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Three Phase Induction Motor: Simulation and Speed Control of Motor Drives Controlling the Applied Voltage

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Abstract – Induction motors are the most widely used electrical motors due to their reliability, low cost and robustness. However, induction motors do not inherently have the capability of variable speed operation. Due to this reason, earlier dc motors were applied in most of the electrical drives. But the recent developments in speed control methods of the induction motor have led to their large scale use in almost all electrical drives. Out of the several methods of speed control of an induction such as pole changing, frequency variation, variable rotor resistance, variable stator voltage, constant V/f control, slip recovery method etc., the closed loop constant V/f speed control method is most widely used. In this method, the V/f ratio is kept constant which in turn maintains the magnetizing flux constant so that the maximum torque remains unchanged. During starting of an induction motor, the stator resistance and the motor inductance (both rotor and stator) must be kept low to reduce the steady state time and also to reduce the jerks during starting. On the other hand, higher value of rotor resistance leads to lesser jerks while having no effect on the steady state time. The vector control analysis of an induction motor allows the decoupled analysis where the torque and the flux components can be independently controlled (just as in dc motor). This makes the analysis easier than the per phase equivalent circuit.

Keywords: Three Phase Induction Motor, Space Vector Modulation, V/F Control, Transient Analysis, Slip, Steady State Analysis, Induction Motor Electric Motor Drive, Matlab, Simulink

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INTRODUCTION

Three phase Induction motors have been the workforce for several industrial, manufacturing, propulsion and transportation applications for the past several years. A rough estimate shows that about 64 percent of the industrial motors belong to induction motors. The operational modes of an induction motor in an industrial environment can be divided into three:

1) starting,

2) speed control and

3) energy efficient operation.

In starting and speed control modes, the dynamic response of the drive is uppermost in the mind, whereas energy efficient operation is performed during steady state operation. Several papers have already been published in the above-mentioned areas. This thesis work employs a few biologically inspired optimization algorithms towards the performance enhancement of the three-phase induction motor during starting, speed control and energy efficient operations. The following sections carry out the literature survey on the above-mentioned modes of operation of induction motor.

Be it domestic application or industry, motion control is required everywhere. The systems that are employed for this purpose are called drives. Such a system, if makes use of electric motors is known as an electrical drive. In electrical drives, use of various sensors and control algorithms is done to control the speed of the motor using suitable speed control methods. The basic block diagram of an electrical drive is shown below:

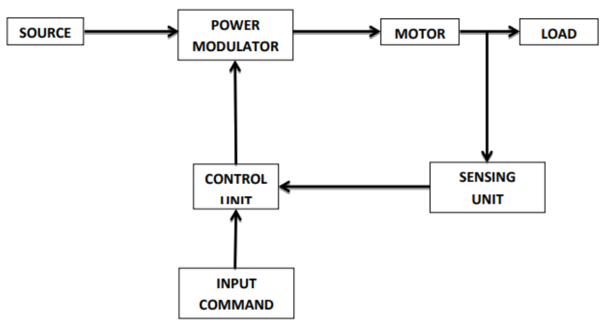

Figure 1: Block diagram of an electrical drive

Earlier only dc motors were employed for drives requiring variable speeds due to ease of their speed control methods. The conventional methods of speed control of an induction motor were either too expensive or too inefficient thus restricting their application to only constant speed drives. However, modern trends and development of speed control methods of an induction motor have increased the use of induction motors in electrical drives extensively. Induction motorϕ

In this paper, we have studied the various methods of speed control of a 3- and compared them using their Torque-Speed characteristics. Also, the transients during the induction motor were studied using MATLAB Simulink and the effects ofϕstarting of a 3- various parameters such as rotor and stator resistances and inductances were analysed. Also different control algorithms such as P, PI and PID control were studied by simulating them in MATLAB Simulink and were compared.

Construction of Induction Motor

The Induction Motor has a stator and a rotor. The stator is wound for three phases and a fixed number of poles. It has stampings with evenly spaced slots to carry the three-phase windings. The number of poles is inversely proportional to the speed of the rotor. When the stator is energized, a moving magnetic field is produced and currents are formed in the rotor winding via electromagnetic induction. Based on rotor construction, Induction Motors are divided into two categories.

