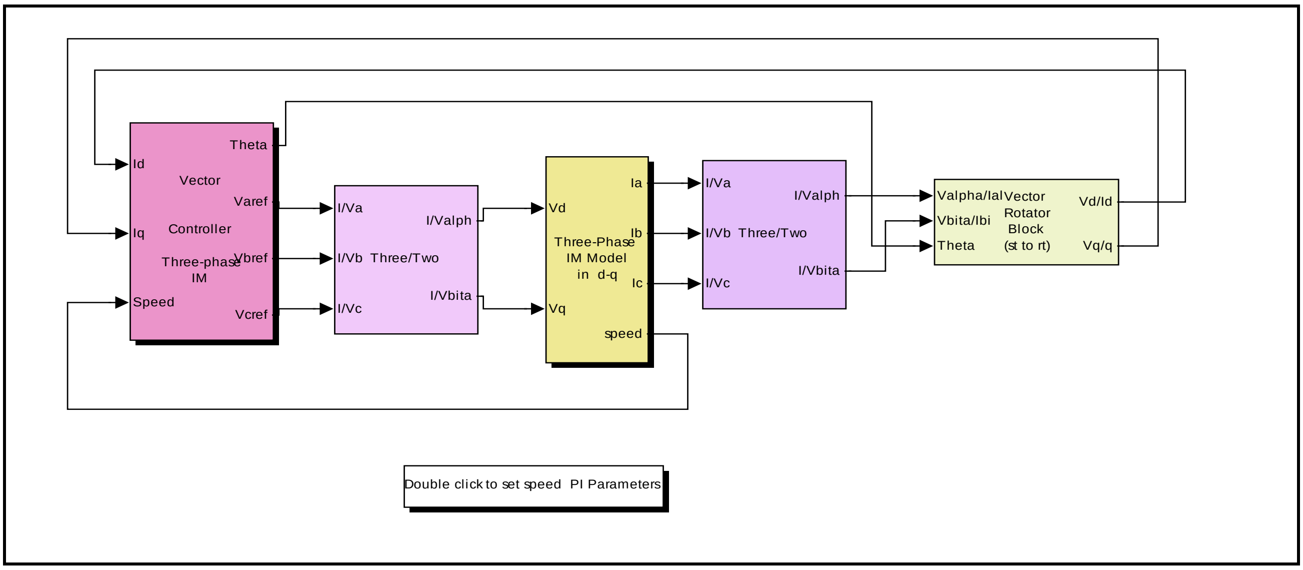

Fig 2: Simulink model of 3-phase vector controlled induction motor drive

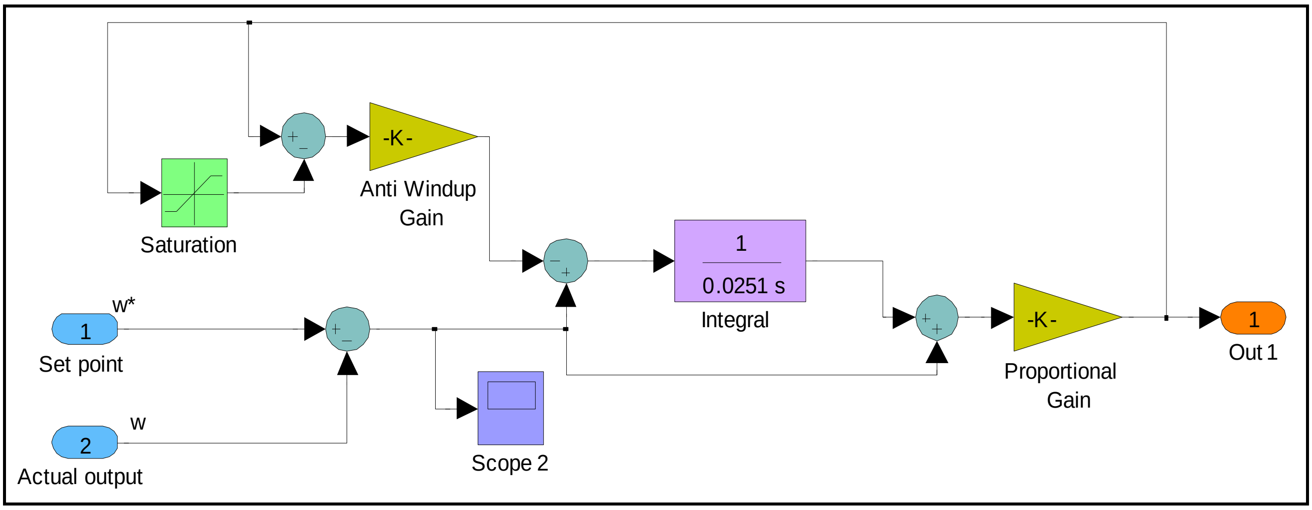

Fig. 3: Block diagram of anti-windup controller

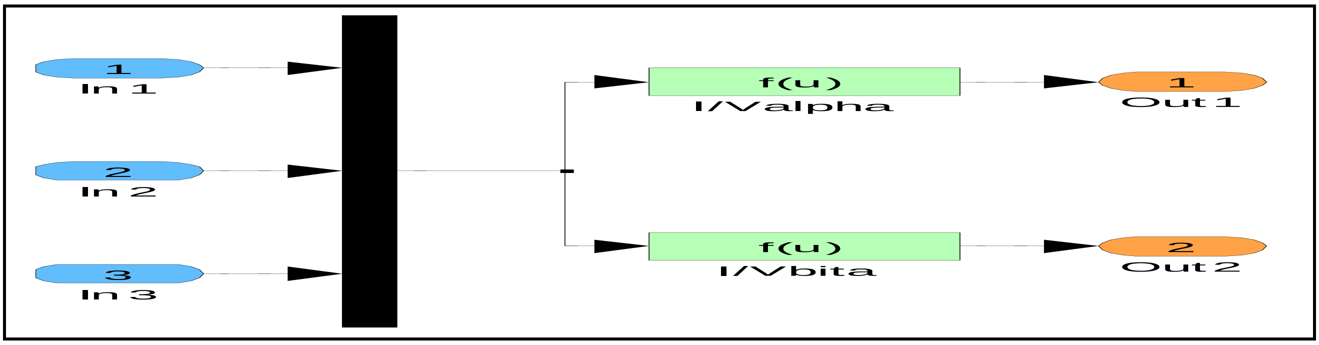

Fig. 4: Block diagram of 3 to 2 phase conversion

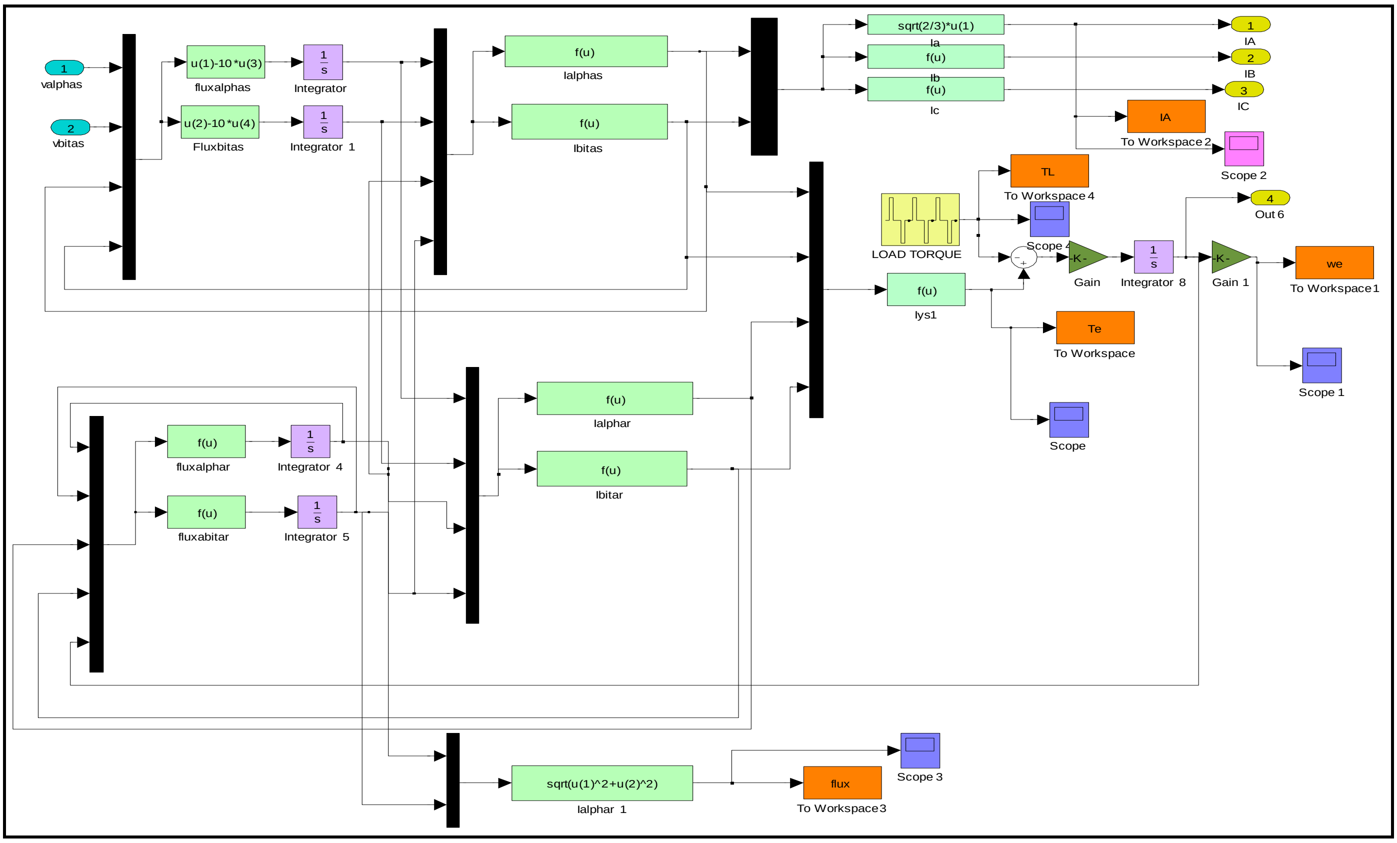

Fig. 5: Block diagram of the 3 phase controller

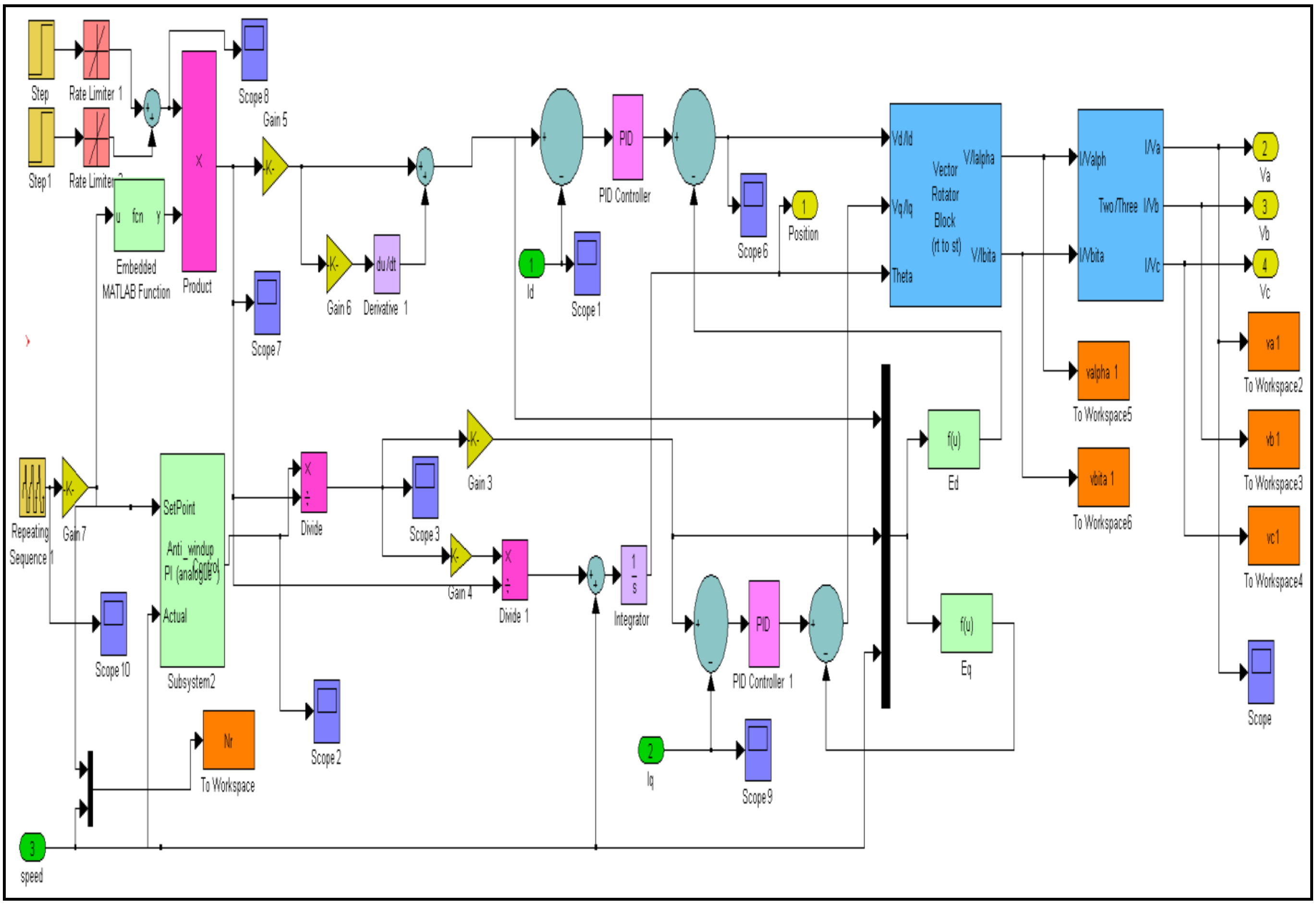

Fig. 6: Block diagram of the 3 phase IM model

C. Vector Rotator Block

This block converts the stator reference quantity into rotating reference quantity. The input to this block is V_α, V_β and θ (from controller) which is converted to output I_d, I_q and fed to the vector controller input.

D. Induction Motor d-q Model

The Simulink model of three-phase induction motor is presented in Figure 6. The input to the block is the two-phase voltages and outputs are three phase stator currents and speed. In this motor modal V_d and V_q are the two inputs from the controller circuit which is used to calculate the three phase current and the speed of motor .These output are then fed to the vector controller and current comparator respectively. The advantage of this model is that the inductors time independent moreover it easier to simulate and is as accurate as phase variable model. This block has various sub-blocks like torque calculation block, the rotor flux calculation block, the speed calculation block etc.

VII. SIMULATION RESULTS OF VECTOR CONTROLLED INDUCTION MOTOR USING SYNCHRONOUS CURRENT CONTROLLER

The proposed controller has been simulated using MATLAB on an induction motor drive system, whose data are listed in Appendix. The simulation tests are presented as follows.

