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Sliding Mode Control of Induction Motor in Power Steering Application

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ABSTRACT

This paper describes the control and estimation methods of Induction Motor parameters based on the Sliding Mode Control (SMC) with it being incorporated in power steering applications used in automobiles. The growing trends in SMC is cause of interesting features such as robustness, control over chattering and invariance. Particularly robustness of Sliding Mode (SM) approach with respect to parameter variations and external disturbance is vital for the control system. Induction Motors are used in many different fieldsto operate the small fans of large automobile engines. Power Steering used extensively in automobiles usually provides a mechanism to control the direction of the vehicle by PWM pulses. In this paper, it is explained how Sliding Mode Control can be effective used to estimate the torque and flux, thereby bringing a more responsive steering application in cars. The paper presents a MATLAB-SIMULINK simulation and a Hardware Setup in which the Sliding Mode estimate is incorporated in a DsPIC controller, which assist in the power steering application. Also the technique of power steering is inducted into the simulation to create real-time perspective. The paper also presents the experimental results and simulation results of speed, torque along with others parameters.

Keywords: Sliding Mode Control, Power Steering, 3 phase induction motor, estimated parameters.

INTRODUCTION

Induction motors are used in many different fields from water pumps to small fans of large automobile engines. Recently, electric vehicles and hybrid electric vehicles have required different operating regions for better exploitation of Induction motors. Electrical power steering (EPS) has increasingly been favoured as alternative to hydraulic power steering (HPS) owingto the advances in electrical machines, sensors, and controlelectronics. EPS offers several advantages over conventionalHPS, such as improved fuel economy, ability to operate evenwhen the engine is OFF, and elimination of hydraulic fluid.These benefits result in significant energy savings.

In Sliding mode control (SMC), the high gain feedback control input doesn't account for the disturbances and errors and has no influence on the output and hence is considered Robust. The sliding-mode methods are characterized by their simplicity of implementation, disturbance rejection, and strong robustness. These schemes are used for control and estimation in several processes. The field-oriented control (FOC) methods improve the performance of the induction machine (IM) drive and have been well established. The FOC methods require the informationof IM state variables, i.e., electromagnetic torque, rotor speed, or *d-q* stator currents. As a consequence, the state estimationproblem has been extensively studied in the literature.

This paper looks at the connection of Induction Motor Control using Sliding Mode with an application in Power Steering. The simulation has been made in such a way that a virtual module are used to recreate

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the working of power steering and the sliding mode control mechanism to maintain the speed and torque of the system. Various simulations are also being presented to extensively elaborate the co-existence of these control mechanism and the driver applications.

INDUCTION MOTOR

A 3-phase Induction Motor designed on an Asynchronous Motor Block has been used in the MATLAB-Simulation. This block can be modelled in a selectable d-q reference plane (Rotor, Stator). The stator and rotor windings are connected in wye to an internal neutral point. The block presents a selectable range of configuration and parameters. For the purpose of this paper, a squirrel cage IM with specifications of 5HP, 460V, 60Hz, 1750RPM is selected.

The behaviour of the IM can be modelled by continuous-time differential equations in a stationary reference frame (*qds*), such as

$$\frac{d}{dt}i_{sq} = -\gamma i_{sq} + \beta\frac{1}{\tau_r}\phi_{rq} - \beta p\omega_r\phi_{rd} + \frac{1}{\sigma L_s}v_{sq}$$
$$\frac{d}{dt}i_{sd} = -\gamma i_{sd} + \beta p\omega_r\phi_{rq} + \beta\frac{1}{\tau_r}\phi_{rd} + \frac{1}{\sigma L_s}v_{sd}$$

$$\frac{d}{dt}\phi_{rq} = -\frac{1}{\tau_r}\phi_{rq} + p\omega_r\phi_{rd} + \frac{1}{\tau_r}L_m i_{sq}$$
$$\frac{d}{dt}\phi_{rd} = -\frac{1}{\tau_r}\phi_{rd} - p\omega_r\phi_{rq} + \frac{1}{\tau_r}L_m i_{sd}$$

$$T_e = \frac{3}{2}\frac{L_m}{L_r}p\left(\phi_{rd}i_{sq} - \phi_{rq}i_{sd}\right)$$
$$\frac{d}{dt}\omega_r = -\frac{B_n}{J}\omega_r + \frac{1}{J}(T_e - T_L)$$

where R_s and R_r are the stator and rotor resistances, L_s and L_r are the stator and rotor inductances, and L_m is the mutual inductance; i_{sq}, i_{sd}, φ_{rq}, φ_{rd}, v_{sq}, and v_{sd} are the stator currents, the rotor fluxes, and the stator voltages, respectively, ω_r is the rotor speed, *Te* is the electromagnetic torque, T_L is the load torque, *J* is the moment of inertia, B_n is the friction coefficient, and *p* is the pole pair number.

The constants in the aforementioned expressions are defined as

$$\tau_r \triangleq \frac{L_r}{R_r}, \sigma \triangleq 1 - \frac{L_m^2}{L_s L_r}, \beta \triangleq \frac{L_m}{\sigma L_s L_r}, \gamma \triangleq \frac{R_s}{\sigma L_s} + \beta\frac{1}{\tau_r}L_m.$$

The expressions of back EMF can be calculated from the current and voltage signals as

$$e_{mq} = v_{sq} - R_s i_{sq} - \sigma L_s\frac{d}{dt}i_{sq}$$

$$e_{md} = v_{sd} - R_s i_{sd} - \sigma L_s\frac{d}{dt}i_{sd}.$$

It is possible to obtain the back-EMF equations from the magnetizing currents in the form

$$e_{mq} = L'_m \frac{d}{dt} i_q M$$

$$e_{md} = L'_m \frac{d}{dt} i_{dM}$$

SLIDING MODE CONTROL

One particular approach for robust controller design is the so called sliding mode control (SMC) methodology. SMC is a novice type of variable structure control (VSC). Variable structure control systems (VSCS) are characterized by feedback control law. The decision rule, termed the switching function, has its input as some measure of the current system behaviour and the output is given as feedback controller which is used at that instant in time.