In Wound-Rotor Induction Motors, the ends of the rotor are connected to rings on which the three brushes make sliding contact. As the rotor rotates, the brushes slip over the rings and provide a connection with the external circuit.

In Squirrel-Cage Induction Motors, a “cage” of copper or aluminum bars encase the stator. These bars are then shorted by brazing a ring at the end connecting all the bars. This model is the more rugged and robust variant of the Induction Motor.

Induction Motor Principle:

Principle: It is an asynchronous motor when 3ph supply is given to the stator, flux is induced in the stator and due to the mutual induction flux is transform from stator to rotor. The current is generated in the rotor due to short circuit copper bars in the rotor cuts the rotating flux .Hence torque is experienced and rotor rotates.

When the stator winding is energized by a three-phase supply, a rotating magnetic field is set-up which rotates around the stator at synchronous speed Ns. This flux cuts the stationary rotor and induces an electromotive force in the rotor winding. As the rotor windings are short-circuited a 8 current flows in them. Again as these conductors are placed in the stator‟s magnetic field, this exerts a mechanical force on them by Lenz‟s law. Lenz‟s law tells us that the direction of rotor currents will be such that they will try to oppose the cause producing them. Thus a torque is produced which tries to reduce the relative speed between the rotor and the magnetic field. Hence the rotor will rotate in the same direction as the flux. Thus the relative speed between the rotor and the speed of the magnetic field is what drives the rotor. Hence the rotor speed Nr always remains less than the synchronous speed Ns. Thus Induction Motors are also called Asynchronous Motors.

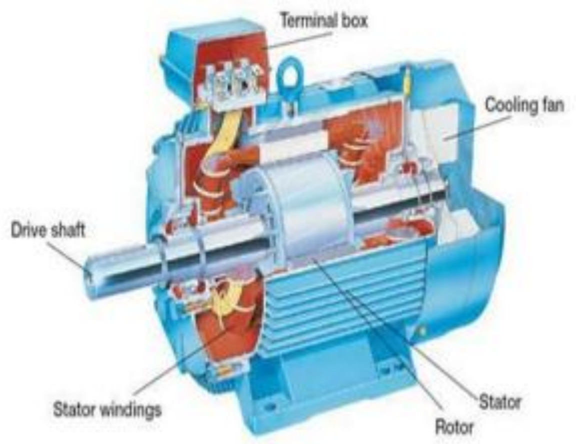

Figure 2: Internal parts of induction motor

Factors Affecting Efficiency of Induction Motor Drives

There are several factors which affect the efficiency of induction motors drives such as partial loading, harmonics, rewinding, power quality, parameter variation etc. These factors are discussed in brief in the following sections.

Partial Loading

Among all electrical AC drives, 3-Φ induction motors are mainly used due to its inherent advantages i.e. ruggedness, reliability, relatively low cost and easy operation. These machines offer years (around 20 yrs) of service when precisely selected, operated and maintained. In general, induction motor handles around 70% industrial load on a utility, therefore it becomes imperative to pay major attention to the maximum efficiency operation of such AC derives. Fundamentally, high efficiency operation of induction machine can be obtained when it is operated near to rated speed and torque. The significant improvement in machine materials, design and construction techniques may further improve the induction motor efficiency.

Harmonics

The operation of inverter fed induction motor at high frequencies causes losses because of harmonics, which are of two types:

1) Those resulting from space harmonics called stray losses.

2) Those caused by time harmonics in the converter excitation applied to the machine resulting in time harmonic losses

Stray Losses

The air-gap of flux wave of the space harmonics causes stray losses (high frequency losses) in the machine. The primary causes of these space harmonics are the stator and rotor slot presence variations and the mmf step harmonics. These losses are related to the fundamental motor frequency and can be expected to increase in importance as motor fundamental frequency is increased.

High Frequency Time Harmonic Losses

An important issue in modern power electronic control is the question of the effect of increasing the time harmonic frequency has on the time harmonic motor losses. There are many good reasons relating to control characteristics and motor acoustic noise which argue for high carrier frequency in the inverter. Opposing these arguments is the possibility of high motor losses caused by high time harmonic frequency of the carrier.

Rewinding

When motor fails, quick repair or replacement are mainly two options in front of motor consumers to avoid production loss. Rewinding through skilled person by excellent material may maintain maximum efficiency similar to previous level, but the poor rewind results in greater energy consumption and shorter life due to higher operating temperatures.

