MODELLING AND SIMULATION OF FAULT TOLERANT HIGH SPEED INDUCTION MOTOR DRIVE

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Submitted by

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Dedicated To

The Department of Electrical Engineering and School of Nuclear Studies, Jadavpur University, for all the knowledge and wisdom imparted to me in this period and for preparing me for my life ahead.

Certificate of Recommendation

This is to certify that Mr. Amresh Kumar Mahato (Exam Roll No. M4NUE19008) has completed his dissertation entitled, " ***MODELLING AND SIMULATION OF FAULT TOLERANT HIGH SPEED INDUCTION MOTOR DRIVE*** ", under the direct supervision and guidance of Prof. Debashis Chatterjee , Professor, Electrical Engineering Department, Jadavpur University. I am satisfied with his work, which is being presented for the partial fulfillment of the degree of Master of Nuclear Engineering of Jadavpur University, Kolkata-700032. To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other university or institute for the award of any degree or diploma.

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The forgoing thesis, entitled as “ ***MODELLING AND SIMULATION OF FAULT TOLERANT HIGH SPEED INDUCTION MOTOR DRIVE***” is here by approved by the committee of final examination for evaluation of thesis as a creditable study of an engineering subject carried out and presented by Mr. Amresh kumar Mahato (Examination Roll No.: M4NUE19008 , Registration No 119719 of 2012-13) in a manner satisfactory to warrant it’s acceptance as a perquisite to the degree of Master of Nuclear Engineering . It is understood that by this approval, the undersigned do not necessarily endorse or approve any statement made, opinion expressed or conclusion drawn therein, but approve the thesis only for the purpose for which it is submitted.

FINAL EXAMINATION FOR EVALUATION OF THE THESIS

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I hereby declare that this thesis contains literature survey and original research work done by me. All the information in this document have been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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ABSTRACT

Now a Days Fault Tolerant Control (FTC) systems are crucial in industry to ensure safe and reliable operation, especially of motor drives. This paper proposes the use of multiple controllers for a FTC system of an induction motor drive, selected based on a switching mechanism. The system switches between sensor vector control. Vector control offers high performance.

Development of Fault-tolerant control of high speed induction motor drives is attracting more interests due to its capability of increasing the reliability of voltage source inverts (VSI). In this paper development of fault tolerance high speed induction motor drives is presented, if one leg is completely lost due to abnormal condition the motor continue to run with a small fluctuation in speed with the help of other additional leg.

On-line condition monitoring of the induction motors has been widely used in the detection of faults. The fault tolerant control of the induction motor is of great importance for its continuous operating capacity even under the faulty condition.

This paper proposes a fault tolerant topology composed of an additional phase leg and a fault- protective circuit for high speed induction motor. Both simulation results and experimental results with an induction motor drive show the scheme to be a fast and effective one for fault detection, while the control methods transition smoothly and ensure the effectiveness of the fault tolerant control system.

Index Terms - Induction motor drive, fault tolerant control, vector control, three phase inverter, mosfet switch.

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CHAPTER-1: INTRODUCTION

1.1 OVERVIEW

1.1.1 Faults in Motor Drives

The three-phase induction machine is one of the most popular rotating electrical machines used in industrial driven equipment due to its ruggedness and versatility. With the development of power electronic inverters and their digital control platforms, the three phase induction machine has become the most widely used electric machine for variable speed drive applications. However, their application has expanded beyond industrial drives and they are now used in aerospace automotive, medical, nuclear and military applications. Some of these drives used in critical process control and cannot be interrupted under the penalty of stopping the whole process. The reliability of an adjustable speed induction machine drive is extremely important, especially if it is used for remote or safety critica applications. For this reason, induction motor drives with a high degree of fault tolerance are required for many applications, where it is very important to ensure that the continuous operation of the drive system is maintained.

The major faults of induction machines can generally be summarised as the following [1]:

- Stator faults resulting in the opening or shorting of one or more turns of a stator phase winding.
- Abnormal connection of the stator windings.
- Broken rotor bar or cracked rotor end-rings.
- Static and/or dynamic air-gap irregularities.
- Bent shaft (similar to dynamic eccentricity) which can result in rubbing between the rotor and stator, causing serious damage to stator core and windings.
- Bearing and gearbox failures.

From the above listed types of faults: the stator faults; the broken rotor bar and end ring faults of induction machines; bearing; and the eccentricity-related faults are the most common failures, and thus require special attention. Several studies have shown that 30-40% of induction motor failures are due to stator winding insulation breakdown [2]. The organic materials used for insulation in electric machines are subjected to deterioration, due to a combination of thermal overloading and cycling, transient voltage stresses on the insulating material, mechanical stresses, and environmental stresses. Among the possible causes, thermal stresses are the main reason for the degradation of the stator winding insulations. Generally, thermal stresses on the stator winding insulation are

classified into three types: aging, overloading, and cycling. Even the best insulation will fail quickly if operated above its temperature limit. As a rule of thumb, for every $\mathbf{10°C}$ increase in temperature, the age of insulation life reduced by 50% [3]. Regardless of the causes, stator winding- related failures can be divided into the following five groups: turn-to-turn, coil-to-coil,
line-to-line, line-to-ground, and single or multi-phase windings open-circuit faults as presented in Fig. 1.1.

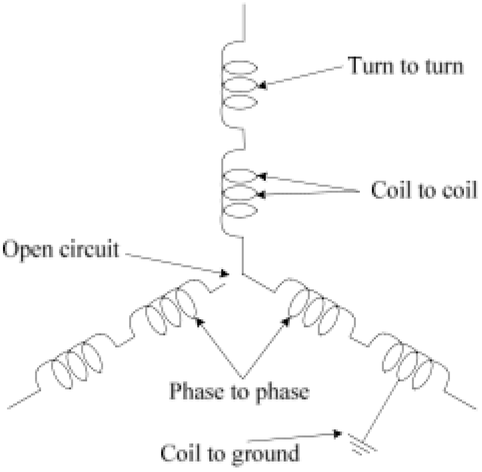


Fig. 1.1 Star connected stator showing possible failure modes [3].

It is generally believed that a large portion of stator winding-related failures are initiated by insulation failures in several turns of a stator coil within one phase which is called stator turn fault [4]. A stator turn fault in a symmetrical three-phase AC machine causes a large circulating current to flow and subsequently generates excessive heat in the shorted turns within a short time, in which the heat is proportional to the square of the circulating current. For a short period of time this fault will develop to be an open circuit winding fault and it can generally result in complete motor failure. The open circuit fault can be caused by other reasons such as mechanical failure of a machine terminal connector, an internal winding rupture, or by an electrical failure in one of the inverter phase legs [5]. Therefore, an open circuit fault can be considered to be one of the most common faults in induction motor drives [6]. However, the worst consequence of an open circuit fault in a safety-critical application would be a serious accident involving loss of human life resulting from an abrupt shutdown of the drive’s operation. This work focuses on electrical faults in induction machines fed from power electronic drives using a Pulse Width Modulation- Voltage Source Inverter (PWM-VSI), and specially focuses on the open circuit fault. The main idea is to increase the stator open circuit fault tolerance of an induction motor drive in particularly for safety-critical applications.

1.1.2 Fault Tolerant Operation of Motor Drives

It is important to emphasize that fault tolerant systems need to incorporate an appropriate control architecture that includes a monitoring system which employs a fault detection strategy, and a controller which can organize reconfiguration for fault handling and subsequent post-fault operation. The definition of fault tolerance is the ability of a controlled system to maintain control objectives, despite the occurrence of a fault [7]. A degradation of control performance may be accepted but the ultimate aim is to avoid the interruption of the process. Based on the idea of keeping the electrical motor drive operating after a fault has occurred, two potential solutions have been suggested to overcome the problem and prevent overall system malfunction [8], namely:

- Redundancy.
- Fault diagnosis and fault-tolerant operating strategies by taking remedial actions.

Redundancy is commonly applied in improving the fault tolerance of electric motor drives. The concept of redundancy is well understood: if part of a system fails, there is an extra or spare that is able to operate in place of the failed unit such that the operation of the system is uninterrupted [8]. Although this approach is the surest way to increase the fault tolerance of an electric motor drive, it greatly increases the cost and complexity of the system. Moreover, redundancy may not be practical for an application that has a severe restriction on the installation space, such as in the case of traction drives in electric or hybrid-electric vehicles [4].

The alternative choice to the redundancy approach is fault diagnosis and fault tolerant strategies. With the appropriate machine monitoring and fault detection schemes early warning signs can be obtained to reduce maintenance, improve safety, and improve reliability for many engineering systems. The purpose of diagnosis is to detect and locate a certain failure from its point of inception so as to prevent major damage to the system and allow adequate timely actions to protect the system. Fault tolerant strategies are based on the concept that a faulty system can maintain its uninterrupted operation with the assistance of a modified topology or control algorithm. Several researchers have proposed fault-tolerant operating strategies to overcome this problem. This has been achieved by using new inverter architectures based on hardware redundancy to add reconfigurability to the system. The proposed solutions include the use of electrical motors with a redundant number of phases [6, 9-12], modifying the standard converter topologies by adding extra bidirectional switches to bypass the faulty power semiconductors, short-circuited or open circuited windings [13-15]. Other approaches include the availability of the motor stator winding neutral connection [14, 16], the use of inverters with a redundant number of controlled power switches [15, 17-19], the use direct AC–AC matrix converters instead the traditional AC–DC–AC drives [20-23], or the use of control adaptation without extra hardware [24, 25]. In addition, the reference signals to generate the post-fault switching patterns have to be modified to properly excite the motor for the resulting topology.

1.1.3 Fault Detection in Motor Drive Systems

In order to activate the fault tolerant control strategy, an accurate fault detection and diagnosis method needs to be utilised to ensure stable and reliable operation for safety critical applications. An accurate fault diagnosis system exhibits high fault detection rates and low false alarm rates, while maximizing the correct classification of detected faults. If the detection capability of a fault diagnosis system is poor, then it is likely to miss developing faults which may lead to critical machine failures and breakdown of entire systems. While, if the fault detection system is too sensitive then it is likely to generate high rates of false alarms and may lead to a wrong decision being made. Different approaches for motor incipient fault detection and diagnosis have been successfully proposed by others. The common technique for online detection of motor faults is known as Motor Current Signature Analysis (MCSA) [26, 27]. It has been shown that there is a relationship between the mechanical vibration of a machine and the magnitude of the stator current component at the corresponding harmonics [1]. The objective of this technique is to detect certain components in the stator-current spectrum that are only a function of a specific fault. The spectrum is obtained using a Fast Fourier Transformation (FFT) that is performed on the signal under analysis. For different motor faults, the fault frequencies that occur in the motor current spectra are unique. However, it has been shown mathematically and experimentally by [28] that the spectral components due shorted turns are not a reliable indicator of stator winding faults. A non-invasive technique for diagnosing machine and VSI failures in variable speed AC drives, based on the identification of unique signature patterns corresponding to the motor supply current Park's vector, was also proposed in [29, 30]. In [31, 32] the multiple reference frames theory was proposed to diagnose stator faults in three-phase induction motors directly connected to the grid. This method exploits the fact that each component present in the motor supply currents can be expressed in a reference frame in such a way that it will appear as constant within that reference frame. Almost all the proposed methods attempt to detect a change of the unbalance in the motor using indicators such as measurement of the negative sequence current [33, 34], negative-sequence impedance [35], zero sequence component [36], external signal injection [37] and change in positive-sequence current due to a stator fault [38]. References [33] and [34] describe more refined versions of the negative- sequence-current-based schemes. In order to prevent a false alarm, causes such as voltage unbalance, saturation, eccentricity, and instrument asymmetry have also been factored in the negative-sequence-current measurement. For example, [34] enhances the work with a formula to account for them. An extensive survey of methods for detection of stator-related faults in induction machines can be found in [2]. It is important to emphasize that the use of different diagnostic techniques to diagnose different types of faults, as it appears that no technique is able to cope easily with all types of faults. In addition, some of the diagnostic techniques proposed so far rely on a detailed knowledge about the motor, usually difficult to obtain when the motors are already installed and in operation.

1.2 MODELLING MOTOR DRIVE SYSTEMS

The design of new high performance vector control algorithms often use simulation models for initial development. These simulations ideally use a good machine model that takes the machine’s non-linearities into account. Researchers working on condition monitoring and fault tolerant control of induction machines often need an accurate model to predict performance and to extract fault signatures [39]. This includes a representation of flux, current and torque harmonics in both healthy and fault conditions. Therefore, there is a real need to derive an accurate model, which can take into account the effect of saturation and field harmonics both in time and space, whilst still being embedded in a simulation, which includes real time control and a representation of power converters. Simplified models based on the machine equivalent circuit are computationally fast and allow integration with real time control strategies, but are not accurate because they neglect the machine geometry and nonlinear magnetization effects. At the other extreme, the finite element model (FEM) provides detailed information about most machine nonlinear effects [40-47], but its solution is time consuming especially if a control algorithm needs to be incorporated [39]. A method providing a compromise between the speed of the conventional methods and the flexibility of finite-element analysis is the Dynamic Mesh Reluctance Modelling (DMRM) technique [48-52]. The analysis is not as accurate as the FEM but its computational time is significantly faster, enabling the use of DMRM models to evaluate control applications. Different nonlinear numerical models have been developed to simulate space harmonics and other nonlinear harmonic effects, which are based on the geometry of the squirrel cage induction motor [39, 53-61]. This modelling technique used coupled magnetic circuits approach combined with the Winding Function Approach (WFA). Such a model based on the geometry and winding distribution, having no restrictions regarding its symmetry, is more suitable for motor analysis and simulation under asymmetric and fault conditions. By comparing the various techniques, the DMRM and the WFA showed a good modelling accuracy and computational time faster than the FEM (2 hours vs 12 hours [62]). However, it is still comparatively slow when fast response current and torque control is required. One of the aims of this work is to focus on deriving an induction machine model, which gives a good compromise between modelling accuracy and simulation time, and can be used to develop fault tolerant induction motor drives. This is achieved by developing and enhancing an equivalent circuit based model of the induction machine to include the space harmonics and machine saturation effects, such that the performance of motor drive system under healthy and faulty conditions can be simulated. The proposed model is able to provide a useful response (in terms of flux, current and torque harmonics) for the simulation of symmetrical and asymmetrical conditions, with only a short simulation time.

1.3 PROBLEM STATEMENT

An open circuit fault in an induction motor drive for a safety critical application should be detected quickly, on-line. The drive should be maintained in normal operation in order to prevent a potentially serious accident involving loss of human life or interrupting critical industrial processes. The scope of this work is to increase the stator open winding fault tolerance of induction machine drives, particularly in safety critical applications. This objective is to be achieved in three stages.

- The development of a more realistic simulation model for an induction motor which reflects saturation and space harmonics effects whilst at the same time having a relatively low computational requirement to allow it to be used in conjunction with the simulation of high performance control algorithm and power electronic equipment.
- b) To use the new model to develop a new fault detection algorithm.
- c) To use the new model to develop new control algorithms for fault ride through.