The drive is subjected to a standard acceleration, loading and reversal transient (benchmark) test, as shown in Figure 7(a). The unloaded motor is required to accelerate from standstill condition to 800 rpm in 0.5 sec. Then reference speed is kept constant at 800 rpm from time, t = 0.5 sec to 3 sec. Load torque of 15 Nm is applied from t = 1.5 sec to 2.5 sec. Then reference speed is changed from 800 rpm at t = 3 sec to 1800 rpm at t = 3.2 sec under no load condition, kept constant at 1800 rpm until t = 3.5 sec, now the reference speed is changed from 1800 rpm at t = 3.5 to -800 rpm at t = 4.5 and kept constant -800 rpm until t = 7.5, Load torque of -15 Nm (three times the rated value) is applied from t = 5.5 sec to 6.5 sec. After that motor is made to stop from -800 rpm in 0.5 sec. Dynamic response of the drive system is shown in Figure 7 (a). The actual speed follows the speed command very well although there are small disturbances at the time when the load is applied and reaches 800 rpm at t = 0.5 sec without any overshoot. When three times the rated load torque is applied, there is a temporary dip in speed (Figure 7 (a)) of 20 rpm. After the load is released, again there is a temporary speed overshoot of 20 rpm. When the reference speed is reduced to zero linearly, rotor speed follows it without any delay, and becomes zero within the same time. For reverse motoring (second half cycle), the dynamic response is similar to that of forward motoring. It is clear from the Figure 7(c) that at the instant load torque is applied the rotor torque gains the same (15 Nm) within the time and in flux weakening region the torque increase to 18 Nm, the overshoots in the torque is due to the fact that at that moment the speed is changing in negligible time so the torque will be near about infinity but in actual condition it has some definite value.

After starting of motor, the rated rotor flux linkage (Figure 7 (d)) of 1 Wb is established in 0.3 sec and remains at the rated value after that, irrespective of speed and load torque changes. During flux weakening control above the base speed (1500 rpm to 1800 rpm), the rotor flux linkage reduces from 1 Wb to 0.83 Wb in 2.08 sec. The quadrature component of the rotor flux remains zero, through-out, indicating decoupling of flux and torque. Also from Figure 7(e) we can see that as the load torque (15 Nm) is applied the stator current increasing to a value of 7.1 Amp and in flux weakening region the current increase to 7.9 Amp Similarly voltage are also increasing as shown in Figure 7 (f).