The induction machine efficiency and power factor may significantly affect after rewinding. Therefore, manufacture and customer should maintain proper record for noload losses and speed during sell and purchase, respectively. These records can be helpful for assessing the rewinding impact.

Unbalance Supply Voltage

The induction motor performance (speed and torque profile) is adversely affected when supplying through unbalance terminal voltages. The available literature from 1950 shows that researchers have focused on the 3-Φ induction motor performance during voltage unbalance in terms of total current drawn, current unbalance factor, torque ripples, efficiency and power factor loss, speed loss, insulation damage due to over-heating, and de-rating factor of the machine [39].

Equal magnitudes and phase angle 1200 apart in phase of three phases, represents the balance 3-Φ system. Any deviation from the prescribed conditions leads to unbalance system. The mathematical definition of unbalance (imbalance) can be presented according to various standards namely National Electrical Manufactures Association's (NEMAs), Institute of Electrical and Electronics Engineers (IEEE's) and International Electro technical Commission's (IECs).

Voltage Sags

The decrease in RMS voltage for short-duration in the interconnected power system is considered as "voltage sag". This power quality problem is mainly due to system faults. This can also happen due to loose connections and immediate starting of heavy loads (large motor starting draws high in-rush current). The IEC definition for this phenomenon is "dip". Voltage sag causes severe process disruptions and sometimes electrical sensitive loads often trip or shut-down resulting in poor quality products, substantial economic losses and also causes temperature rise in the motor.

Parameter Variation

A huge number of the performance investigations have been carried out by both academia and researchers to the control of AC drives and DC drives, efficiently and precisely. The investigations lead them to the theory of vector-control. Vector-control of AC drives is very much similar to the independent control of torque and flux. The high performance of an induction motor can be obtained through vector-control. Vector control methods are very much sensitive for the machine parameters variation. However, the motor parameters changes with temperature and magnetic core saturation. In vector control, machine flux is estimated offline through parameters which may have error due to variation in parameters. In case the error is not updated to the vector-controller, the machine performance may deteriorate in form of steady-state error and transient oscillations in speed and torque.

LITERATURE REVIEWS

During the past 15 years, there has been a substantial amount of research into the development of new condition monitoring techniques for induction motors. Excellent examples of typical failures in random wound, low voltage induction motor are shown in **Bonnet and Soukup (1992)**. Pre-warning of motor failure such as in Bonnet and Soukup (1992), **Thomson (1984)** can only be achieved if shorted turns within a coil can be initially diagnosed via on-line diagnostic techniques. This requires continuous on-line monitoring to diagnose the faults stated in **IEEE Survey (1985), Thomson and Dalva (1997)** for low voltage induction motors.

In order to assess the efficiency and effectiveness of the manner in which induction motors are used in industry, the U.S. Department of Energy and the Bonneville Power Administration (BPA) investigated a three-phase study into the estimation of the efficiency of in-service induction motors in 1994. Phase one of the study was conducted by the Oak Ridge National Laboratory (ORNL) and the results of the ORNL study are available, in **Hsu et al (1995)** and **Kueck et al (1996)**. Phase two of the BPA program has been undertaken by Washington State Cooperative Extension Energy Program and the Motor Systems Resource Facility (MSRF) at Oregon State University. Phase three of the program considered the above two studies that appear most appropriate, following laboratory testing and apply them in industry **(Wallace et al 1997).**

Following the macro review of IEEE and ERPI on potential motor troubles, effects and the resultant failure categories, (IEEE Motor Reliability working group 1985 and 1987, **Hobson 1965, Bonnet 1978)** the majority of motor troubles is categorized into four groups:

i) Unbalance Voltage Effects

ii) Single phasing effects

iii) Overloading Effects

iv) Environmental and Maintenance Effects

The knowledge about fault mode behavior of an induction motor drive system is extremely important from the stand point of improved system design, protection and fault tolerant control. **Mohammed et al (2000)** had taken the initial step to investigate the efficiency of current monitoring for diagnostic purposes.

Zhongning Ye and Bin Wa (2001) presented the simulation of three-phase induction motor drive system with emphasis on the electrical faults of the induction motor. Using the basic components of MATLAB/ SIMULINK tool boxes, the drive system is modeled. It is shown that the stator current can be used for detection of the electrical faults in the induction motor.