To provide an accurate description of the behaviour of an open circuit fault in an induction machine drive, a model of an induction machine with open winding faults is derived and integrated with a PWM-VSI model. In the derivation of the machine model, an equivalent circuit based approach is adapted for a faster simulation speed. For more realistic simulations, this model is extended to include space harmonics and machine saturation effects and provides a useful tool for simulation of symmetrical and asymmetrical conditions that require a short simulation time, even for the case where a high performance controller is included in the simulation. The improvement is obtained by including a variation of the machine inductance with rotor position and flux position. The space harmonic effect is incorporated on the machine’s mutual inductance as a function of rotor position and the saturation effect is incorporated as a flux position-dependant component in the stator mutual inductance. It is expected that by including the space harmonics and saturation effects, the model will help to identify some of the current harmonic components appearing under fault conditions. Thus, one of the main aims of the proposed model is to provide a tool for fault analysis in drives. As the model is a compromise between speed and accuracy, the model should give illustrative information about the harmonics present under various operating conditions. The on-line open circuit fault detection method for a delta connected induction machine drive begins with a thorough evaluation of the state of the art open circuit winding fault detection methods for PWM-VSI driven applications. A novel on-line fault detection and diagnosis algorithm based on the measurement of the third harmonic component in the motor line currents has been proposed. The basis of the proposed method is that when an open circuit occurs for a delta connected machine, the machine is transformed into a two phase star connected machine with access to the neutral point. As a result of the affected winding configuration, the triple harmonics (third harmonic component) appear in the line currents since the system is not symmetrical. This will be reflected on the distribution of the harmonics over the three line currents, especially for the case of the third harmonic component. Therefore, the location of the open circuit winding fault is based on detecting a magnitude reduction for the third harmonic component of the current flowing to the motor's mid point connection. The use of the third harmonic component in the line current for open winding fault detection gives distinct benefits over conventional current fault detection methods. It is quite simple and easy to implement online and embedded into the processing platform of the drive as a subroutine without extra cost (i.e. no extra hardware is required), as the current sensor is already available in any PWM-VSI drive. A new open circuit fault tolerant operating strategy specifically designed for a delta connected induction machine suddenly affected by an open circuit winding fault is proposed in this work. The description of open circuit fault tolerant operating strategy begins with a thorough evaluation of the state of the art. Most of the work addressed open circuit faults for star connected machines and most of the previous strategies have unsatisfactory performance characteristics with respect to cost, efficiency, or availability. The fault ride through is achieved without any modification to either the power converter or the motor circuit and more importantly, it does not result in the complete loss of availability of a drive in the presence of a stator open circuit fault. In fact, the proposed approach is also applicable to a fault tolerant drive containing an extra inverter leg connected to the neutral point of a star-connected machine. A novel feedforward compensation algorithm is introduced for the zero sequence component of the dqo reference voltages which considerably reduces the current and the torque ripple in the faulted drive motor. Two methods fo controlling the neutral point voltage are also presented so that the available voltage capacity of the inverter is maximised in both normal and fault mode. For high speed operation, a field-weakening controller must be adopted by controlling the flux level to prevent inverter saturation. The main idea as speed increases is try to keep the stator voltage applied to the machine constant by reducing the magnetic flux. Two different methods for field weakening control are presented; an open loop field weakening controller using a conventional method and a new closed loop field weakening controller that relies on the inverter voltage references and the maximum output voltage of the inverter so that the available voltage capacity is maximized in both the normal and the fault mode. Another important contribution of the proposed strategy is that the same principle can be applied to both induction machines or permanent magnet synchronous machines.

CHAPTER-2:

FAULT TOLERANCE CONTROL TECHNIQUE

2.1 LITERATURE SURVEY

The research work carried out by various researchers in the field of modeling, control and implementation of speed control of IMs using various control strategies is presented in this chapter. Various researchers have worked on the speed control of IMs using various control techniques. Some of the techniques are the SVPWM method, the PI method, the sliding mode control method etc. These are discussed one after the other in succession along with their advantages and disadvantages. This is followed by motivation for carrying out the research work and the problem definition.

2.2 REVIEW OF CONVENTIONAL-TYPE CONTROL METHODS

The classical or conventional type of control is used in most of the electrical motor drives. It requires mathematical model to control the system. When there are system parametric variations, the behavior of the system is unsatisfactory and it deviates from the desired performance [5]. The dynamic behavior of a closed-loop, variable-speed induction motor drive that uses 3 SCRs (Δ-connected) was investigated by Ahmed and Farag in [6]. The use of a linear, state-variable feedback controller and the choice of the controller parameters with the purpose of optimizing a performance criterion related to the dynamic operations of the drive were used in their method. The transient responses for load and reference speed perturbations were obtained analytically using the theory of state variables. The choice of the coefficients of the linear combination to minimize the given functional was also suggested by them. Pillay and Levin [7] developed mathematical models like the dq model and the abc models incorporating the various forms of impedance and/or voltage unbalances and designed controllers to control the various parameters of the IMs using the d–q method and the abc method. The new minimum-time, minimum-loss speed control algorithms are developed for IM to obtain better performance, efficiency, under FOC with practical constraints on voltage and current in [8]. A novel control technique for controlling some of the parameters of IM using the SVPWM method is presented in [9] and [10]. Also an excellent 3Φ bridge inverter, which was used to apply a balanced 3Φ voltage to the SCIM, was developed. Maamoun [11] presented an SVPWM technique based inverter for v/f control method, and it was used for open loop speed control of IM. Ben-Brahim proposed a modified 'v/f' method of developing a controller for high-rating IMs in his paper in [12], which yielded excellent results. Scalar control is another type of control scheme used to control various IM parameters while operating in the steady state. In this method, the amplitude and frequency of the supply voltage are varied [13] to control the speed of IM. FOC or vector control [14] of an IM results in decoupled torque and flux dynamics, leading to independent control of the torque and flux as for a separately excited DC motor. FOC have a major disadvantage: they are sensitive to rotor time constant and incorrect flux measurement or estimation at low speeds [15]. Consequently, performance deteriorates and the conventional controller may be unable to maintain satisfactory performance. Furthermore, an efficient method of controlling the speed of an IM by considering a specific example was proposed by Zhang and Jiang in [16] using indirect field control coupled with synergetic control. The parameter sensitivity of the rotor flux oriented system (FOC) with rotor flux estimation was discussed by Xingyi Xu in [17]. There, a stator-flux orientation strategy was proposed. It is a well-known fact that the estimation of stator flux of an IM is independent of flux leakage. Because of this, the IM's performance in the steady state is not sensitive to leakage inductance. The authors proved that the previously mentioned concept improved the dynamic performance of the IM system. They also carried out digital simulations in Matlab and showed that the stator flux-based IM system's performance was superior/excellent compared to that of a de-tuned motor flux-based IM system. Compared to vector-controlled drive or field-oriented control drive, the scalar-controlled drive is very easy to implement, with the disadvantage being inferior performance of the drive. There is limited speed accuracy in the control design, particularly when the range of speed is low. Another disadvantage is the poor dynamic response of the torque. Moreover, the design and tuning of the conventional controller mentioned in the previous paragraphs increase the implementation cost and add additional complexity in the control system and, may reduce the reliability of the control system. The main drawbacks of the linear control approaches were sensitivity in performance to the system parameters variations and inadequate rejection of external perturbations and load changes [19].

2.3 REVIEW OF DTC METHOD

Brahmananda Reddy et. al. [20], proposed a new concept of hybrid SV PWM scheme for the control of IM using DTC methods. They considered reduced switching losses in the inverter coupled with ripples in the torque, flux, current in the steady state while designing the controller. The designed pulse width modulation technique was based on the concept of stator flux ripples. Stator flux ripples were taken as a measure of line current ripples in their research work.

They performed the simulation in Matlab/Simulink and the results showed the superiority of the method proposed by them compared to the conventional method. Ming Meng presented a voltage vector controller for the speed control of IMs using the concept of motion EMF in [21]. Furthermore, he also showed that not only constant power but also constant torque control could be achieved by his method. The rotor motion electromotive force was evaluated using 3 categories: FOC, DTC and DSC. Jagadish Chaudhari et. al. [22] proposed the conceptual view of an SPWM of the voltage applied to the IM's stator. By using the SVPWM concept, the duty cycle of the inverter was calculated. This method was considered as one of the excellent methods for torque control and it was completely different from the FOC method. However, the above-mentioned methods presented by the authors in [6] - [8], [11], [17] are classical in nature. The controller is designed on the transfer function approach and the steady-state vector method. In the classical control methods, the systems parameters are assumed to be linear, but in actual practice, the systems parameters are purely non-linear in nature. The system parameters are time-dependent; moreover, based on the disturbance, the values will vary. However, the IM is highly non-linear in nature. Hence, proper control through the classical control techniques may not yield appropriate results. Usually, classical control used in motors drives has certain drawbacks. There are a number of difficulties involved in the design and implementation of conventional controllers for induction machines. Few of them are as follows [23]:

- The conventional control uses an accurate mathematical model, which is very difficult to obtain. Of course, it can be obtained using system identification techniques.
- The performance of classical control system drop off for non- linear systems (drives).
- The variations of some of the parameters of the IM are caused due to the sudden disturbance in load variations, due to thermal or temperature changes or due to motor saturation effects.
- In the case of classical control (PI) using linearity concepts, high performance is achieved only for unique operating points.
- Classical control cannot produce good results when improper coefficients are chosen during the simulation. Especially when the set point varies, the problem may still deteriorate and optimum results may not be obtained

.

One of the conventional methods, namely the DTC, gives faster and robust responses of various parameters in the IMs, as seen in [20] - [23]. The drawbacks in this conventional method are the output responses of torque, flux is noisy due to the noise effects and improper estimation of speed. There are two advantages of using the DTC method for control of IMs: constant torque control and constant power control. The DTC method improves the performance of IM to a very great extent, when compared with the conventional speed control methods. The DTC scheme presents many disadvantages like variable switching frequency, violence of polarity consistency rules, current and torque distortion caused by sector changes, start and low-speed operation problems, and high sampling frequency needed for digital implementation of hysteresis comparators. Hence, to overcome the drawbacks of these classical approaches (PI/DTC/v–f, etc), the fuzzy method can be used along with the classical control approaches.

2.4 REVIEW OF PI CONTROL METHODS USING FUZZY

Design of an FLC-based self-tuning proportional integral controller for control of speed in IMs was addressed by Mokrani and Abdessemed in [24]. The tuning of the conventional proportional integral controller was obtained using the fuzzy rules obtained from tests. A number of operating conditions were considered in the controller design. Some of the operating conditions were steep change in load torque, speed reversion, decrease or increase in rotor resistance, change in the inertia of the system or self-inductance of the system. Bhim Singh and S.C. Choudhari [25] presented a comparative study of PI, FL, Fuzzy pre-compensated PI, Fuzzy PI and hybrid speed controllers for vector control of IM drives in their research paper. They used an indirect vector-controlled strategy for the control of current- controlled voltage source inverters. They studied the responses using these 5 types of controllers for starting, speed reversal and load perturbations. However, there are certain drawbacks of the PI-based fuzzy approach [24], [25] regarding control of the various parameters of the IM: e.g. the fixed gain in PI as a result of which optimal results may not be obtained. By using fuzzy, appropriate gain can be selected by using the fuzzy rule base.

CHAPTER-3:

3.1. FAULT TOLERANCE

The definition of fault tolerance is the ability of a controlled system to maintain control objectives, despite the occurrence of a fault [7]. A degradation of control performance may be accepted but the ultimate aim is to avoid the process stoppage. For this purpose, the controller design has to be prepared for such conditions and the control hardware requires some redundancy in its structure to overcome the problem when the fault occurs. It should also, ideally control the motor with minimum additional torque ripple and minimum additional losses.

Based on the idea of keeping the induction-motor drive operating after open fault detection in the machine winding or failures in the power converter, several authors have proposed fault-tolerant operating strategies to overcome this problem. This has been achieved by using a new inverter architecture based on hardware redundancy to add reconfigurability to the system. The proposed solutions were the use of induction motors with a redundant number of phases, modifying the standard converter topologies by adding extra bidirectional switches to bypass the faulty power semiconductors or short and open circuited windings, the availability of the motor stator winding neutral connection, or the use of inverters with a redundant number of controlled power switches. In addition, the references to generate the post-fault switching patterns have to be modified to properly excite the motor with the resulting topology. Open circuit fault tolerant techniques for 3-phase induction motor drives generally require a neutral motor connection to enable separate current control of the remaining healthy phases once a fault occurs. Reference [14, 16] proposed the use of triacs to connect the star point of the machine to the DC link midpoint of the inverter as shown in Fig. 3.1(a). After the fault is detected, the control system isolates the faulty leg through fast active fuses and connects the stator windings neutral point to the DC link middle point. A degree of control can be achieved here, but there is a significant limit to the maximum available motor line voltage [14], which restricts considerably the operating range of the machine. The strategy consists in reformulating the current references so that the rotating MMF generated by the armature currents do not change, and to minimize the electromagnetic torque ripple component, even if one phase is open circuited after a fault occurrence. In addition, this approach also provides a path for the 3rd harmonic current and can therefore lead to additional losses and torque pulsations. Another approach is proposed and discussed in [13-15], in which a pair of back-to-back-connected SCRs is used to switch off the faulty motor phase current as shown in Fig. 3.1(c). After the fault, a phase remains permanently connected to the midpoint of the DC voltage or, when insufficient voltage is available, the neutral is connected back to the midpoint, that has to be derived by using series-connected capacitors. The technique, in principle quite simple, becomes complicated by the need for preventing the capacitor midpoint voltage from drifting from the correct point. Also, the DC link filter capacitor needs to be overdesigned (by a factor of 5 to 10) in order to absorb the large fundamental frequency neutral current [25]. In order to overcome this problem and the low frequency pulsating torque without the use of the neutral-point connection, an alternative approach was proposed in [24, 25]. It is based on the injection of odd harmonic voltages at appropriate phase angles. None of these techniques requires an extra number of controlled power switches, only control-software adaptation. In [17-19] another solution is proposed to prevent using the mid-point of the DC link capacitors. It is a different topology based on the connection of the motor's star point to a fourth inverter leg as shown in Fig. 3.1(b). Furthermore, in [15] a further topology is proposed based on using fourth leg as in Fig. 3.1(b) but the three machine terminals were connected to the fourth inverter leg through a bidirectional switches as shown in Fig. 3.1(d). This topology is employed to by pass the faulty power switches in the converter only. By using an adequate control strategy for the additional leg in Fig. 3.1(b), the drive can deliver the same speed and torque ranges as those before the fault, at least on a reduced operating duty. Such a control strategy is presented in [19] where a "double controller" scheme employs one controller for the positive sequence and another for the negative sequence. In [17, 18] a similar method was presented and was applied to a PMSM. A feedforward compensation was used to eliminate the unwanted current and torque components. A comparison study of these emerging topologies in terms of cost, features, and limitation is presented in [14]. An approach used recently employs direct AC–AC matrix converters instead the traditional AC–DC–AC drives for fault tolerant machine control as reported in [20-23]. It has been mentioned that the matrix converters have shown many advantages compared with traditional drives [21, 22]. For example, no DC-link capacitor is used, sinusoidal input and output currents (unity power factor) are obtained, and the resulting converter size is reduced. However, expensive solutions for overvoltage protection and complex control algorithms are required [90]. In [20, 21], a fault- tolerant topology to tolerate open and short phase failures for matrix converter drives has been proposed, where a new matrix converter structure and switching scheme have been suggested to generate three - phase balanced sinusoidal output currents, even after short circuit phase failures in the matrix converter drive. The open-phase faults considered in [20, 21] include, opened-switch faults in the converter and open circuit winding fault in the machine. In [21], the neutral connection approach was utilised as a fault-tolerant solution by connecting the motor neutral to the neutral point of three-phase supply utility as shown in Fig. 3.1(e). However, the neutral point of the supply voltage sources is not necessarily available in some power systems. Therefore, references [20, 23] address a fault-tolerant solution based on four-leg configuration to implement fault-tolerant matrix converter drives with no neutral point available from the supply utility. Similarly, in [23] only an open phase fault in the machine winding is considered and the four-leg matrix converter topology with the fault-tolerant capabilities for open phase failures is shown in Fig. 3.1(f). Reference [22] presents detailed fault conditions of the matrix converter induction motor drive system and a novel protection strategy is proposed for the converter shutdown. The key to the proposed protection strategy was to provide a controlled free-wheeling path for the motor currents when a fault happens. It is demonstrated that the fault modes can be classified into two types: faults leading to an over-voltage, and faults leading to an over-current. In order to detect an abnormal operation, three over-current thresholds are used. Control switches are provided for a proper freewheeling path of the motor currents, so it is possible to eliminate the stored electric energy as quickly as possible.