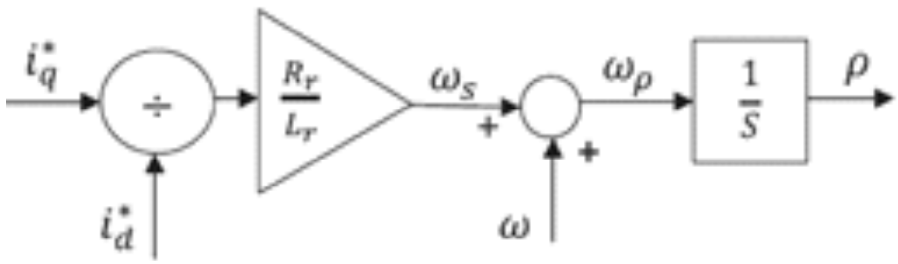

Figure 1: Indirect FOC

The high performance applications of IM had been achieved through Field Oriented Control (FOC). In FOC, the IM can be controlled in the same manner that of separately excited direct current (DC) motors. The system block diagram of FOC is shown in Fig. 4. The basic idea for FOC is that torque control is decoupled by two methods: the control of the torque current component, i_q, and of the flux current component, i_d independent of one another. By aligning the rotor flux vector with the d-axis of the rotating frame decoupling is achieved, this is called as field orientation.The shift dynamic response is achieved by decoupling control between the flux and the torque.

Nomenclature in FOC for induction machine.

i_d, i_q	Two phase stator currents in (d,q) field oriented or rotationary frame
i^*_d, i^*_q	Two phase stator reference currents in (d,q) rotationary frame
u^*_d, u^*_q	Two phase stator voltage command in (d,q) rotationary frame
u^*_a, u^*_b, u^*_c	Stator voltage command in (a,b,c) phase or stationary frame
$T(p)$	The reference frame transformation from stationary to rotationary
$T^{-1}(p)$	The reference frame transformation from rotationary to stationary
$u_{qd}, i_{qd}, \lambda_{qd}$	Complex space vector or two phase stator voltages, stator currents and stator fluxes in (d,q) rotationary frame
$\lambda_{dr}, \lambda_{qr}$	Rotor fluxes in (d,q) rotationary frame
λ_{qdm}	Complex space vector for air gap flux in (d,q) rotationary frame

Field orientation control is future classified into two classes based on the approach used for controlling:direct field oriented control (DFOC) and indirect field oriented control (IFOC).

In DFOC, there are two ways to obtain the rotor flux position. In the first method, a flux sensor is setup thereby mathematically computing the rotor flux. The disadvantage of this approach is that special flux sensors are necessary;

This installation is not possible in commercial off the shell motors. Contrarily in the second method the detected stator voltage and the stator current is first integrated which is used to compute the rotor flux and stator flux respectively. This method though has a major drawback as it is very sensitive with respect to stator resistance and also puts forth integration problems at low rotor speed cause of stator IR voltage drop.

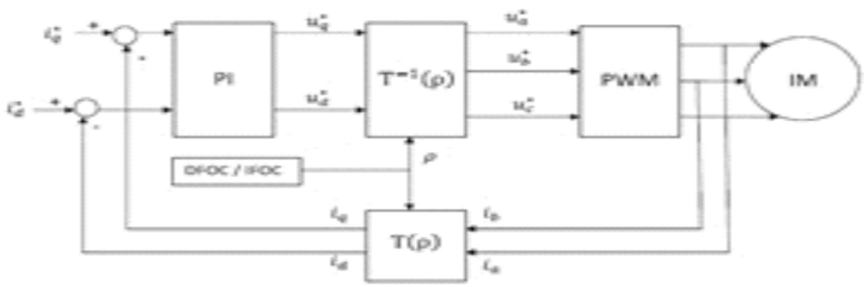

Figure 2: Field oriented control system block diagram

In IFOC, the stator current and rotor speed are first measured using angular position of rotor flux.The stator current and rotor speed are used to derive the rotor flux angle by summing the rotor angular position corresponding to the rotor speed and the calculated reference value of slip angle corresponding to the slip frequencies. Thus, the angular speed of the rotor flux is obtained by adding the slip frequency with rotor speed. The time derivative of slip is slip frequency, which gives us the difference between the rotor flux and electrical rotor angular position. The control variables and the states of field oriented coordinate frame are changed based on rotor flux angular position q, this is known as rotor flux angle. Thus an incremental encoder is used for rotor speed measurement in IFOC, the slip frequency calculation is directly related to the rotortime constant, L_r/R_r which is changes with temperature and with varying flux level.

POWER STEERING

Power steering also known as also **power assisted steering (PAS)** helps the driver turn the steering wheel by reducing his efforts. Control assist is added to the steering mechanism with the help of electric actuators to reduce the efforts of the driver regardless of the driving conditions. Power steering adds great value when the vehicle is stopped or moving slowly. A feedback is given in power steering mechanism which act on the front wheel to give the driver a view of the interaction of the wheels with the road.Hydraulic cylinder, which is a part of servo motor system, augments the steering efforts through power steering system in cars. A direct mechanical linkage exists between the steering wheel and the shaft that links the steering wheels. Therefore, even if the power steering system fails the vehicle can be controlled manually.

Electrical power steering (EPS) has increasingly been favoured as alternative to hydraulic power steering (HPS) owing to the advances in electrical machines, sensors, and control electronics. EPS offers several advantages over conventional HPS, such as improved fuel economy, ability to operate even when the engine is OFF, and elimination of hydraulic fluid.