Hamid Nejjari et al (2000) presented a methodology by which induction motor electrical faults can be diagnosed. The proposed methodology is based on the Park's vector approach. Nakamura et al (2006) proposed a new method for fault diagnosis of induction motors based on Hidden Markov Model, which is widely used in the field of speech recognition.

Toliyat and Lipo (1995) have shown through both modeling and experimentation that faults result in asymmetry in the machine impedance causing the machine to draw unbalance phase currents. This is the result of negative sequence currents flowing in the line. However, negative sequence currents can also be caused by voltage unbalance, machine saturation, etc.,

Kliman et al (1996) model these unbalances which also includes instrument asymmetries. Detection of stator voltage unbalance and single phasing effects using advanced signal processing techniques have been described in **Benbouzid et al (1999)**.

Analysis of the steady state performance of an induction motor connected to unbalanced three phase voltages is presented by **Yaw – Juen Wang (2001)**. Dynamic behavior of an induction motor under voltage unbalance was concerned by **Harley et al (1989)**. Knowledge of how and to what extent the voltage unbalance influences the steady state performance of induction motors has been important and well documented by **Woll (1975)**, **Lawril (1991)**, **Smollack (1992), Kerstings and Phillips (1997), Wang (2000)**. It is the theoretical basis of engineering recommendations and standards related to induction motor operation, protection and failure identification.

AIMS AND OBJECTIVES

- To examine the concepts and elements of three stages induction motor drive and distinguish the requirement for a proficient speed control scheme.
- To study the simulation and speed control on motor drives controlling the connected voltage.
- To study the speed control methods of induction motors.
- To research and find exploratory outcomes and investigations of speed control of induction motor.

RESEARCH METHODOLOGY

The proposed methods of induction motor starting, speed control and energy efficient operation through intelligent techniques proposed in this thesis need to be verified through simulation study as well as experimental work. This chapter explains the development of a comprehensive dynamic model of ac voltage controller fed induction motor drive in Matlab/Simulink. The d-q axis model of induction motor together with ac voltage controller is suitably integrated such that the model can be effectively used for the transient response analysis during starting and speed control and steady state performance analysis during energy efficient operation of voltage controlled induction motor drive. A dedicated experimental setup was also developed in the laboratory and certain simulation findings are verified through experimental results.

Induction Motor Drive

The drive scheme consists of controlled parts, these are: two stage back to back converters (an uncontrolled rectifier and PWM controlled inverter) and induction motor. Others are optimal energy control and speed control. Converter and inverter are linked with a dc link capacitor. The front-end diode converter converts three-phase AC supply into dc supply. Source resistance (R) and inductance (L) are included and are connected in series with the input supply voltages (Ea, Eb, Ec). The PWM inverter fed induction motor drive draws power from the dc output of the front end diode converter. The PWM inverter feeds three-phase variable frequency and variable amplitude AC currents to the induction motor. The three-phase currents required by the induction motor are also controlled to be nearly sinusoidal by PWM current controller of the drive. The sinusoidal motor and supply currents are achieved by fast switching actions of IGBT power switches of the inverter and the converter. The precise speed of the induction motor can be achieved using the variable frequency supply since the speed is a function of system frequency. The PWM inverter alone is capable to produce the variable frequency supply and in order to reduce the cost of operation, the controlled rectifier used in the first stage is replaced by an uncontrolled diode rectifier. The sinusoidal pulse width modulation (SPWM) is used to control the turning on and off of the inverter switches.