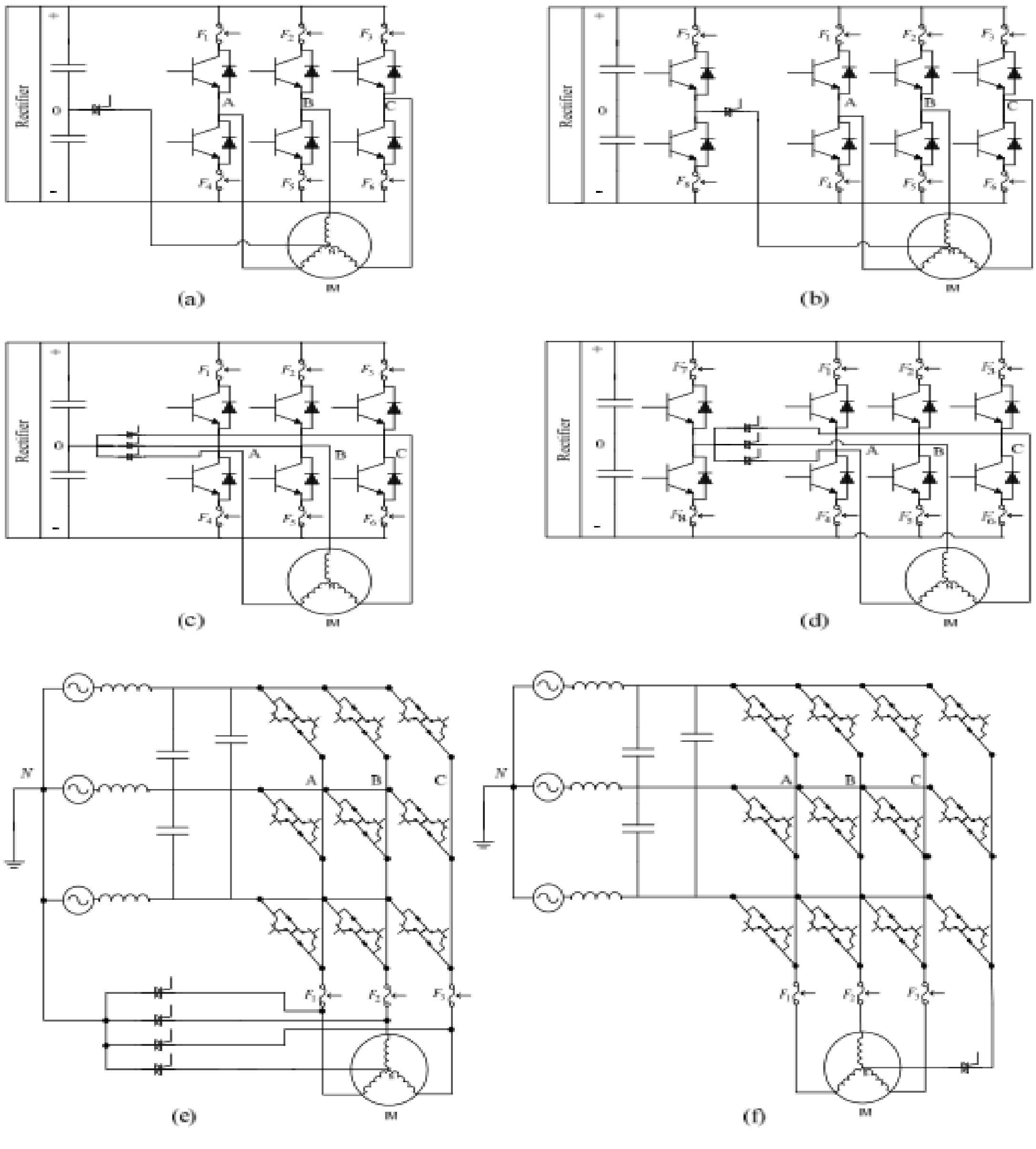


Fig. 3.1 Fault tolerant motor drive configurations

Most of the control strategies that been mentioned above to drive three-phase induction machines under fault conditions need a hardware redundancy. Other approaches have been explored in the literature which consider multiphase machine design for fault tolerant operation [6, 9-12]. Multiphase machines are advantageous over conventional three-phase machines for fault-tolerant operation.

This is because in multiphase machines, when faults occur in one or more of the phases, the machines can still continue to operate using the remaining healthy phases [9] without needing to access i.e. the neutral point. Furthermore, fault-tolerant operation in multiphase machines does not require any additional hardware [6, 9-12], as it can be achieved just by using a modified control strategy. However, the choice of the number of phases is mainly a balance between the higher fault tolerance capabilities (a higher phase machine is able to give) and the lower reliability of the drive in terms of increased device count. Apart from improving fault tolerance, a multiphase machine has other advantages such as lower torque ripple, greater power density, lower stator current per phase without increasing the voltage per phase, and lower stator copper losses [6, 12]. These advantages make the multiphase machines suitable candidates for applications where high reliability is demanded. In [6, 9-12], the multiphase machines are considered to develop a fault-tolerant control strategy under open circuit fault condition (loss of one or more legs of the inverter or motor phase). The fault-tolerant operations of the multiphase PM machines and the multiphase induction machines, both with only sinusoidal stator winding distributions, are discussed in [11] and [9], respectively. In these cases, the stator phase currents are calculated to keep the rotating MMF undisturbed during faults. Reference [10] presents the application of using a third harmonic injection method to reduce the output torque ripple of a five-phase PM machine under various open circuit faults. While reference [6] designs an optimal control technique based on the instantaneous power balance and the ohmic loss minimization theory for multiphase PM machine under open circuit fault.

3.2 FAULT TOLERANT DRIVE CONFIGURATION

The main aim of fault tolerant drive system is to continue the operation of the drive in a satisfactory way in the presence of a fault. This means that control and a minimum level of performance should be kept after a fault occurs. It should be noted that when operating with a fault, the system efficiency is typically reduced. Since operation with a fault represents an abnormal condition, the system efficiency is a secondary concern as long as the system is thermally able to accommodate the increased losses safely. Those additional losses during post-fault operation are typically modest and dependent on the selected topology [14].

A star connected 3-phase machine without a neutral connection effectively becomes a single phase machine when a phase open circuit occurs. It is clear that under this condition the machine cannot produce a smooth rotating MMF [16], and large torque pulsations will be produced at a twice the electrical frequency due to the presence of a large negative sequence component in the stator current [50]. If the neutral point of the machine is connected directly to the midpoint of the DC link [16], or to a fourth leg of an inverter [17-19] as shown in Figs. 3.2a and 3.2b, then the stator currents can be controlled to produce a dominant rotating magnetic field that can emulate the normal operation of a healthy machine.

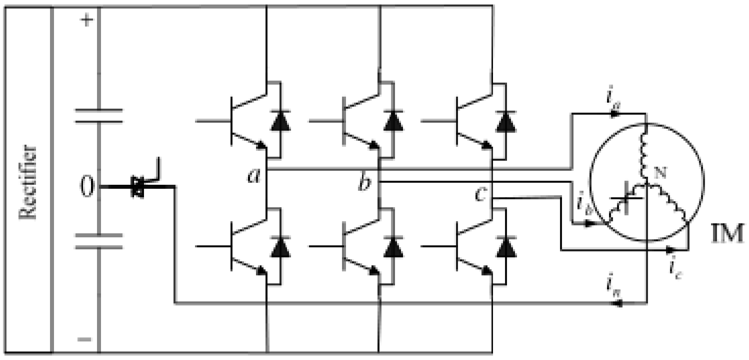


Fig. 3.2a Fault tolerant scheme based on the stator neutral point connected to the midpoint of the DC link

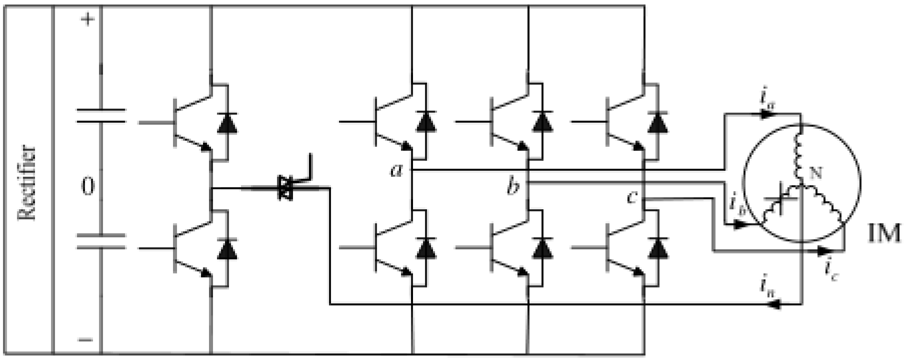


Fig. 3.2b Fault tolerant scheme based on the stator neutral point connected to a fourth inverter leg.

When the system detects an opened phase fault as in Fig. 3.2a, the neutral point of the windings will be connected to the midpoint of the DC link capacitors by firing the TRIAC element so a path for zero sequence current can be provided. Since the faulted phase is disconnected, the two remaining healthy phase currents need to be shifted 30° away from the axis of the faulted phase, and the amplitude of these current should be increased by $\sqrt{3}$ compared to the pre-faulted value in order to maintain the same torque level observed during healthy conditions [16]. This means that the same MMF (observed during healthy operation) will be kept when operating with a fault. Note that the increased value in the currents will be observed as a non-torque producing zero sequence current which achieves a constant flux trajectory and ensures a disturbance free operation of the system [14, 16]. A limited amount of control can be achieved here; however there is a significant limitation on the maximum available DC link voltage that can be applied to the machine which restricts motor line voltage and the operating range of the motor considerably. Note that the maximum phase voltage can be applied is limited to ±1/2 of the DC link voltage. As a result of the increase in the line currents ($\sqrt{3}$ times higher than the ones obtained during pre-fault operation) the semiconductor rated current needs to be increased by $\sqrt{3}$ times of the value used for the normal condition. Unfortunately, this approach also provides a path for 3rd harmonic current which can lead to additional torque pulsations. In order to overcome this problem, [17-19] used a different topology based on the connection of the winding neutral point to an additional inverter leg as shown in Fig. 3.2b. By implementing a suitable control strategy for the additional leg, the available DC link voltage of the inverter during faulty operation is similar to that produced by a healthy system. In this way, the drive can supply the same speed and torque ranges as those observed before the fault. However, the drive voltage limits under operation with a fault may differ from those of healthy operation since the behaviour of the drive is also effected by the capability of the inverter in delivering zero-sequence voltage (as extra voltage). As a consequence of this a reduction in the speed and torque ranges produced during faulty operation can be observed respect to those produced in healthy condition. This will be discussed in the following sections. The topology of Fig. 3.2b has significant advantages with respect to that of Fig. 3.2a [16]. Since this scheme can improve the reliability of a standard three phase induction motor drive [19], by increasing the voltage capability of the inverter. One main advantage is that a connection to the midpoint of the DC bus is not required which avoids problems related to voltage unbalance in the DC link capacitors [14]. Further, the scheme avoids voltage fluctuations across the DC link capacitors when the machine operates at low speed [17, 18]. In summary, in order to maintain a constant flux trajectory and the same torque level observed during healthy conditions, the magnitude of the two remaining healthy phases need to be increased by a factor of $\sqrt{3}$ with a phase shift of 60° between them should be applied in the presence of the open circuit fault. Note that the neutral leg in this fault tolerant scheme will carry $\sqrt{3}$ times the phase current [17]. For the particular case of a delta-connected machine, an open circuit fault in one of the phases turns the machine into a two-phase system that has a connection to the motor mid point as shown in Fig. 3.2c. This has a similar configuration to that in Fig. 3.2b. The inverter drive configuration does not need to be modified and the path for the zero sequence component is provided to develop an undisturbed rotating MMF even with one phase open circuit. In this case, the inverter is capable of applying ±1/2 of the DC link voltage across each of its terminals continuously for pre-fault and post-fault operation. Regarding the machine side for the case of the faulty condition, the winding current needs to be increased by $\sqrt{3}$ compared to the value under healthy conditions in order to maintain the same torque. In this case when an open circuit fault occurs, the phase currents passing through the remaining healthy windings are the line currents, while the inverter is still delivering the same current through its terminals. To keep the system working efficiently at rated torque with one phase open circuit, the system needs to be thermally able to accommodate the increased losses due to the increment in the current magnitude. In this case, a compromise has to be made as to whether to limit the operation at a lower torque with nominal currents, or operation at full torque with a higher current. However, in this case there could be a reduction in the speed and torque ranges produced when operating with a fault compared to that produced during the healthy condition.

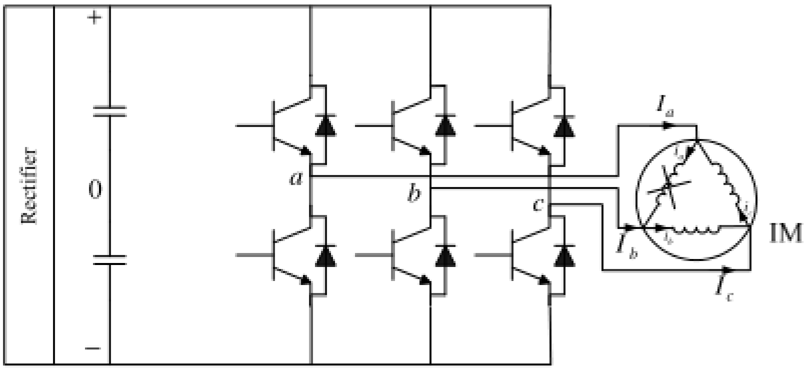


Fig. 3.2c Fault tolerant scheme for a delta connected machine with open circuit fault in Phase a

CHAPTER-4: THEORY OF INDUCTION MOTOR DRIVES

4.1. INTRODUCTION

An induction motor also known as “asynchronous motor” is an ac electric motor in which the electric current flowing in the rotor windings produces torque which is obtained by electromagnetic induction from the magnetic field of the stator winding. An induction motor can therefore be made without electrical connections to the rotor.

Three phase induction motors are the most popular type of ac motors and are widely used as industrial drives because of the following advantages:

a. Robust in construction
b. Reliable
c. Efficient
d. Economical

Single phase induction motors are used extensively for smaller loads such as household appliances like fan.

Although traditionally used in fixed speed service, induction motors are now increasingly being used with variable frequency drives (VFDs) in various variable speed applications.

VFDs offer especially important energy saving opportunities for existing and prospective induction motors in variable torque centrifugal fan, pumps, and compressor load applications.