In the MATLAB-SIMULINK environment, it is not possible to simulate an actual Power Steering Module (EPS or HPS). So through a variety of other simulation blocks or modules a virtual environment is created which for all extensive purposes performs the roles of the power steering mechanism.Mostly, power steering systems uses hydraulic system which multiply force applied to the steering wheel.The vehicle's engine drives the rotary vane pump through which the hydraulic pressure comes. The force is thus applied on the steering gear through a double acting cylinder. Pressure to the cylinder is controlled by the valves which are in turn controlled by the steering wheels. The more torque the driver applies to the steering wheel and column, the more fluid the valves allow through to the cylinder, and hence, the more force is applied to steer the wheels.

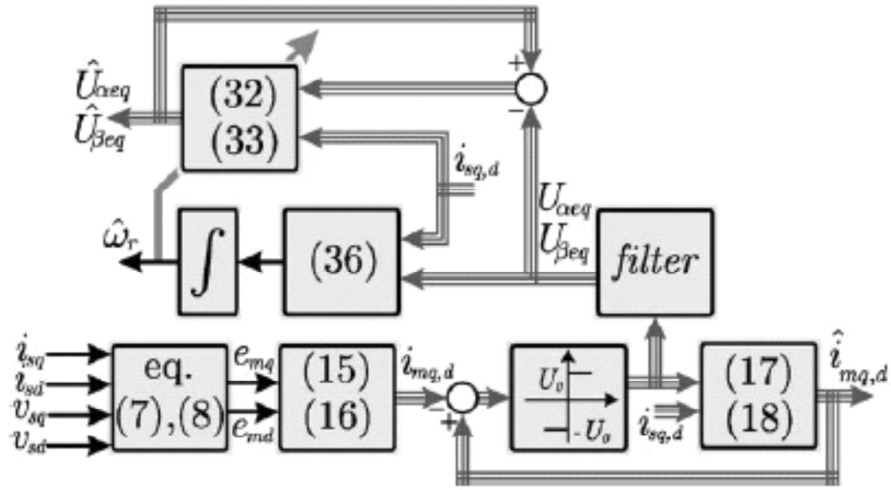

Figure 3: Rotor speed observer block diagram

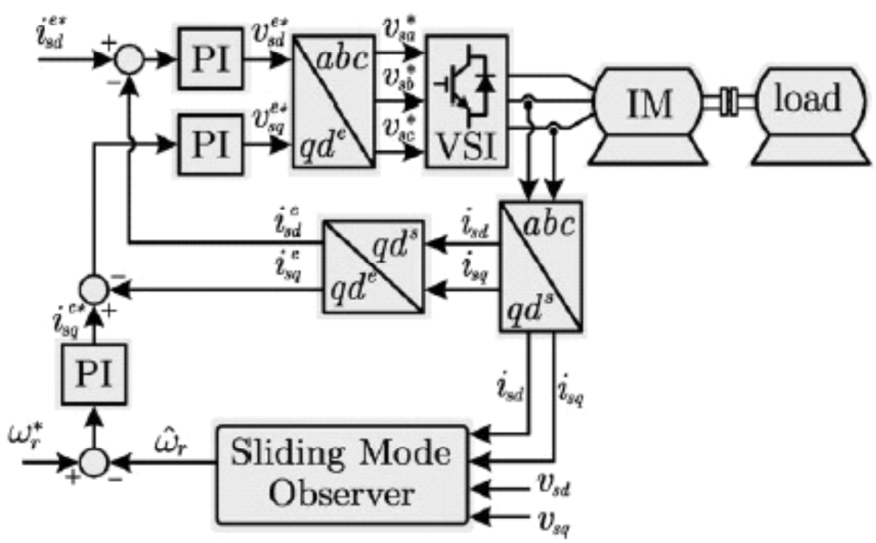

Figure 4: Control system diagram

Variable rate and damping suspensions are tailored with steering gear responses to optimise ride and steering condition for each vehicle.

The driver of the vehicle is assisted by the electric motor which is the mechanism used in Electric power assisted steering (EPS/EPAS) or motor driven power steering (MDPS)Sensors detect the position and torque of the steering column, and a computer module applies assistive torque via the motor, which connects to either the steering gear or steering column. Thus, by applying EPS various amount of assistance can be used during multiple driving conditions.

Table 1
IM Parameters

$S_{\text{rated}=}$ 5.0HP	R_s = 3.24 ohm
$n_{rated=1750}$ RPM	R_r = 0.228 ohm
$p = 2$	L_s = 402.4 mH
f= 60 Hz	L_r = 35.5 mH
	L_m = 34.7 mH

A mechanical linkage between the steering wheel and the steering gear pertains in EPAS. In case of power failure or electrical failures, the mechanical linkage serves as a reliable backup. One of the pioneer reasons for introduction of power steering is its fuel efficiency as no belt driven hydraulic pump is used. EPAS also elimination belt-driven engine accessories, and high-pressure hydraulic hoses between the hydraulic pump, mounted on the engine, and the steering gear.

SIMULATION CIRCUITS

The MATLAB-SIMULINK circuit for the Power Steering Control of a 3-phase Induction Motor using Sliding Mode Scheme is shown above. It consists of a 3-phase IM block of 5HP, 460V, 1750RPM, 60Hz. It's a squirrel cage motor. It is fed through a converter consisting of MOSFET's which are in turn powered by a 650V DC supply.