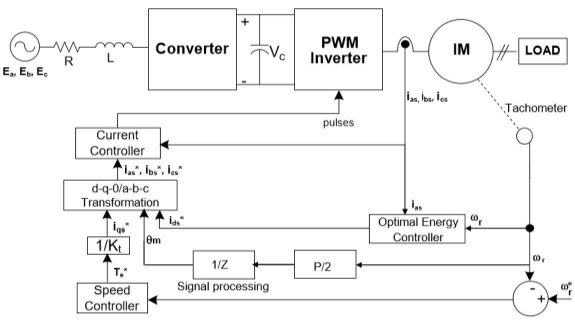

Figure 3. Schematic Block Diagram of Induction Motor Drive Scheme

The speed and stator currents are given to energy optimal controller of the induction motor drive, which generates flux producing current command. Particle Swarm Optimization (PSO) is used to find the optimal flux producing current of motor through its loss model. Continuous measurement of input power or dc link power is done when search control is incorporated in the optimal energy control block. Reference and actual motor speeds are given to speed controller of the IM drive, which generates torque command. Torque component of the current is obtained by dividing the torque command with the IM torque constant. The rotor position is calculated through digital signal processing for obtaining two phase (dq0-axis) to three phase (abc-axis) reference currents transformation. The PWM current controller of the IM drive has comparators. The actual stator current is measured and compared with the reference current to generate the sine modulating signal. Using the SPWM technique, pulses are generated for IGBT switches of the inverter. This closed loop control technique generates variable voltage variable frequency AC supply for smooth control of the induction machine speed with optimal efficiency (minimum loss).

Control of Induction Motor Drive

The PWM inverter converts the fixed DC supply generated from the first stage conversion using the uncontrolled rectifier into variable AC supply for the induction motor. To operate the inverter, only two stator currents are sensed and third current is negative sum of the two currents as shown in Fig. 2.2. Three phase reference currents are generated, which produce desired torque to accelerate and decelerate the motor for the desired speed regulation. The actual stator currents are measured and compared with the reference currents to obtain current error. One PWM current controller is used for each phase. The three-phase current errors are sent to respective phase PWM current controllers. The current controller of phase ‘a’ provides switching signals for devices T1 and T4, current controller of phase ‘b’ provides switching signals for devices T3 and T6, and current controller of phase ‘c’ provides switching signals for devices T5 and T2 to regulate phase ’a’, phase ’b’ and phase ‘c’ currents respectively. The switching devices are IGBTs with inbuilt anti-parallel diodes for freewheeling action. The switching actions apply the dc link voltage across three-phase line-to-line terminals of the motor. The three phase currents are independently controlled in the stator reference frame and care is taken to avoid unbalancing of the currents. Variable frequency and regulated current are obtained through the PWM inverter as needed for the induction motor. PWM technique, flux angle calculation, inner current controller and outer speed controller of the drive are briefly explained in following section.

A number of control strategies have been successfully applied in the past to three phase converters and inverters, some of which include sinusoidal pulse width modulation (SPWM), hysteresis current control, indirect current control, SPWM with instantaneous current control and space vector modulation (SVM). All these modulation algorithms are capable to control the switching of the inverter in such a manner so as to obtain minimum value of Total Harmonic Distortion (THD). Among the above stated methods, the sine PWM (SPWM) method is easy to implement and gives comparable performance with other techniques. In the present work, SPWM is used to control the switching. In this method, there are two signals; carrier wave and modulating wave. The high frequency carrier signal is compared with a sinusoidal modulating signal and pulses are generated. These pulses are used to turn on the power electronic devices.

The induction motor receives three-phase sinusoidal voltages at the stator terminals and produce rotating magnetic flux. This stator flux should be sinusoidal to obtain ripple free torque. Hence, the motor needs three-phase sinusoidal current to produce ripple free torque. As mentioned earlier the speed controller gives torque command. Using the torque command q-axis current command is calculated. Accurate position of the rotor is required to transform the rotor reference q-d axis currents into stator reference a-b-c axis currents. The reference slip frequency value of the rotor is added to the sensed rotor speed value and then a discrete integration is performed to determine the flux angle and hence rotor position. The rotor positions are sampled at a fixed time interval to obtain the speed of the motor. The speed controller utilizes rotor speed and current controller makes use of the rotor position to perform respective control actions. There are two control loops in the proposed drive scheme, one is the current control loop which controls the torque of the motor and other is the speed control loop which maintains the reference speed of the machine. The error in the speed (reference and measured) is processed in speed PI controller which generates the reference value of torque component of current (q-axis component). The difference in the reference current and the measured current is processed in torque PI controller. The torque controller (inner loop) being the electrical loop is faster than the speed controller (outer loop) because the mechanical time constant is greater than the electrical time constant.