4.2. CONSTRUCTION

A three phase induction motor essentially consists of two parts:-

- The Stator
- The Rotor

- **The Stator:**
  The stator is the stationary part of an induction motor through which energy flows to the rotating part of the system. It is built up of high grade alloy steel laminations (to reduce eddy current losses) which are slotted

on the inner periphery and are insulated from each other. They are supported on a stator frame of cast iron or fabricated steel plate. The insulated stator conductors are placed in these slots and the conductors are connected to form a three phase winding which may be either star or delta connected.

- **The Rotor:**

  The rotor is the rotating part of an induction motor whose rotation is due to the interaction between the rotor windings and magnetic field produced in the stator which produces a torque around the rotor axis.It is also built up of thin laminations of the same material as stator. The laminated cylindrical core is mounted directly on the shaft or a spider carried by the shaft. These laminations are slotted on their outer periphery to receive the rotor conductors.

  The induction motors are classified into types based on rotor construction:-

  a) Squirrel cage rotor induction motor
  b) Phase wound or slip ring induction motor

4.3. PRINCIPLE OF OPERATION

In a dc motor supply is needed to be given to the stator winding as well as the rotor winding. But in case of an induction motor only the stator winding is fed with an ac supply. When a three-phase balanced supply is given to the stator of an induction motor, a **rotating magnetic field (RMF)** of constant magnitude is produced. This rotating magnetic field rotates at a constant speed known as **synchronous speed**. The relative speed between stator RMF and rotor conductors causes an induced emf in the rotor conductors according to **"Faraday's laws of electromagnetic induction".** The rotor conductors are short circuited and hence rotor current is produced due to induced emf. That is why such motors are known as induction motors.

Now induced current in rotor will also produce alternating flux around it and this rotor flux lags behind the stator flux. The direction of induced rotor current, according to **Lenz's Law** is such that it will tend to oppose the cause of its production. As the cause of production of rotor current is the relative velocity between rotating stator flux and the rotor, the rotor will try to catch up with the stator RMF. Thus the rotor rotates in the same direction as that of stator flux to minimize the relative velocity. However, the rotor never succeeds in catching up the synchronous speed. This is the basic working principle of an induction motor.

4.4.SPEED AND SLIP

The rotational speed of the stator RMF is called as synchronous speed. However, an induction motor cannot run at the synchronous speed. Let us consider for a moment, that the rotor is rotating at the synchronous speed. Under this condition, there would be no cutting of flux by the rotor conductors, and thus there would be no generated voltage, no current and hence no torque.

Hence, the rotor speed is slightly less than the synchronous speed. Thus an induction motor may also be called as "Asynchronous motor" as it does not run at the synchronous speed. The difference between the synchronous speed and the actual rotor speed is known as slip speed. Thus the slip speed express the speed of rotor relative to stator magnetic field.

If = synchronous speed (rpm) then,

$$\boldsymbol{N_s} = \frac{\mathbf{120}\boldsymbol{f}}{\boldsymbol{p}} \qquad (4.4.1)$$

Where f = supply frequency

p = number of poles

If N_r = actual rotor speed (rpm) then,

$$\text{Slip speed} = \frac{N_S - N_r}{N_S} \quad \text{(p u)} \qquad (4.4.2)$$

$$\text{Or, percentage speed} = \frac{\mathbf{N_s - N_r}}{\mathbf{N_s}} * 100 \qquad (4.4.3)$$

4.5.TORQUE OF AN INDUCTION MOTOR

The developed torque or induced torque in an induction motor is actually the torque generated by the internal electromechanical power conversion. Hence the torque is also known as **electromagnetic torque.** The developed torque is given by-

$$\tau_d = \frac{\text{mechanical powed developed}}{\text{mechanical angular velocity of rotor}} = \frac{P_{md}}{\omega_r} \qquad (4.5.1)$$

Where, $p_{md} = (1\text{-s})p_g$ (4.5.2)

$$\omega_r = (1 - s)\omega_s \qquad (4.5.3)$$

Hence, $\tau_d = \frac{p_g}{\omega_s}$ (4.5.4)

Where, p_g= air gap power.

ω_s= synchronous speed.

Hence, the electromagnetic torque of an induction motor can be expressed as-

$$\tau_e = k \frac{sE_{20}^2 R_2}{R_2 + s^2 X_{20}^2} \qquad (4.5.5)$$

Where, $k = \frac{3}{2\pi N_s} = a\ constant$

4.6. TORQUE-SLIP CHARACTERISTICS:

The torque-slip characteristics of an induction motor gives us the information about the variation of torque with slip. The variation of slip can be obtained with the variation of speed ie, when speed varies the slip will also vary and the torque corresponding to that speed will also vary. The torque-slip characteristics curve can be divided roughly into three regions:-

1. Low slip region
2. Medium slip region
3. High slip region

The curve shown below shows the torque-slip characteristics of the induction motor:-

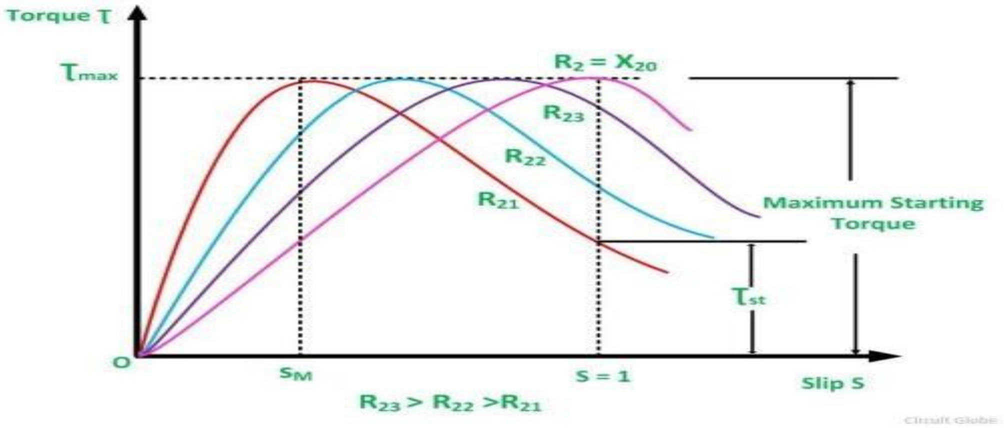


Fig.4.6. Torque-slip characteristics (Figure is taken from public domain)

4.7. TORQUE-SPEED CHARACTERISTICS

The torque speed characteristics of an induction motor are the curves plotted between the torque and speed of the induction motor. It is seen that although the maximum torque is independent of rotor resistance, yet the exact location of T_{dmax} is dependent on it. Thus, greater the value of R_2 ,greater is the value of slip at which maximum torque occurs. It is also seen that as the rotor resistance is increased, the pull out speed of the motor decreases, but the maximum torque remains constant. The curve shown below represents the torque-speed characteristics.

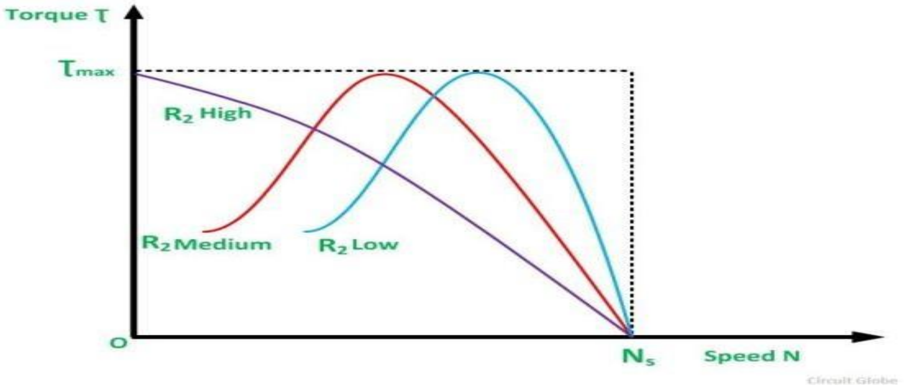


Fig.4.7. Torque-speed characteristics (Figure is taken from public domain).

4.8. SPEED CONTROL OF INDUCTION MOTOR

A three phase induction motor is practically a constant speed motor. That means for the entire loading range change in the speed of motor is quite small. Hence, it is somewhat difficult to control its speed. The speed control of induction motor is done at the cost of decrease in efficiency and low power factor.The speed of rotor of an induction motor is given by-

$$N_r = (1\text{-s})N_s$$

Where, $N_s = \frac{120f}{p}$

$$\therefore\ N_r = \frac{120f}{p}(1\text{-s}) \qquad (4.8.1)$$

Hence, the various methods for the speed control of induction motor are-

4.8.1 V/f control or frequency control

Synchronous speed of induction motor is

$$\boldsymbol{N_s = \frac{120f}{p}} \qquad (4.8.1.1)$$

Therefore, the speed of the motor can be controlled by varying the supply frequency The emf induced in the stator of the induction motor is given by,

The variable frequency supply is generally obtained by the the following converters

i) Voltage source inverter
ii) Current source inverter
iii) Cycloconverter

4.8.2 Variable supply voltage control

The speed of the three phase induction motor can be varying by the supply voltage and torque developed is directly proportional to the square of supply voltage

$$T_d = \frac{K_S E_S^2 R_2}{R_2^2 + S^2 X_2^2} \qquad (4.8.2.1)$$

The operation at voltages higher than the rated voltage is not permissible, this method is allowed only below the normal rated speed, thus this method is only used for small size motor.

4.8.3 Variable rotor resistance control

The speed of the wound induction motor can be controlled by connecting external resistance in the rotor circuit through slip ring. This type of method is very simple. It is possible to have large starting torque, low starting current at small value of slip. The major disadvantage of this type of control is that, the efficiency is low, due to additional losses.

4.8.4 Stator pole changing

Basically there are two method of pole changing to control the speed of induction motor.

4.8.4a Multiple Stator winding: In this method the stator is provided with two separate winding which are wound for two different pole numbers. In this method only one winding energized at a time.

Just suppose that a motor has two winding for 6 and 4 poles for 50 hz supply frequency, the synchronous speed will be 1000 rpm and 1500 rpm respectively. If the full load slip is 5% then the operating speed will be 950 rpm and 1425 rpm.

4.8.4b Method of consequent poles: In this method no of poles can be changed with only simple change in coil connection.
In figure (4.8.4b) total no of poles is 4. Then synchronous speed is 1500 rpm for 50 hz supply frequency.
The flux of the groups must pass through the spaces between the groups thus inducing magnetic poles in the interpoles spaces.
The induced poles are called consequent poles.

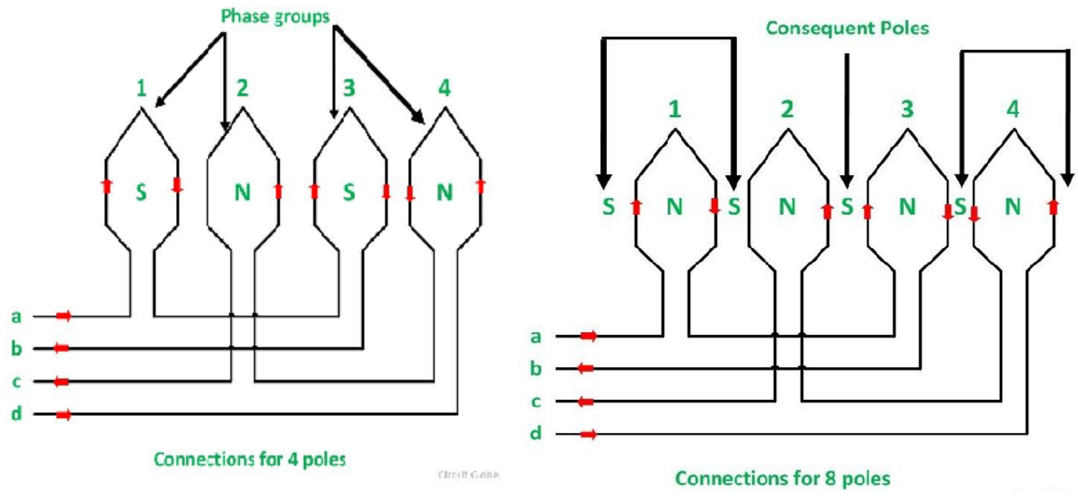


Fig4.8.4.1b Connection for 4 and 8 poles

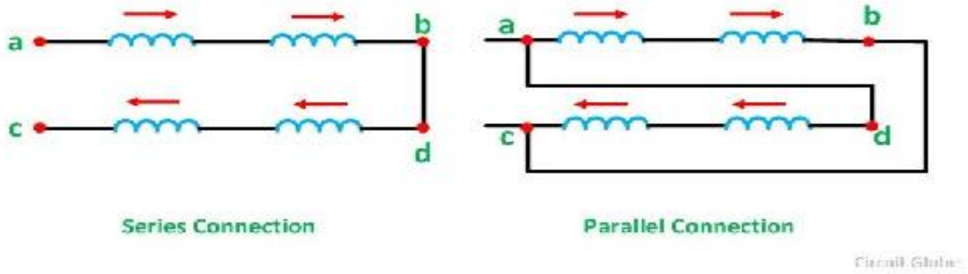


Fig 4.8.4.2b Series and parallel connection

4.8.5 Slip power recovery

Tis method is known as static scherbius drive. A portion of rotor ac power is converted into dc by a diode bridge.

The rectified current is smoothed by the smoothing reactor.The output of the rectifier is an inverter converts a fixed dc voltage to ac voltage.

The slip power from the rotor circuit can be recovered and feedback to ac source so as to utilize it outside the motor.

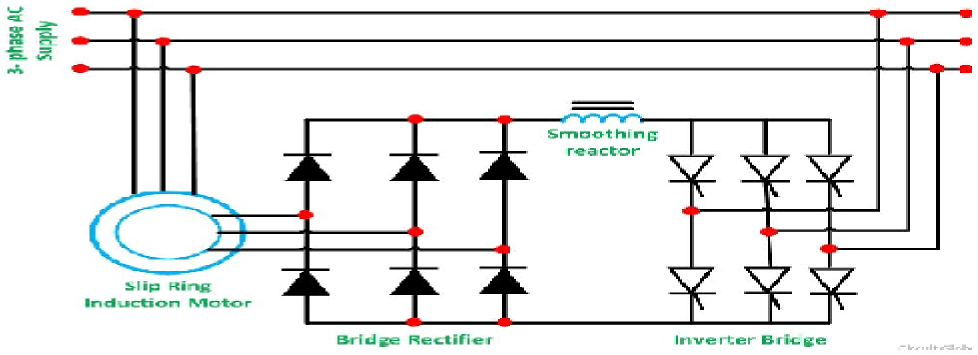


Fig 4.8.5 slip power recovery

4.8.6 VECTOR OR FIELD ORIENTED CONTROL

Scalar control is simple to implement, but the inherent coupling effect in scalar control method (ie, both flux and torque are functions of voltage or current and frequency) gives sluggish response and the system is prone to instability because of a high order system effect. If the torque is increased by increasing the slip or frequency, the flux tends to decrease and this flux variation is very slow. The decrease in flux is then compensated by the flux control loop which has a large time constant. The temporary dipping of flux reduces the torque sensitivity with slip and lengthens the response time. The variation in the flux linkages have to be controlled by the magnitude and frequency of the stator and rotor phase currents and their instantaneous phases.