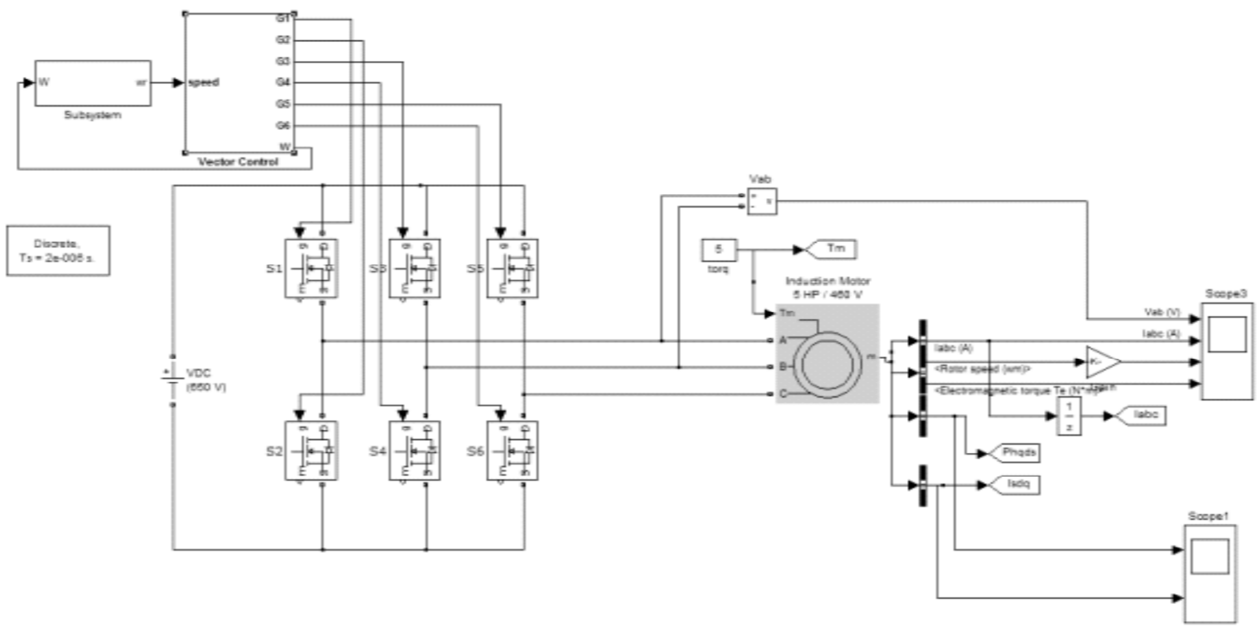

Figure 5: Main simulation circuit

The Pulses required to trigger the MOSFET's are provided by a block named Vector Control. The Vector Control module is essentially a Link Module which on further extrapolation provides us the feedback circuit needed for the operation of the IM.Several Parameters of the Induction Motor are measured using the Bus Selector.This block accepts a bus as input which can be created from a Bus Creator, Bus Selector or a block that defines its output using a bus object.The parameters which are measured are the Voltage (V_{abc}), Current (I_{abc}), Rotor Speed (ω_m), Electromagnetic Torque (T_e), Flux and Stator Current in the reference axis (d-q axis).

Upon further working the Vector Control Module provides a link to the feedback circuit which is as shown above. Here we find that the pulses for triggering the transistors are obtained from a Sub-system whose input is none-other than the voltage across the three-phases in our system. The voltage itself is obtained from an intricate system of modules and blocks.

First, the Stator Current and Flux from the reference d-q axes are taken as input through the feedback system. These two parameters helps us in finding the Electromagnetic Torque in the system. The Torque is obtained by the following formulae:

$$T_{e} = (\varphi_{sd} - i_{sq}) * (\varphi_{sq} - i_{sd})$$

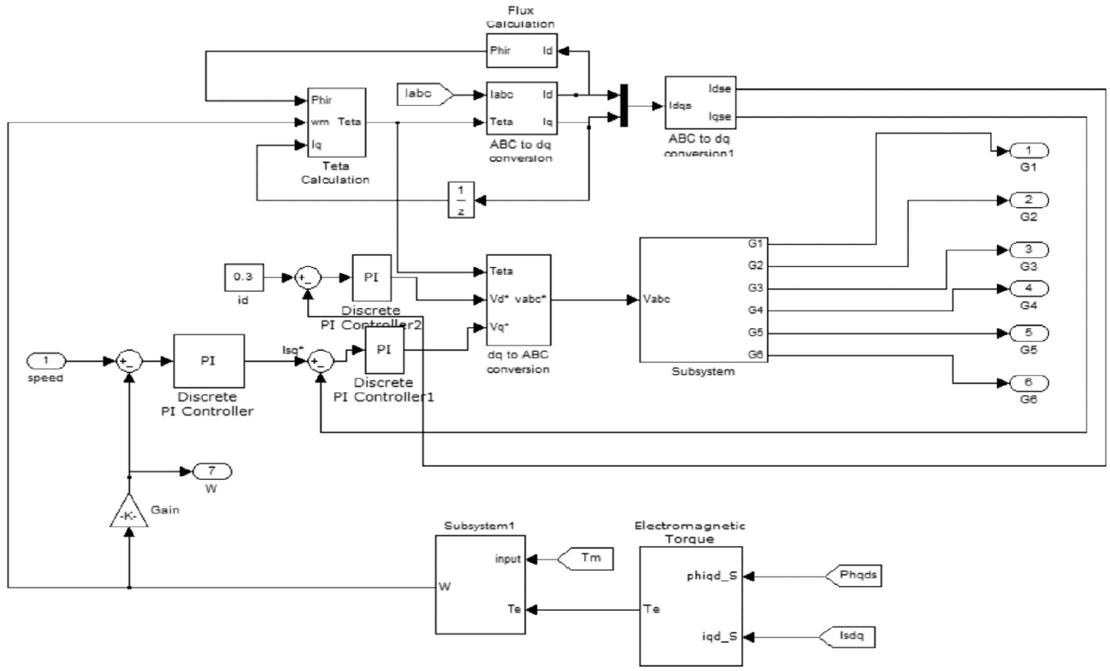

Figure 6: Vector Control Block

The estimated Torque and the Reference Torque are then used to obtain the rotor speed using a sub-circuit block in the simulation.Here the torques are used in such a way that the rotor speed at the required time is estimated i.e., the Rotor Speed at a given instance is predicted and hence is used in further processing. These blocks and modules where the torque and Speed are estimated use the Sliding Mode Control Technique. The Sliding Mode Control as explained earlier is a mechanism used to estimate the value (magnitude) of a parameter at a given instance which maybe in the past or future with respect to the current time interval.Again the estimated speed is matched with its reference speed and the resultant is the stator current with reference to the d-q axis which again is matched with the estimated quantity to provide the voltage in the respective axes. Using the teta value, the voltage V_{abc} is found.In the upper section of the simulated circuit, the current $I_{abc\ is}$ converted into I_d and I_q respectively.