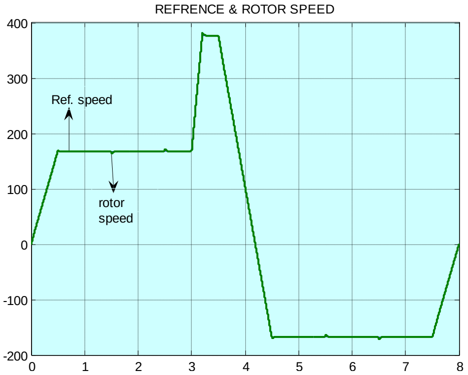

Fig. 7(a): Reference & Rotor speed of 3-Ph induction motor drive

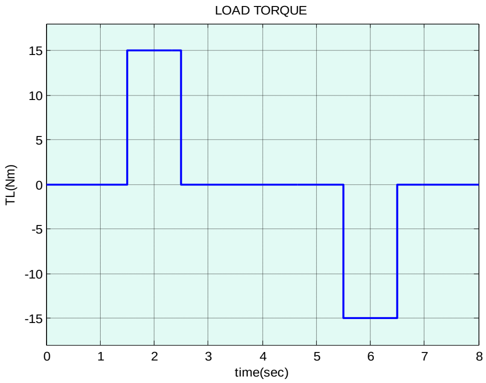

Fig. 7(b): Load torque applied to the 3-Ph Indution Motor drive

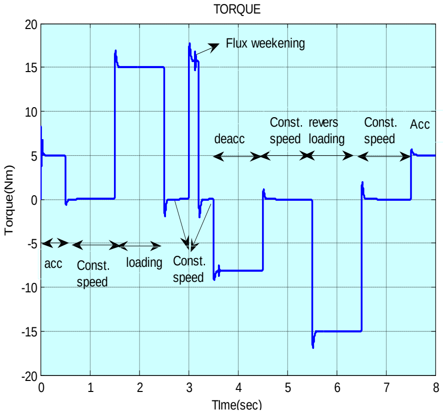

Fig. 7(c): Electromagnetic torque of 3-Ph Indution Motor drive

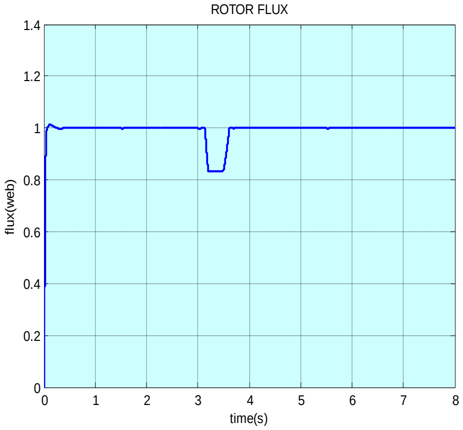

Fig. 7(d): Rotor flux of vector controlled 3-Ph IM

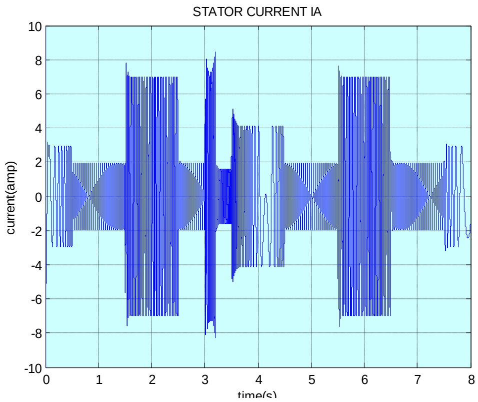

Fig. 7(e): stator phase 'a' current of vector controlled 3-Ph IM

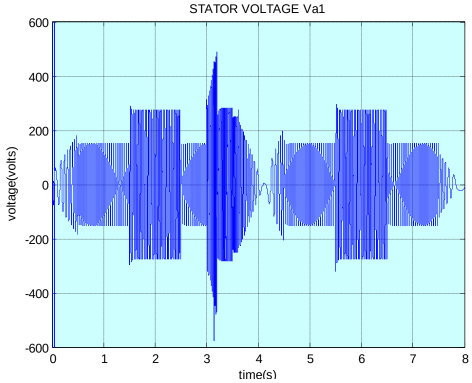

Fig. 7(f): Stator phase 'a' voltage of vector controlled 3-Ph IM

VIII. APPENDIX

Three-Phase Induction Motor Rating:

Rated speed =1500 r.p.m

Rated voltage = 220 V (phase)

Rated current =2.1 A (phase)

Rated torque = 5 N-m, 4 pole

Three-Phase Induction Motor Parameters

Stator Resistance	R_S=10Ω
Rotor Resistance	R_R=6.3 Ω

Stator Leakage Inductance	L_{1S} =0.46 H
Rotor Leakage Inductance	L_{1R}=0.46 H
Mutual Inductance	L_M=0.42 H
Moment of inertia	J= 0.03 $Kg.m^2$
Viscous friction coefficient	β= 0.0 N m s/rad

IX. CONCLUSION

Finally from the Simulink result it was found that speed response does not have any overshoot. The fact that, speed response does not have any over shoot is a great advantage of this controller. Speed response also tracks the command value very fast. Fast torque response is another advantage of this system. However, when the model of induction motor is not known exactly, or the parameters used in the model changes due to change in operating conditions the performance is also changed.

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