Also the scalar control aims at controlling the magnitude and frequency of currents or voltages only but not their phase angle. But the induction motor drives requires a coordinated control of stator current magnitude, frequencies and phase magnitude making it a complex control. The stator current phasor can be resolved along the rotor flux linkages and the component along the rotor flux linkages is the **field producing current**, but requires the position of rotor flux linkages at every instant. The requirement of phase, frequency and magnitude of the currents and hence the flux phasor is made possible by inverter control, which can be achieved in field coordinates and hence it is often termed as **field oriented control** or **vector control** because it relates to the phasor control of flux linkage.

CHAPTER-5:

MODELLING OF FAULT TOLERANCE HIGH SPEED INDUCTION MOTOR DRIVE IN MATLAB

5.1 INTRODUCTION

The simulation is one of the key steps in the validation of the design process of the motor drive system, which eliminates the designing mistakes and the resulting errors in the prototype construction and testing. The model of induction motor in direct and quadrature axes can be derived from fundamental equations of transformations. The analysis of symmetrical induction motor in an arbitrary reference frame has been intensively used as a standard simulation approach from which any particular mode of operation may be developed.

Matlab/Simulink has an advantage over other machine simulators in modelling the induction motors. Generally modelling of these equations is considered difficult but in this paper they are presented in their simplified form. The transformations used at various steps are based on simple trigonometric relationships obtained as projections on a set of axes. The model is used to obtain transient responses, small signal equations, and a transfer function of induction motor. The mathematical modelling of induction motor are done in order to have a better understanding of the behaviour of induction motor in both transient and steady state.

The mathematical modelling sets all the mechanical equations for torque and speed versus time. It also models all the differential voltage, current and flux linkages between the stationary stator and the moving rotor. This mathematical model has been done by using Matlab/Simulink which represents the three-phase induction motor including a three phase to d-q axes transformation. The main advantages of using Matlab/Simulink is that the electromechanical model can be accomplished in a simple way and it can be simulated faster using simulation blocks.

5.2. MODELLING OF 3-PHASE PWM INVERTER IN MATLAB

An inverter is a circuit that converts dc input power into an ac power at the output at a desired voltage and frequency. The conversion can be achieved by controlled turn on and turn off devices like MOSFETs. Ideally the output voltage of an inverter should be strictly sinusoidal. However, since the outputs are usually rich in harmonics and hence are always almost non-sinusoidal. Square wave and quasi square wave voltages are applicable. The dc power input for the inverter operation is given through a dc voltage source. The modelling of the three phase inverter consists of the following two steps:-

a) Design of power circuit with extra leg
b) Design of control circuit

5.2a. DESIGN OF POWER CIRCUIT

The power circuit of the 3-phase inverter consists of three legs containing two MOSFETs (a1,b2; b1,c2; c1,a2) in each leg. The MOSFETs in each leg conduct for of a cycle ie, they are turned on with a time intervalof 180°. It means that if, a1conductsfor 180°then b2 will conduct for the next 180° of a cycle. Similarly when b1 or c1 conducts for 180° of a cycle then c2 or a2 respectively will conduct for the next 180°of the cycle.

The MOSFETs in the upper group (ie, a1, b1, c1) conduct at an interval of 120°.Similarly, the MOSFETs (ie, b2, c2, a2) in the lower group will also conduct at an interval of 120°. It implies that if a1 is fired at$\omega t = 0°$, then b1 must be fired at $\omega t = 120°$and c1 at$\omega t = 240°$.

Hence, it can be said that if a1 is fired at$\omega t = 0°$then b2 must be fired at $\omega t = 180°$ Similarly, if b1 is fired at$\omega t = 120°$then, c2 must fired at $\omega t = 120° + 180° = 300°$ and in the same way if, c1 is fired at$\omega t = 240°$, then a2 must be turned on at$\omega t = 240° + 180° = 420°\ or\ 60°$.

.

Thus on the basis of above firing scheme, a table is prepared as shown below-

Mode	A1	A2	B1	B2	C1	C2
$0° - 60°$	ON	OFF	OFF	OFF	ON	ON
$60° - 120°$	ON	ON	OFF	OFF	OFF	ON
$120° - 180°$	ON	ON	ON	OFF	OFF	OFF
$180° - 240°$	OFF	ON	ON	ON	OFF	OFF
$240° - 300°$	OFF	OFF	ON	ON	ON	OFF
$300° - 360°$	OFF	OFF	OFF	ON	ON	ON

The simulink model of a three phase inverter with extra leg is shown in the fig.5.2a :

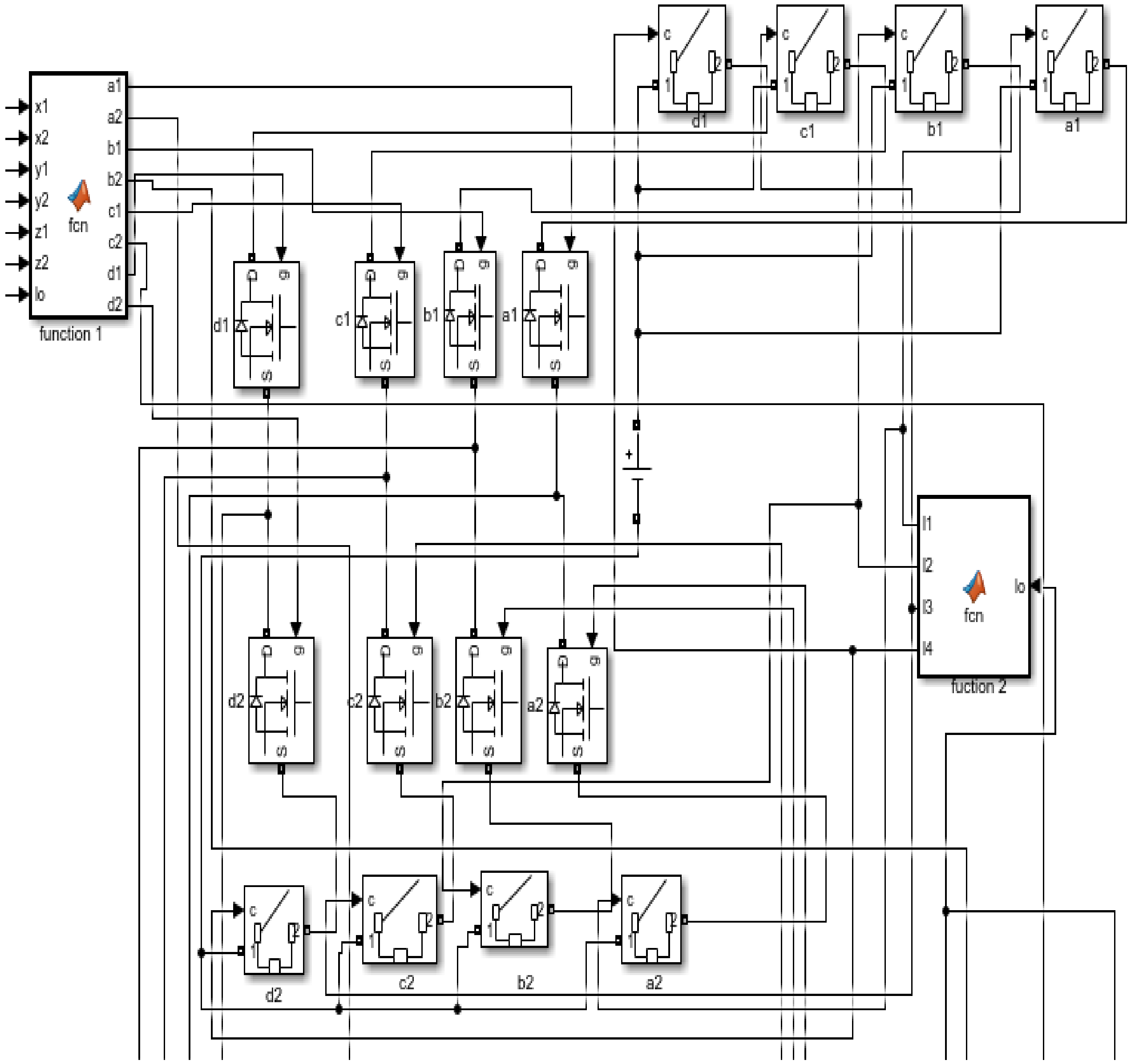
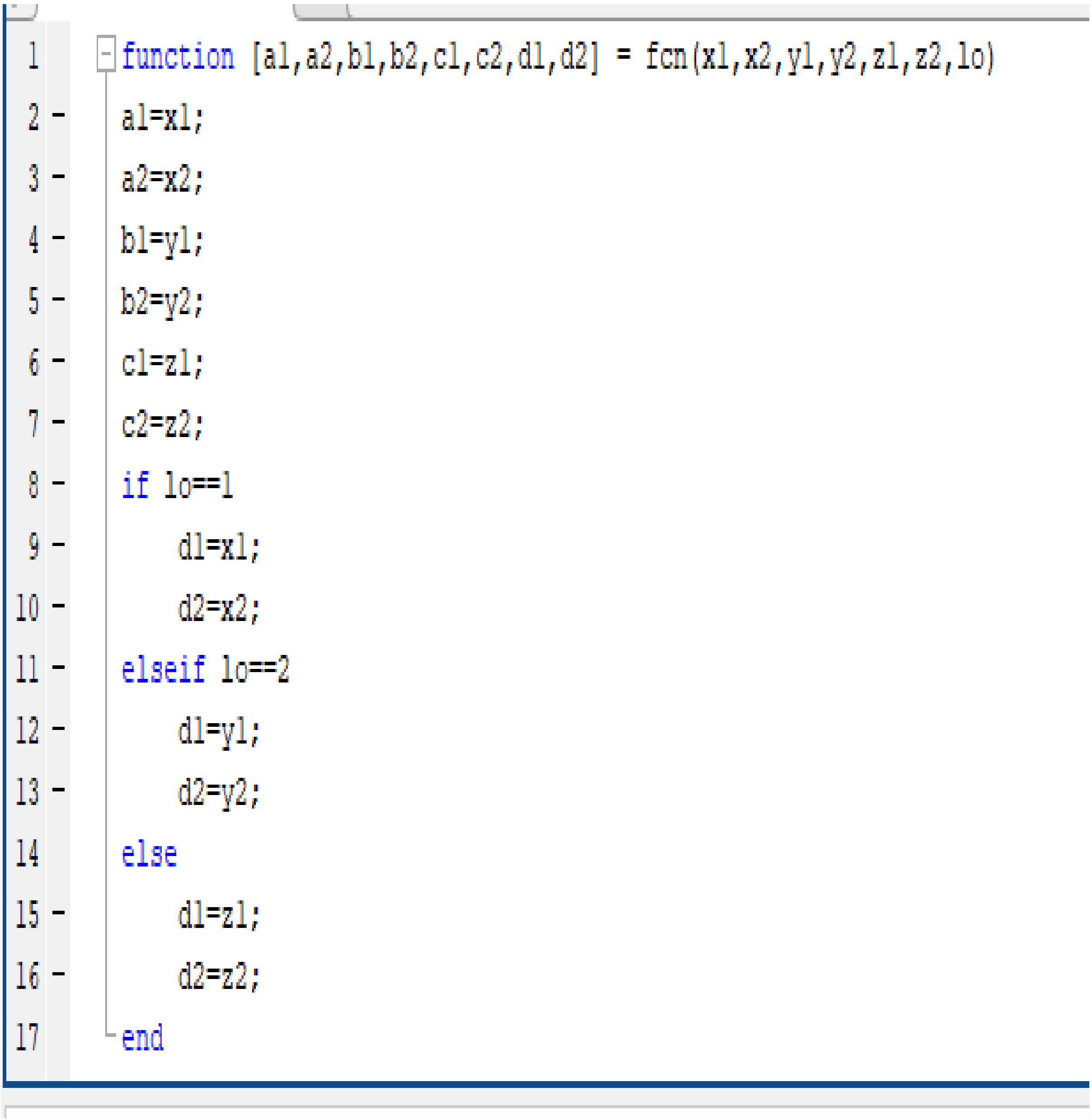


Fig 5.2a. Simulink model of three phase pwm inverter created in Matlab.

5.2b. DESIGN OF CONTROL CIRCUIT

The control circuit consists of six pulse generators with logic Io that generates pulses at regular intervals. These signals are applied to the gates of each of the MOSFETs so as to trigger them. These six pulse generators are named as x1, x2, y1, y2, z1, z2 connected to the gate terminal of respective MOSFETs as shown in below function1 figure.



```
function [a1,a2,b1,b2,c1,c2,d1,d2] = fcn(x1,x2,y1,y2,z1,z2,lo)
a1=x1;
a2=x2;
b1=y1;
b2=y2;
c1=z1;
c2=z2;
if lo==1
    d1=x1;
    d2=x2;
elseif lo==2
    d1=y1;
    d2=y2;
else
    d1=z1;
    d2=z2;
end
```

5.3. MODELLING OF VECTOR CONTROL PWM INVERTER FED INDUCTION MOTOR WITH EXTRA LEG IN MATLAB

The three phase PWM inverter modelled is now used to fed a three phase induction motor ie, the three phase output of the PWM inverter is now given to the induction motor. The induction motor is modelled using the simulink block ‘Asynchronous Machine’. A constant starting load torque of is applied to it. The circuit shown below in the fig 5.3 is modelled using Matlab-Simulink. The various specifications related to the modelling of the induction motor are given in table 5.4 . The simulink circuit in the fig5.3 is simulated for

2 seconds and the waveforms obtained for the output voltages, currents, speed and torque are shown accordingly.