The Current I_d is further used in the calculation of Flux which is later used in the phase angle or θ calculation. The θ calculation also uses the rotor speed obtained using the Sliding mode control. Thus the major parameters used for the control of the Induction Motor are the Rotor speed, Torque and Phase angle Teta.The parameter θ is the Electrical Angle (θ_m) which is obtained by integrating the sum of the speed of the rotor and the frequency of the rotor.The values obatained are provided to a subsystem.

The system links to an another circuit whose function is explained.As shown in the circuit the three phases of the voltage are seperated and are compared with a triangular waveform generated by a sub-circuit.A triangular waveform is prefered over a sawtooth wave or a square wave as pulse width modulation (PWM) is achieved relatively easier in a triangular waveform. Thus six outputs are obtained which are then used as the triggering pulses for the MOSFET's. In addition to the six pulses, the estimated mechanical speed of the motor is also taken as output.

The last part of the simulation is a subsystem, which is infact the timer circuit required to time the entireoperation.As witnessed, it consists of two timer blocks, each very essential to the operation. The upper timer block consists of two inputs modules, one denotes the entire time period of the opeartion with the required intervals being specified. The other denotes the time required for the power steering operation to take place. These blocks in the simulation are where the power steering action is specified and worked into the the simulation module. The lower timer module also consists of two two inputs.

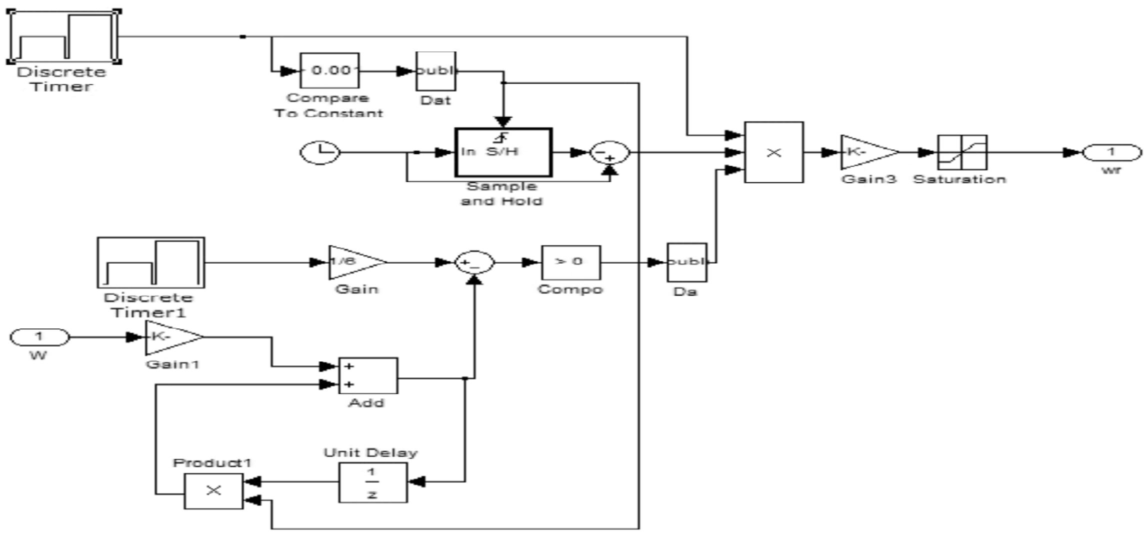

Figure 7: Input Subsystem block

The first is similar to the upper block denoting the entire time period of the operation with specific intervals. Finally an intricate system of blocks and modules are used to obtain the output which is a speed block. The importance of the timers and their action will be discussed along with simulation results.

SIMULATION RESULTS

The following MATLAB-SIMULINK output shows the parameters the Voltage(Vabc), Current(Iabc), Speed and the Electromagnetic Torque(Te) pittede against Time(ms).These output parameters are obtained by using a scope block which is connected to the induction motor.