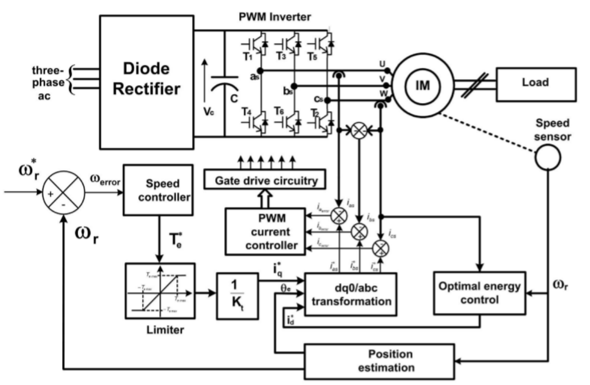

Figure 4. Induction Motor Drive Control Scheme

To get optimal efficiency of motor, energy controller produces optimal flux producing current (ids) command for the desired speed and load torque. Flux adjustment in the motor in accordance with the given load and speed results in loss minimization of the motor or entire drive systems. The reference values of the q-axis, d-axis currents and rotor position (angle) are used to calculate three-phase reference currents □ □ bsas i , i and □ csi using Park's transformation. Actual stator currents ias and ics are sensed and the third current ibs is calculated as the negative sum of the two sensed currents as shown in Fig. 4. To get current error the actual currents are compared with the reference currents and thus obtained current errors are sent to respective PWM current controllers. Outputs of the current controllers are the desired switching pulses of the inverter switching transistors. The switching pulses are applied to the switching devices through the gate drive circuitry. Every semiconductor switch is provided with a gate drive circuit which increases the level of the signal and at the same time the snubber circuit overcomes the overcurrent and overvoltage. Due to controlled switching of the inverter devices PWM phase voltages are applied across the motor phase windings to obtain actual currents almost equal to the reference currents. Once the actual currents follow the reference currents, the desired torque is developed to track the reference speed of outer loop.

Modelling of Induction Motor Drive

The mathematical model of the drive scheme includes model of the induction motor, model of the PWM inverter, PI speed controller and detailed loss models of both motor and inverter. The assumptions made for the modeling of the drive scheme are as follows;

1) The three phase stator windings of the induction motor are balanced and produce sinusoidally distributed Magneto Motive Force (MMF) in the space.

2) The DC link voltage available at the input terminals of inverter are assumed ripple free.

3) The three-phase sinusoidal currents flowing into the motor are also assumed ripple free.

4) Switching transients in the inverter and converter are neglected.

5) Switching transition times of the switching devices are negligible.

6) Three-phase input currents to the converter are sinusoidal.

Methods for Controlling Induction Motor Drives Speed

V/f control or frequency control: We vary the stator voltage in such a way that the flux remains constant by simultaneously varying the supply frequency such that the ratio V/f remains constant. The AC supply is rectified and then applied to a PWM inverter to obtain a variable frequency, variable magnitude 3-ph AC supply.

The electromagnetic torque developed by the motor is directly proportional to the magnetic field produced by the stator and the flux produced by the stator is proportional to the ratio of applied voltage and frequency of supply. Therefore, by varying the voltage and frequency by the same ratio, flux and hence, the torque can be kept constant throughout the speed range. This makes constant V/f method the most common speed control method of an induction motor.

Changing the number of stator poles: In this case of speed controlling method , it is very complicated to change the stator poles where it is time taking and there is change in design of the induction motor .so in this method we cannot make any change in stator poles so, we rarely use this method.

Controlling supply voltage: A very simple and economical method of speed control is to vary the stator voltage at constant supply frequency. The three-phase stator voltage at line frequency can be controlled by controlling the switches in the inverter. As seen from the equation (3.10) the developed torque is proportional to the square of the stator supply voltage and a reduction in stator voltage will produce a reduction in speed. Therefore, continuous speed control may be obtained by adjustment of the stator voltage without any alteration in the stator frequency

Change in the resistance of stator and rotor circuit: In this method of speed control of three phase induction motor rheostat is added in the stator and rotor circuit due to this voltage gets dropped .In case of three phase induction motor torque produced is given by $T \propto sV2\ 2$. If we decrease supply voltage torque will also decrease. But for supplying the same load , the torque must remain the same and it is only possible if we increase the slip and if the slip increase motor will run reduced speed. In this way we can control the speed of induction motor