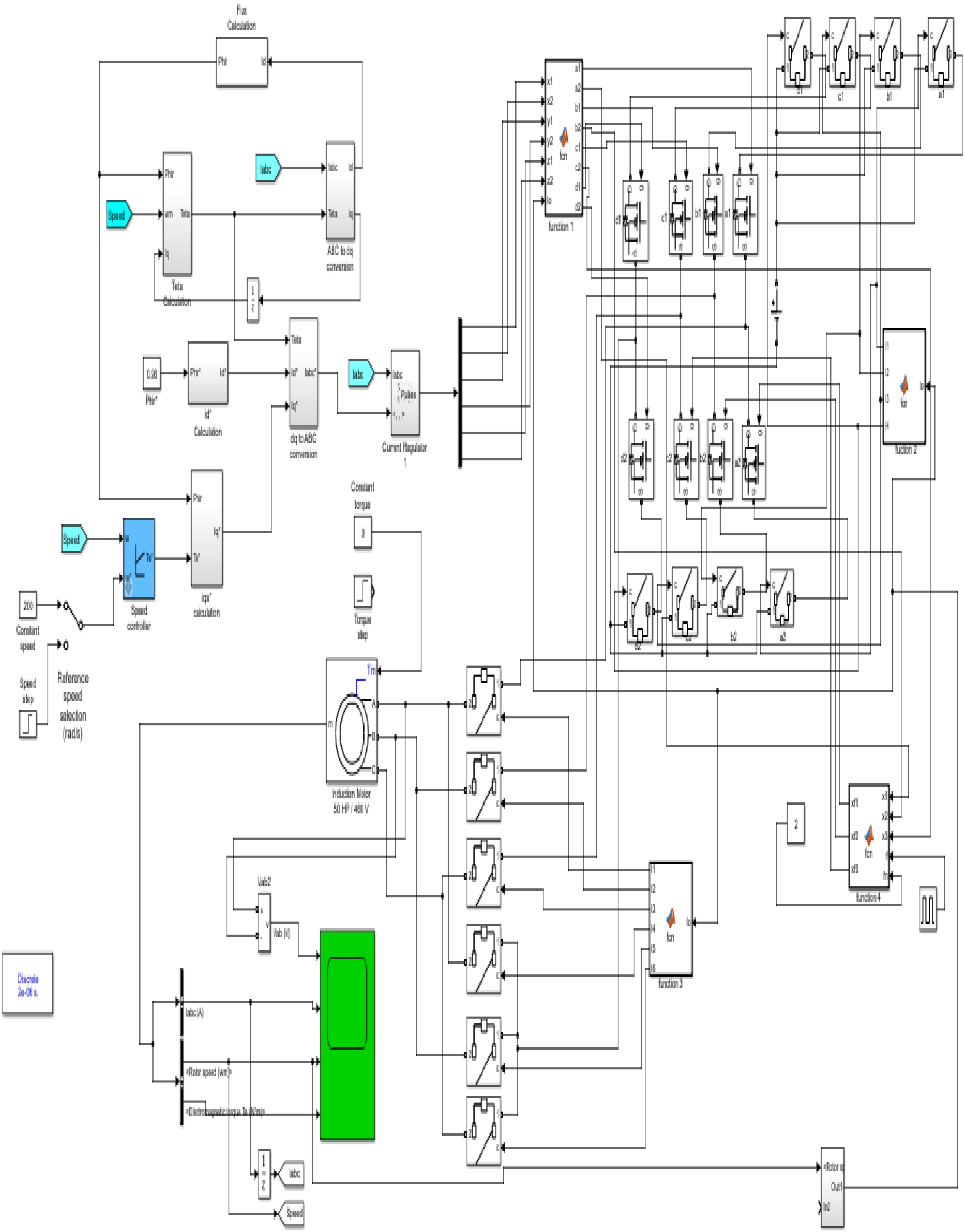


Fig 5.3 Simulink model of PWM inverter fed induction motor created in Matlab

5.4. Specification of Induction motor

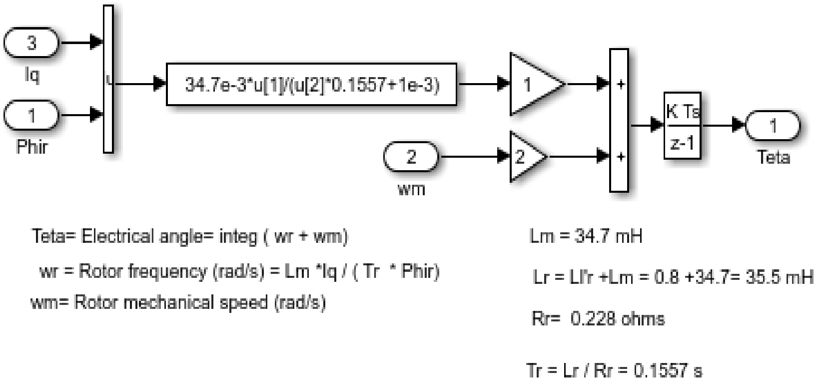
HP	50
Voltage (v)	460 V
Frequency (f)	60 Hz
Phase	3
Poles (p)	4
Speed (rpm)	1800 rpm
Stator resistance (ohm)	0.087 Ω
Rotor resistance (ohm)	0.228 Ω
Stator inductance (H)	0.8e^-3 H
Rotor inductance (H)	0.8e^-3 H
Mutual inductance (H)	34.7e^-3 H
Type	Squirrel cage

Table 5.4 Induction motor specifications

Thus with an input dc voltage of 700V, the circuit produces a 3-phase ac output voltage. The output voltage of the three phases are 120° apart from one another. Thus inverter action is obtained.

5.5. MATLAB IMPLEMENTATION

5.5.1 Theta Calculation



Teta= Electrical angle= integ (wr + wm)

wr = Rotor frequency (rad/s) = Lm *Iq / (Tr * Phir)

wm= Rotor mechanical speed (rad/s)

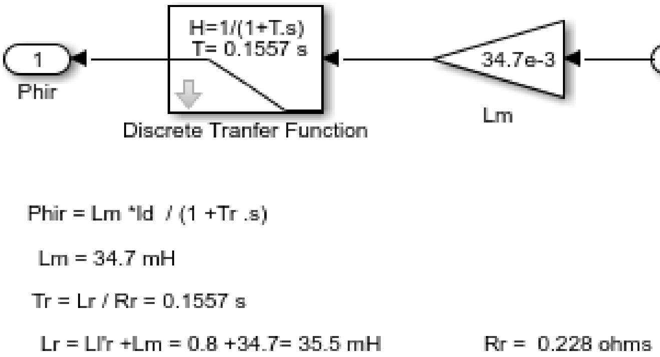
Lm = 34.7 mH

Lr = Ll'r +Lm = 0.8 +34.7= 35.5 mH

Rr= 0.228 ohms

Tr = Lr / Rr = 0.1557 s

5.5.2. Flux Calculation



Phir = Lm *Id / (1 +Tr .s)

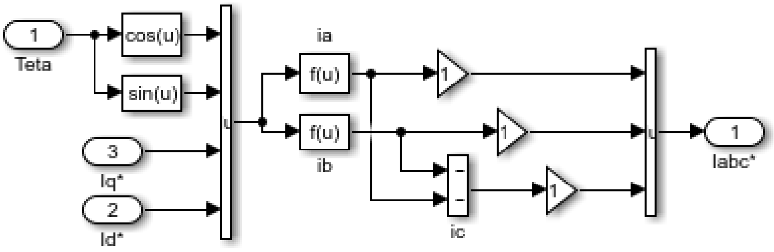
Lm = 34.7 mH

Tr = Lr / Rr = 0.1557 s

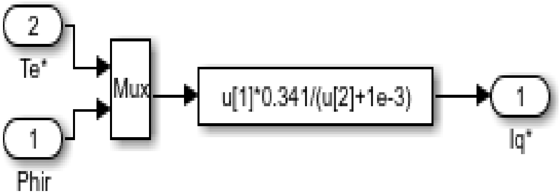
Lr = Ll'r +Lm = 0.8 +34.7= 35.5 mH

Rr = 0.228 ohms

5.5.3. Dq to Iabc Conversion



5.5.4. Iq Calculation



Iq= (2/3) * (2/p) * (Lr/Lm) * (Te / Phir)

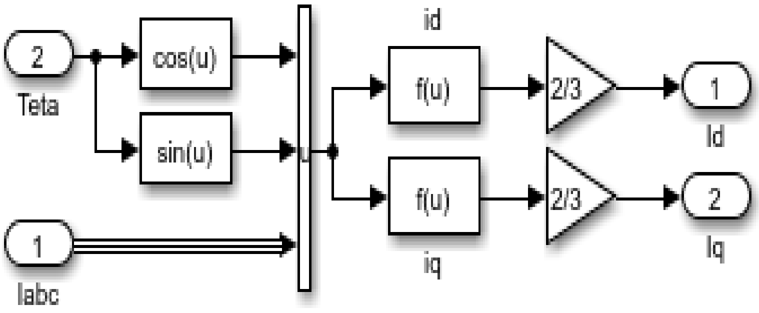
Iq= 0.341 * (Te / Phir)