Voltage(Vabc) Vs Time

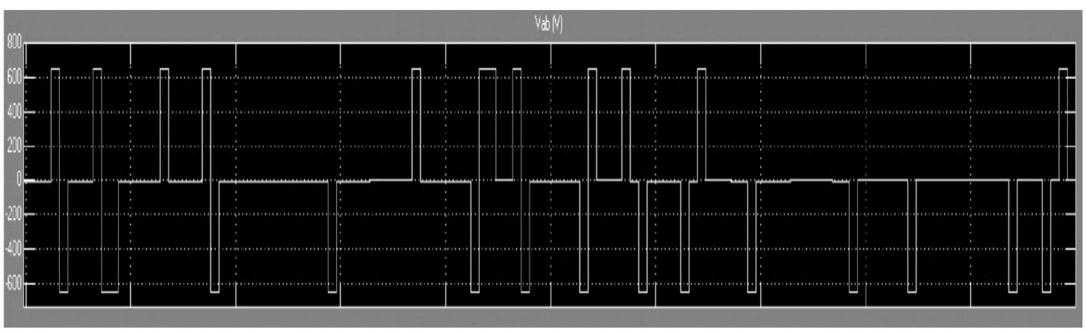

Figure 8: Voltage

Current(Iabc) Vs Time

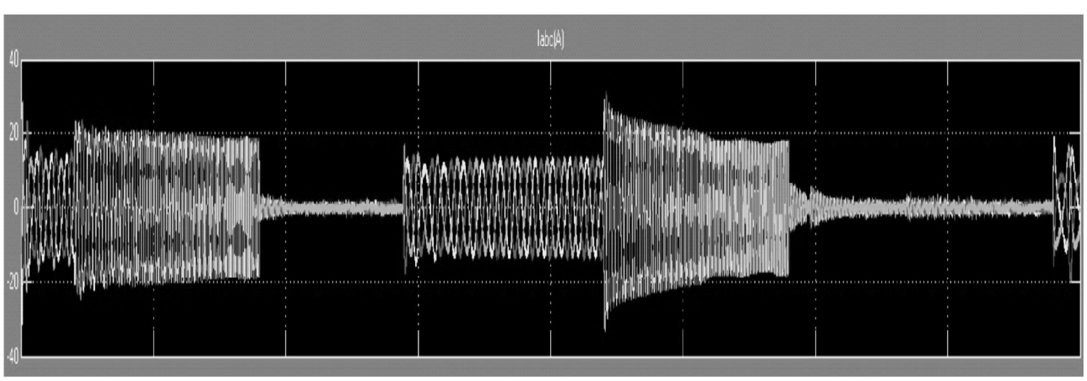

Figure 9: Current

Flux Vs Time

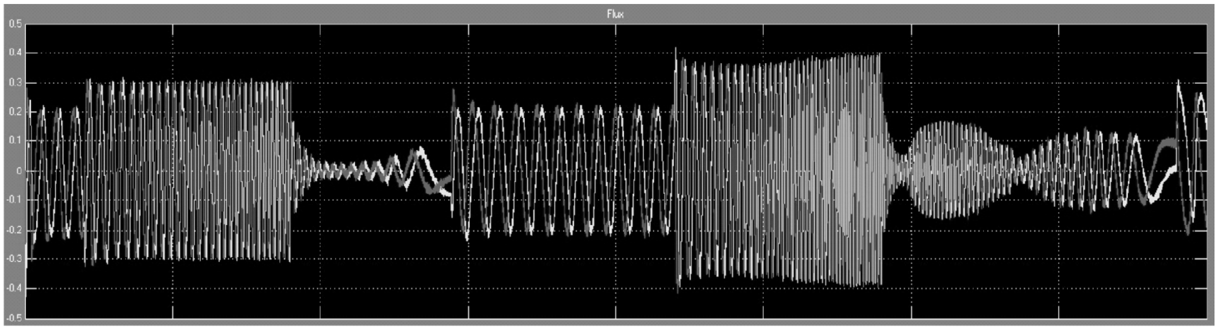

Figure10: Flux

Current (Is) Vs Time

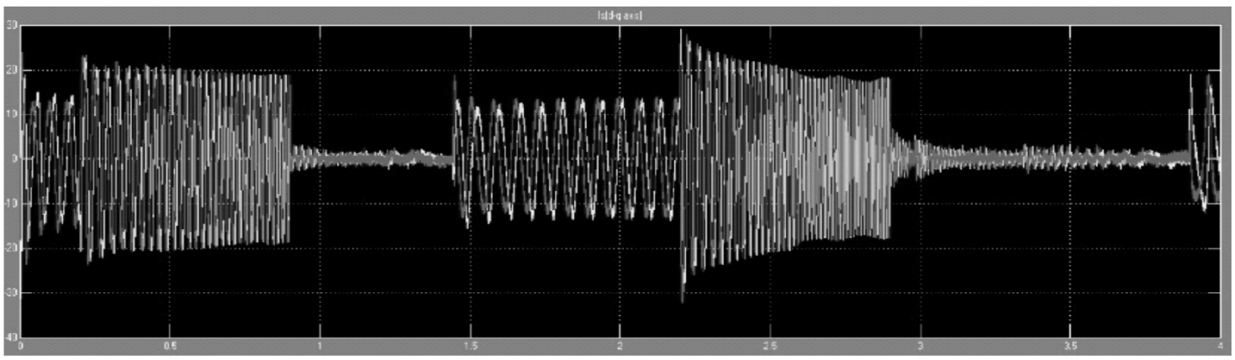

Figure 11: Current(I_s)