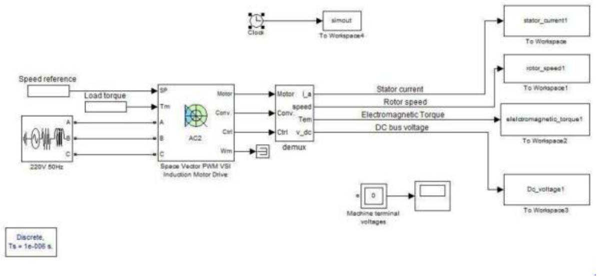

Figure 3: open loop PI controller for v/f ratio control method

The waveforms of open loop PI controller of v/f ratio method:

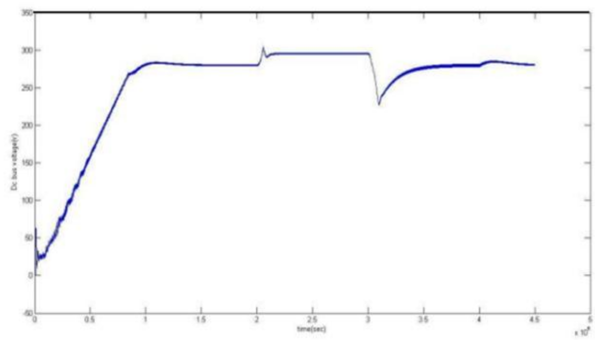

Figure 4: variation of dc bus voltage versus time

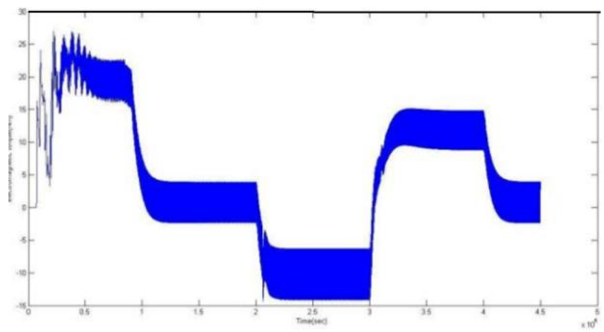

Figure 5: variation of torque versus time

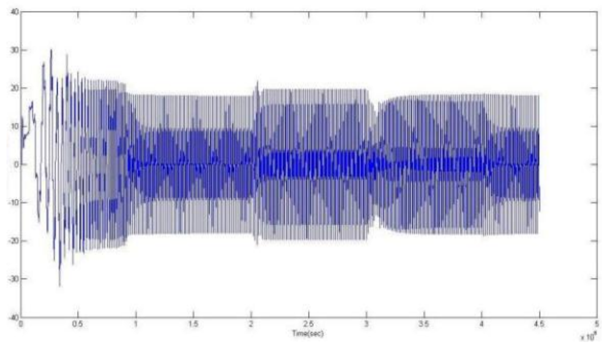

Figure 6: variation of stator current versus time

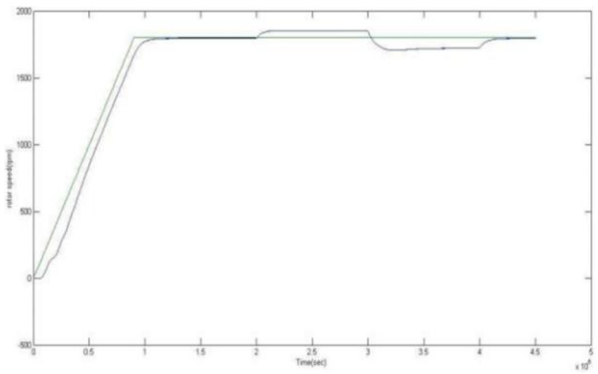

Figure 7: variation of rotor speed versus time

CONCLUSION

In V/f ratio control method we can control the speed of induction motor by changing the frequency. But in this case if we change the frequency the voltage at the secondary side also changes. So, for the low speeds the frequency of the supply voltages is small when compared to high speeds. So the supply voltage automatically decreased for maintaining V/f ratio constant. Therefore, the torque is decreased because the torque is directly proportional to square of the voltage. So, this is not a efficient method for speed control. Further we can conclude that we can change the resistance for the speed control of induction motor. In this method in order to get the maximum starting torque we can increase the rotor resistance. But in the running condition, the copper losses are increased due to having high resistance. So, the efficiency of the motor is decreased. So, we can conclude that it is also doesn't play a major role in speed controlling and we need to further check for other method.

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