Lm = 34.7 mH

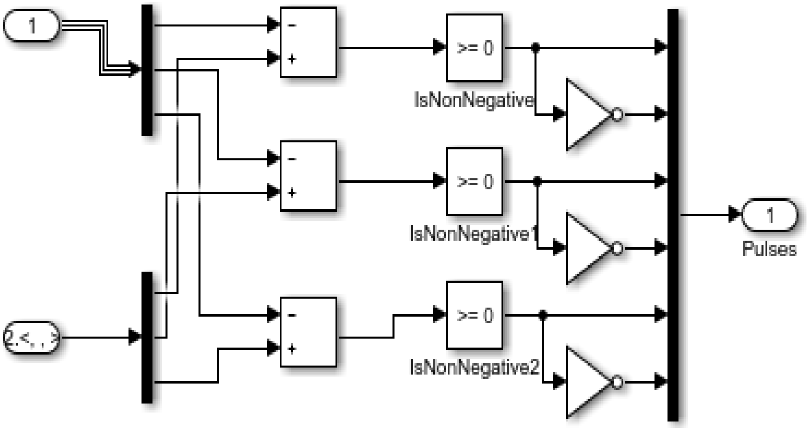
Lr = Ll'r +Lm = 0.8 +34.7= 35.5 mH

p= nb of poles = 4

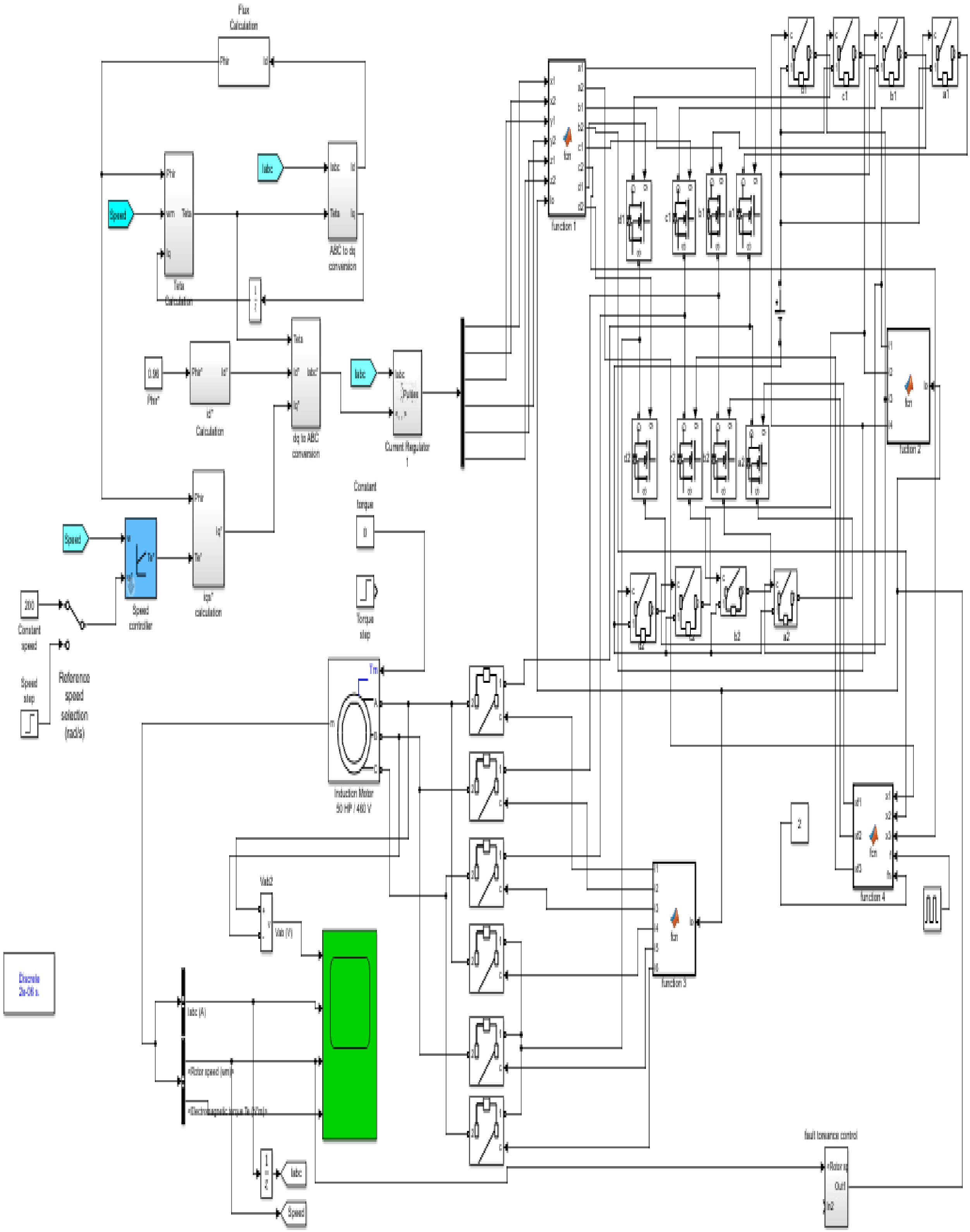
5.5.5 Iabc to Dq Conversion



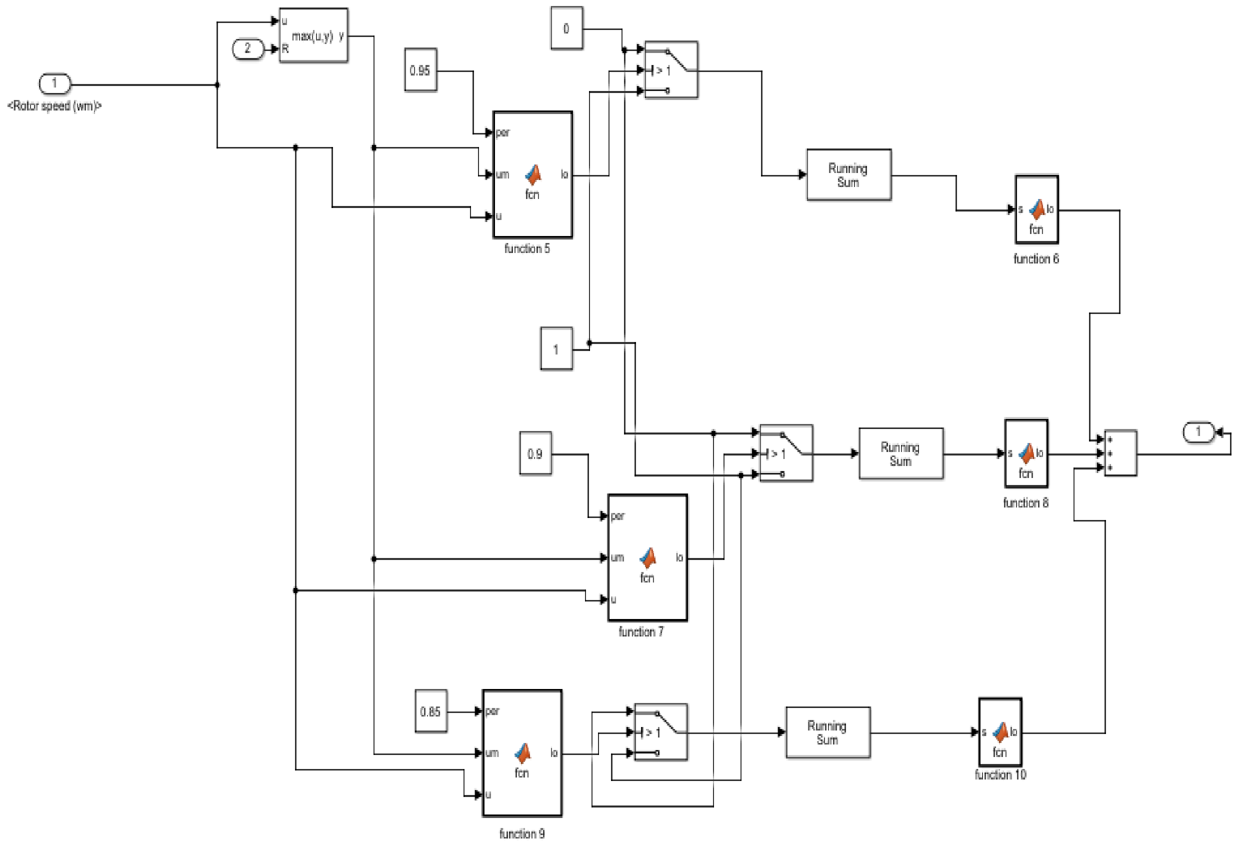
5.5.6. PWM Generation



5.5.7 Inverter Connection of Induction motor with extra leg.



5.5.8. Fault tolerance control Topology

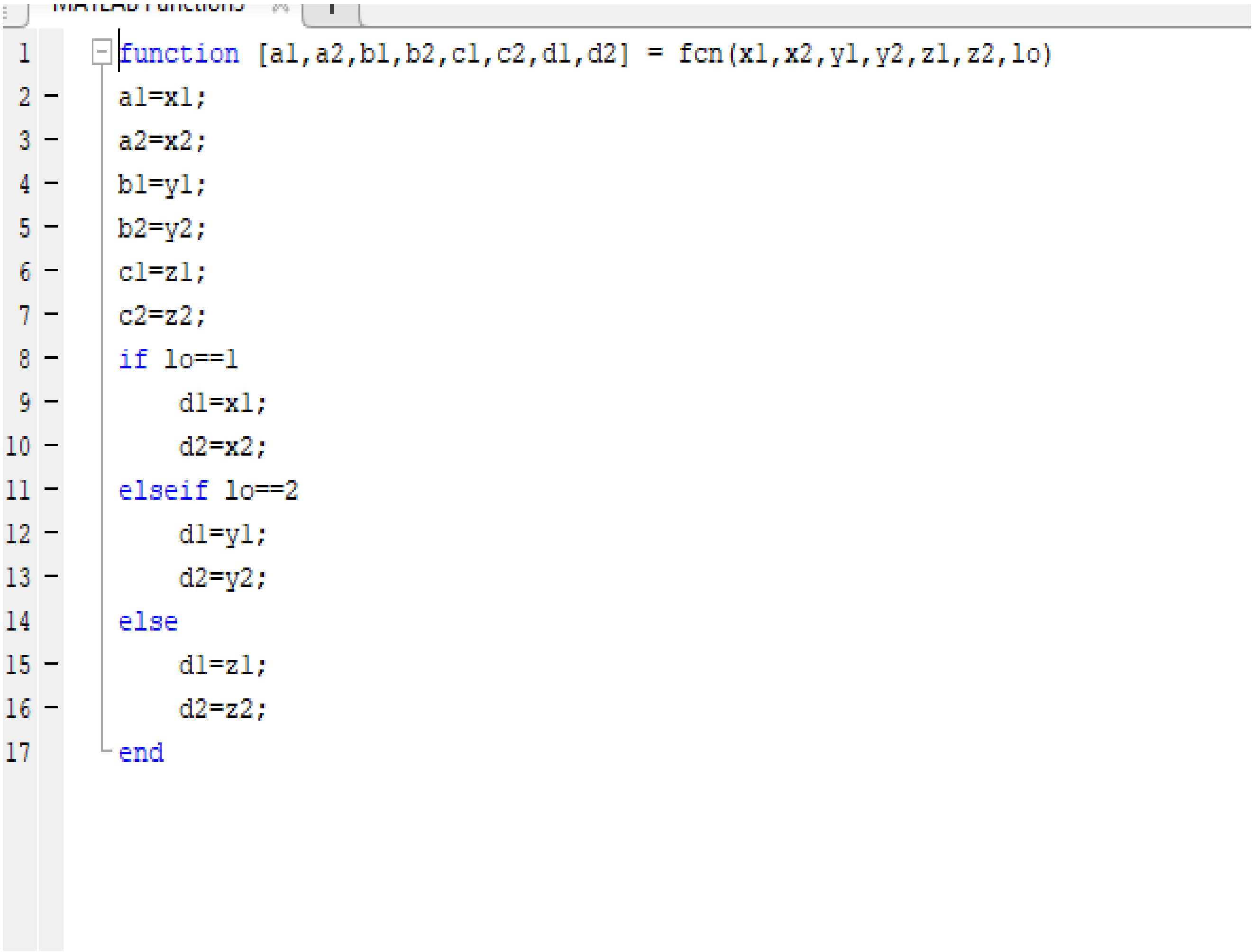


5.6 Inveter Connection Explanation:

As the six pulses are coming from the PWM generation signal and it is given to x1, x2, y1, y2, z1, z2 in the function block 1 and from function block 1 signal a1, b1, and c1 directly connected to the upper upper leg of the 3-phase inverter and a2 to x1, b2 to x2, and c2 to x3 and from there xf1, xf2, and xf3 connected to lower leg via function block 4. Here I have used 14 automatic circuit breaker to work as a switch for making or breaking the circuit as per the requirement and it is excited with the 700 dc voltage. Dc voltage is connected to CB a1,b1,c1,d1, and a2,b2,c2,d2. From function block 2, I1 connected to CB a1 and a2, I2 connected to CB b1 and b2, I3 connected to CB c1 and c2, I4 connected to CB d1 and d2 and then CB d1, c1, b1, a1 connected to the upper leg of the inverters d1, c1, b1, a1 similarly CB d2, c2, b2, a2 connected to the lower leg of the inverters d2, c2, b2, a2.

5.7 Programmed logic in all Functions Block

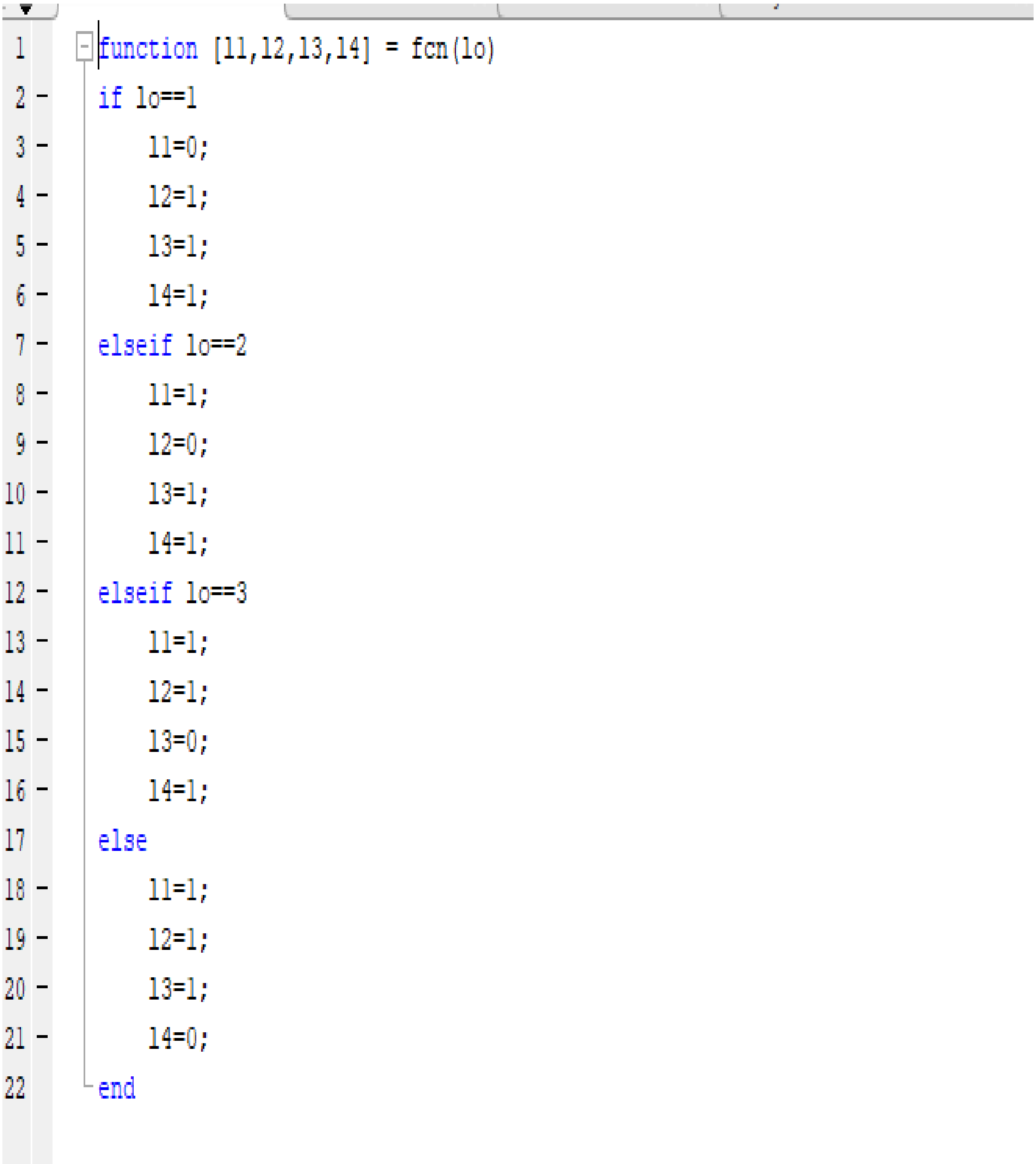
5.7.1 Function 1



```
function [a1,a2,b1,b2,c1,c2,d1,d2] = fcn(x1,x2,y1,y2,z1,z2,lo)
a1=x1;
a2=x2;
b1=y1;
b2=y2;
c1=z1;
c2=z2;
if lo==1
    d1=x1;
    d2=x2;
elseif lo==2
    d1=y1;
    d2=y2;
else
    d1=z1;
    d2=z2;
end
```

Here the function shows if logic lo==1 then x1 and x2 signal directly connected to extra leg d1, d2 and fault occur in leg1 similarly if lo==2 then 2nd leg connection goes 4th leg which an extra leg and fault occur in 2nd leg and so on..

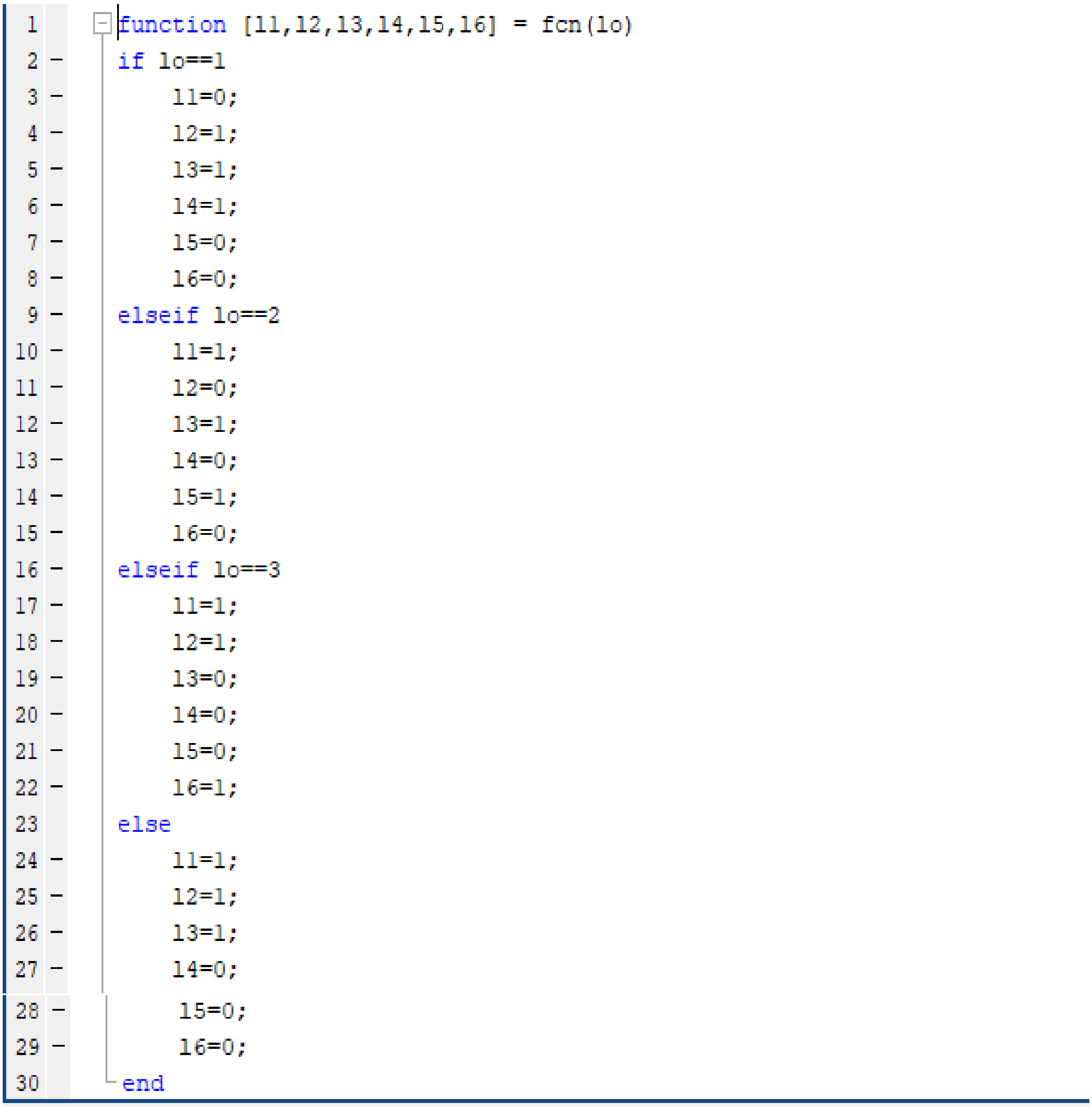
5.7.2 Function 2



```
function [l1,l2,l3,l4] = fcn(lo)
if lo==1
    l1=0;
    l2=1;
    l3=1;
    l4=1;
elseif lo==2
    l1=1;
    l2=0;
    l3=1;
    l4=1;
elseif lo==3
    l1=1;
    l2=1;
    l3=0;
    l4=1;
else
    l1=1;
    l2=1;
    l3=1;
    l4=0;
end
```

It is connected to the circuit breaker for making and braking the circuit. Work of the function 2 block is if logic lo is 1 then fault is occur in the 1st leg and the 1st leg connection is automatically connected to the 4th leg with the help of circuit breaker similarly if lo is 2 then fault occur in the 2nd leg and so on.