Speed Vs Time

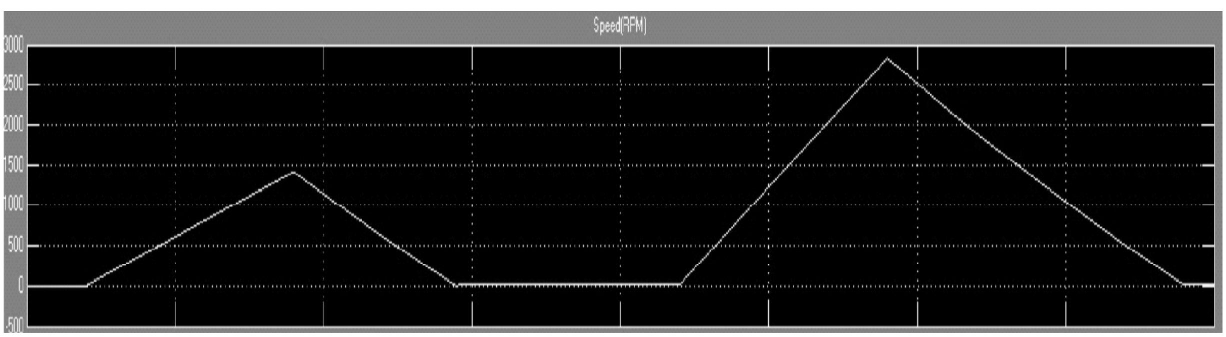

Figure 12: Speed

Torque(Te) vs Time

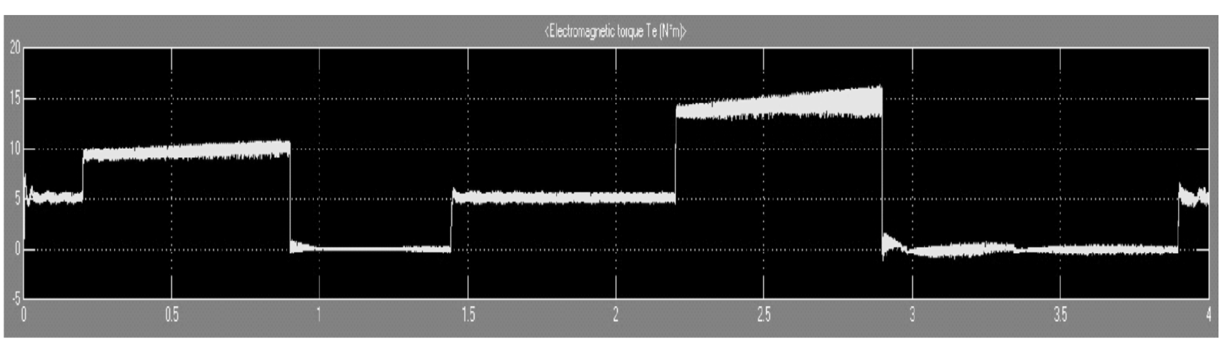

Figure13: Torque

The results of the parameters are provided above and the main point of interest for the power steering control are the Speed-Time graph and the Torque-Time graph.In the Speed Vs Time simulation, a momentary increase and decrease with two peaks are shown. This is connected directly to the Timer modules. The first peak is shown to be obtained quicker and the slope is smaller. This is because the modules is set in such way that the first wave reaches its peak in a smaaler time and the phase angle related with is 45° while the phase angle related with second wave has a phase angle of 90°.

In terms of mechanical power steering, in the first case the speed is required to be reached in smaller time frame and thus the phase angle related has a gradual slope than the second one and thus a smaller speed. In case of the Torque Vs Time, the values seem to have negative values of torque, which in electrical terms becomes so to counter- act the increasing speeds.

HARDWARE

The hardware setup designed for this topic is shown in the figure below.

The Inverter module is given supply thro' a separate transformer while the driver circuit is powered by a group of 12V transformers.The idea behind the hardware setup is that the three phase supply is rectified by a bridge rectifier and the ripples are removed using a capacitive filter circuit. The output of this operation is a single phase parameter. This single phase output is given to the inverter module which again converts it to a three phase value. The inverter module is made up of six thyristors with each of pair of thyristors correspond to a phase of the three phase of the output. The thyristors are triggered by the Driver circuit which consists of an Opto Isolator, transistors and MOSFET drivers.

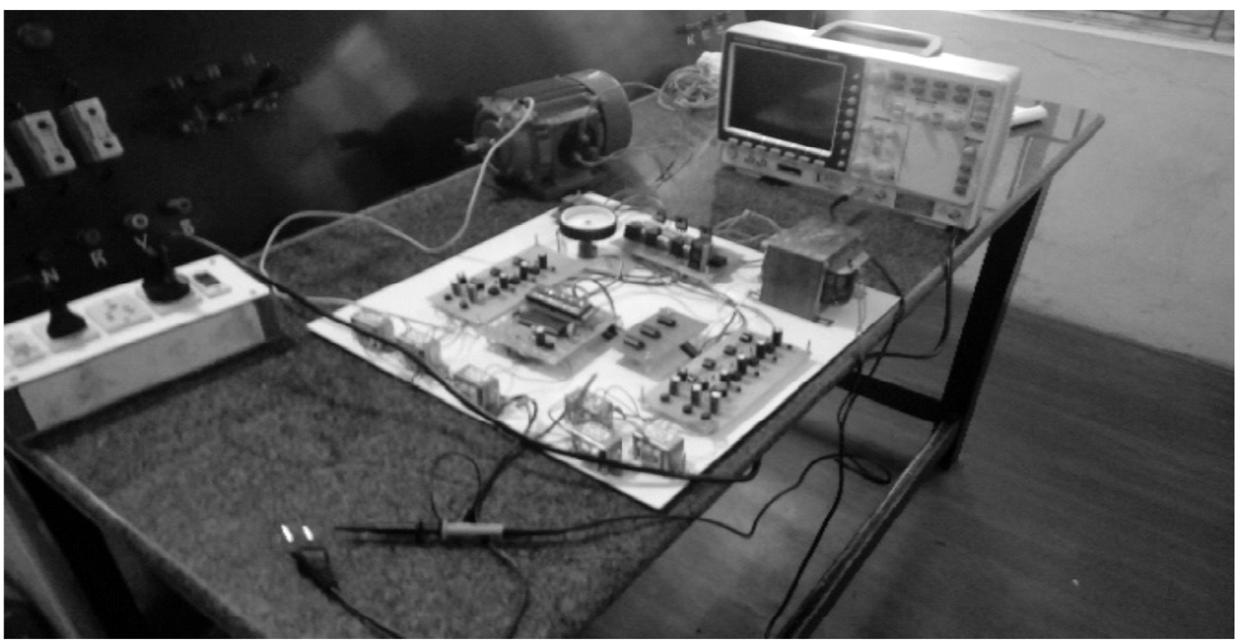

Figure 14: Hardware Setup

All these three together provide the necessary firing pulses needed to firing of the thyristors in the inverter module. For each thyristor, all three components are needed. The driver circuit is in turn connected to the Controller unit. The Controller unit consists of a Microprocessor which is coded with the necessary information which creates pulses with the variance in the resistance of the circuit which is achieved by using a potentiometer. The power steering application is incorporated into this hardware using variance of two parameters namely phase angle and time. The angle through which the steering is turned and the time in which the desired speed is attained is emulated through the potentiometer turns.

The opto isolator comprises of two photodiodes. The Opto Isolator is used for protection purpose. One photodiode is connected to the transistors in the driver circuit and the other photodiode is connected to the controller. In case the current flow increases in the circuit the opto receptor stops conduction thereby acting as a device which protects the processor and the thyristors. BC547/BC557 Transistors acts as a switch. It has common emitter configuration, it is a general purpose NPN bipolar junction transistor. It acts as a switch between -5V to +10V. The emitter part of the transistor is connected to the opto Isolator. The opto receptor works as both transmitter and receiver.The base of the transistor is connected to the 6 bridge thyristor circuit. The pulses of the thyristors are used to switch ON and switch OFF the transistors. Then there is 7667 MOSFET driver which is a 16 pin IC. The opto receptor is connected between the 2^{nd} and the 4^{th} pin. The output to the MOSFET is taken from the 5^{th} and the 7^{th} pin.

The Inverter is the power electronic circuit, which converts the DC voltage into AC voltage. The Inverter module in the hardware setup consists of 6-MOSFET's along with a corresponding Snubber circuit. The Snubber circuit has two components Snubber resistor and capacitor. They are used as the voltage pulses across the Gate-source of the MOSFET's are usually distorted and has higher magnitude. These snubber components remove the additional distorted pulse and gets heated up thereby saving the MOSFET's from damage.The inverter circuit is made up of six MOSFET, one for each of the thyristors. The inverter circuit is basically used to convert back DC to AC.

The controller unit consist of DsPIC 30F4011 microcontroller which is an enhanced flash 16-bit digital signal controller. It creates the pulses which are used in the driver circuit so to operate the MOSFET's in the Inverter module. The controller is placed as a separate module and is interfaced to the LED display. The controller is also connected to two other components. One is the 3 part IC which is effectively an AND gate. This is used to create a continuous multi pulse waveform by joining together the mono pulses which are generated by the microcontroller. The Other component to which the controller is connected is the Potentiometer. The potentiometer is provided as a small module to replicate the steering available in automobiles. The use of the Potentiometer in this setup is for the Pulse Width Modulation (PWM) that is being done to the output pulses. Here the PWM depends on the angle of rotation of the potentiometer and the time in which it is turned. In addition to the above mentioned components a relay circuit is also placed in the hardware setup. The three phase output from the Inverter module is connected to relay and through the relay the three phase supply is provided to the motor. The relay is used to protect the setup. Sometimes after the motor runs, back EMF is created which causes the motor to behave like a generator and starts to produce current. Without the relay the current thus created which pass the setup and thereby damaging the setup permanently.When the supply is provided, the potentiometer is turned at a specific angle at a specific time. This angle and time is shown in LED display. When this happens each module performs its function and the motor runs. The motor's count is measured by a proximity sensor and the speed can be obtained from a Tachometer. The voltage across the Gate-source of the MOSFET's can be obtained from the oscilloscope.

HARDWARE RESULTS

PWM Pulses

The induction motor is driven through an inverter which is controlled using a DsPIC controller which produces Pulse Width Modulated pulses. The on and off time of this PWM pulse depends upon the sliding mode estimate and the input (angle from steering) which we provide. The following tabular column shows the change in PWM pulses as observed during running the IM.

Table 2
PWM Pulses

ANGLE	*ON(µS)*	*OFF(µS)*
30	30	170
45	35	165
80	45	155
130	50	150

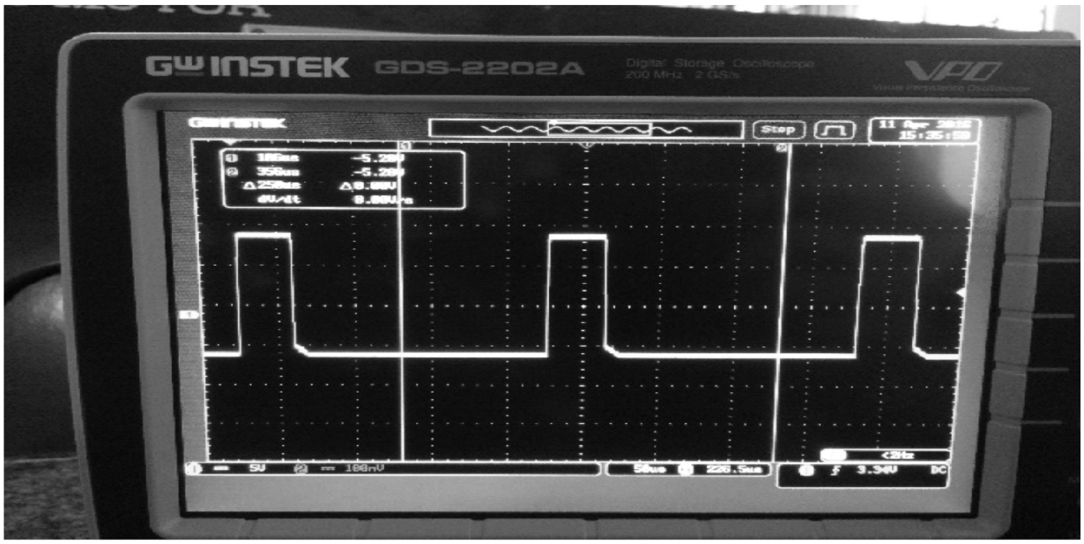

Figure 18: Waveform

Response time

The following tabular column shows the acceleration time T1, turning time T2 and deceleration time T3 of the induction motor during the operation.The acceleration time depends upon the time in which the angle is achieved. The turning time depends upon the angle which is to be achieved since the input.

This is briefly tabulated below. All time are in seconds.

Table 3
Response Time

Angle	*Time*	*T1*	*T2*	*T3*
35	9	5.5	10	4.5
50	9	6	4	3
50	11	7	9	5
100	9	5	16	6.5
175	22	6.5	20	4

CONCLUSION

This paper has developed a scheme for improving the response characteristics of a power steering induction motor and uses sliding mode control for flux estimation. The proposed method calculates and estimates the Speed, Torque and the Electrical angle Ÿ for the system. Furthermore, this paper presented simulation results, aiming to validate and to demonstrate the effectiveness of the proposed scheme. Also the concept of Power Steering incorporated with the Sliding mode control for a three phase Induction motor is viewed

Figure 19: Hardware Setup

and its effectiveness is analysed. Thus, this technique is a more robust and reliable method for induction motor control in steering applications.

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