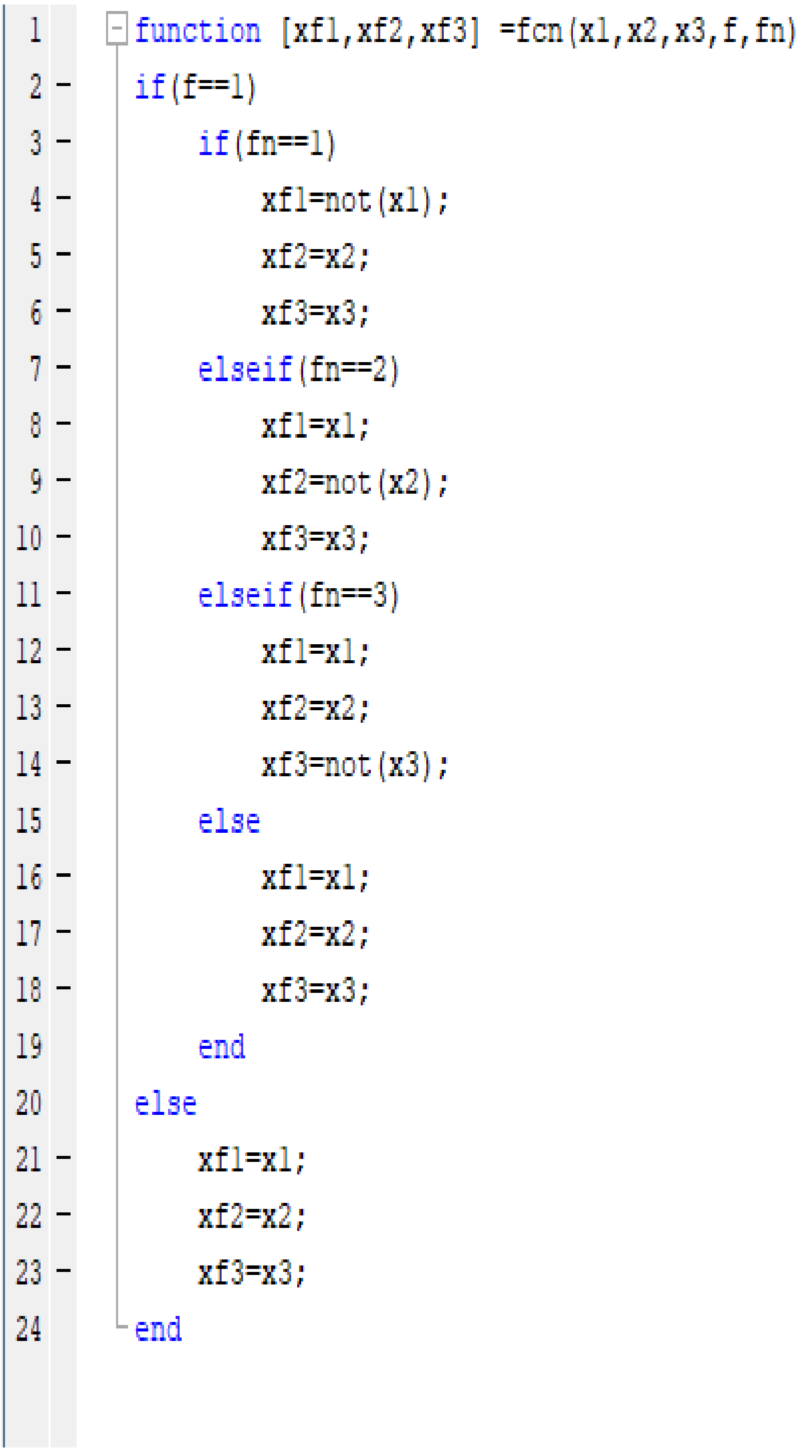
5.7.3 Function 3



```
function [l1,l2,l3,l4,l5,l6] = fcn(lo)
if lo==1
    l1=0;
    l2=1;
    l3=1;
    l4=1;
    l5=0;
    l6=0;
elseif lo==2
    l1=1;
    l2=0;
    l3=1;
    l4=0;
    l5=1;
    l6=0;
elseif lo==3
    l1=1;
    l2=1;
    l3=0;
    l4=0;
    l5=0;
    l6=1;
else
    l1=1;
    l2=1;
    l3=1;
    l4=0;
    l5=0;
    l6=0;
end
```

Here 6 circuit breaker is used c1, c2, c3 are used for the direct connection of the three phase coming from the three phase inverter, which is connected c1 to a12, c2 to b12, c3 to c12 and the next three c4, c5, c6 connected to d12 which are initially open, used according to the fault condition. When logic lo is 1 the fault occur in the 1st leg so CB c1, c5, c6 becomes open and c4 which is initially connected to 4th leg d12 after some delay becomes c1and leg 4 act as leg 1. Similarly when lo is 2 then c2 becomes open circuit and c5 act as a c2 which is connected to the 4th leg. This means fault occur in 2nd leg after some delay 2nd leg signal goes to the 4th leg, similarly so on.

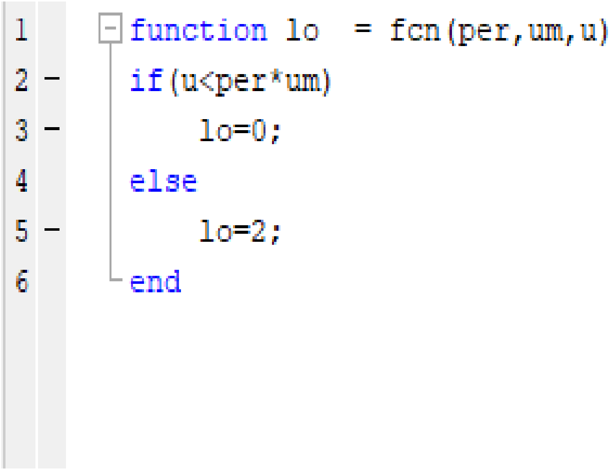
5.7.4 Function 4



```
function [xf1,xf2,xf3] =fcn(x1,x2,x3,f,fn)
if(f==1)
    if(fn==1)
        xf1=not(x1);
        xf2=x2;
        xf3=x3;
    elseif(fn==2)
        xf1=x1;
        xf2=not(x2);
        xf3=x3;
    elseif(fn==3)
        xf1=x1;
        xf2=x2;
        xf3=not(x3);
    else
        xf1=x1;
        xf2=x2;
        xf3=x3;
    end
else
    xf1=x1;
    xf2=x2;
    xf3=x3;
end
```

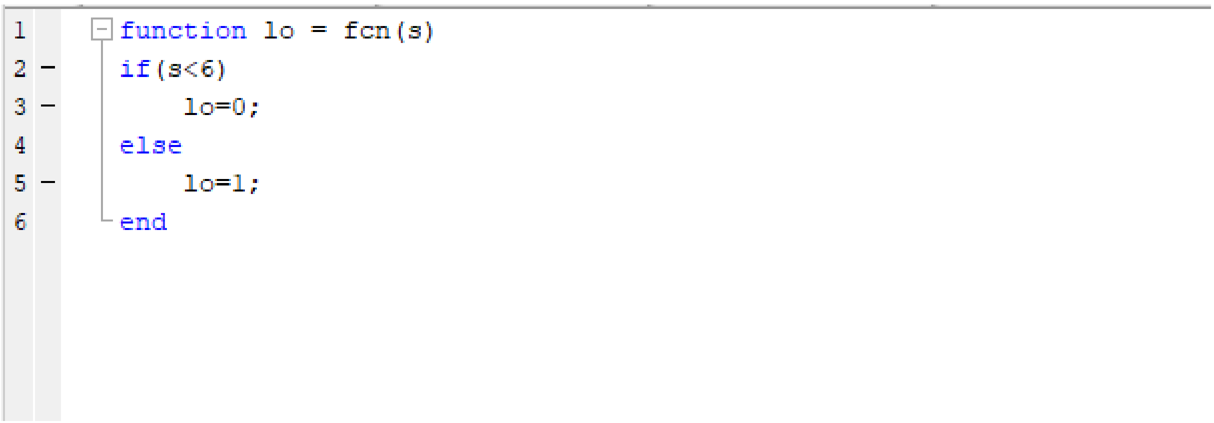
In this function block x1, x2, x3 is the output signal from the function block 1, which is same as a2, b2, c2 and fn is the constant function which shows if fn value is 1 the fault occur in the 1st leg, if fn value is 2 then fault occur in the 2nd leg, if fn value is 3 then fault occur in the 3rd leg and simultaneously 4th leg becomes 1st leg, 2nd leg, 3rd leg. If fn value is other than 1, 2, 3 then no fault occur in the inverter 3 phase inverter.

5.7.5 Function 5



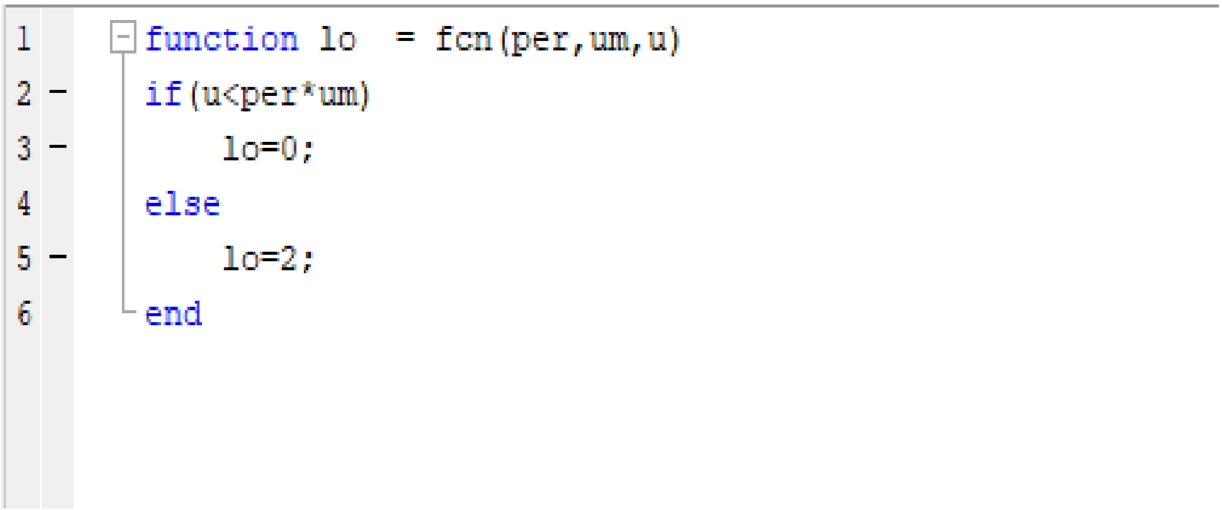
```
function lo  = fcn(per,um,u)
if(u<per*um)
    lo=0;
else
    lo=2;
end
```

5.7.6 Function 6



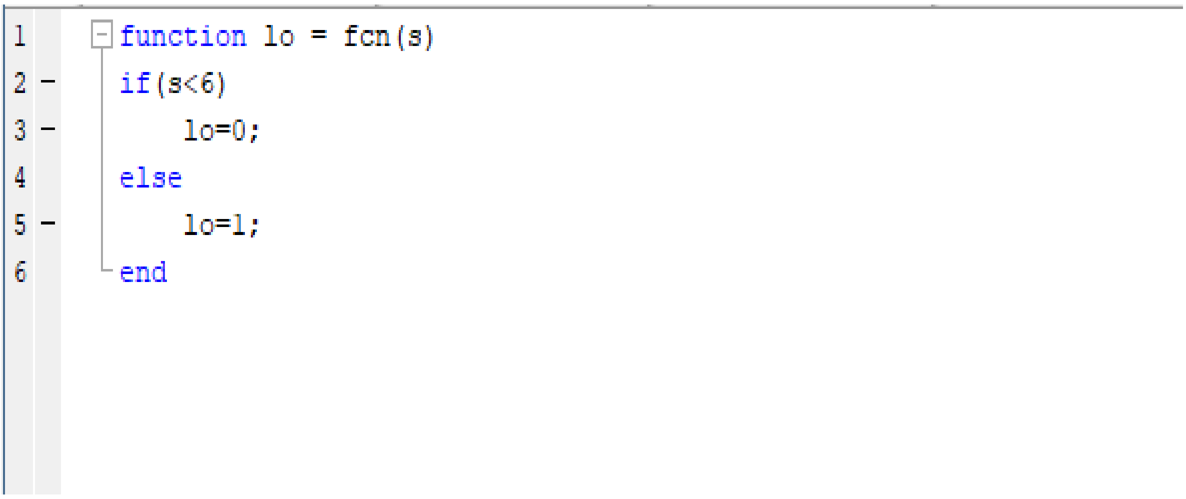
```
function lo = fcn(s)
if(s<6)
    lo=0;
else
    lo=1;
end
```

5.7.7 Function 7



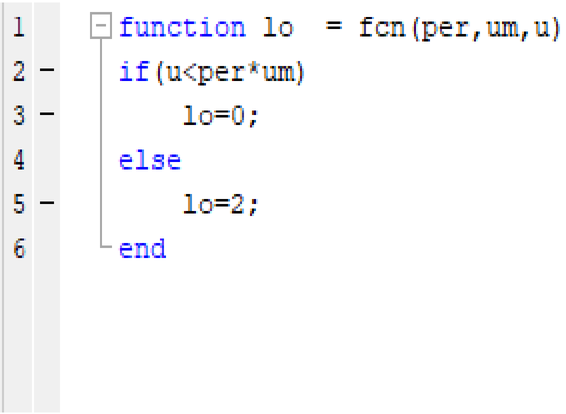
```
function lo  = fcn(per,um,u)
if(u<per*um)
    lo=0;
else
    lo=2;
end
```

5.7.8 Function 8



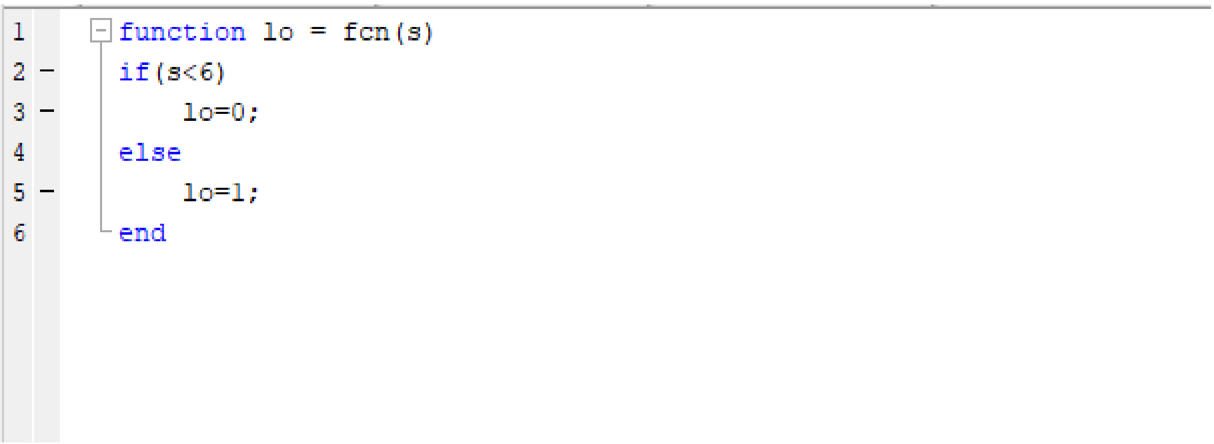
```
function lo = fcn(s)
if(s<6)
    lo=0;
else
    lo=1;
end
```

5.7.9Function 9



```
function lo  = fcn(per,um,u)
if(u<per*um)
    lo=0;
else
    lo=2;
end
```

5.7.10 Function 10



```
function lo = fcn(s)
if(s<6)
    lo=0;
else
    lo=1;
end
```

Here the function block from 5 to 10, the used function is same, the only change is function 5 and 6 is for the 1st leg where the fault is occur 0.95 of the full load speed of the induction motor, function 7 to 8 is for the 2nd leg where the fault is occur 0.90 0f the full load of the induction motor and function 9 to 10 is for the 3rd leg where the fault is occur 0.85 of the full load of the induction motor.

5.8 SIMULATION RESULTS:

The system has been simulated and analyzed in four cases as explained in function 4 block , the first case is the normal operating in which no fault is occurred in any phase, the second case is when fault is occurred in phase A and phase A signal automatic goes to 4th Leg which is now act as Phase A, the third case is when fault is occurred in phase B and phase B signals automatic goes to 4th Leg which is now act as phase B and the fourth case is when fault is occurred in phase C and phase C signal automatic goes to 4th leg which is now act as phase C.

5.9 NORMAL OPERATING WITHOUT FAULT

A fault tolerance inverter fed vector control of three phase induction motor drive system has been simulated in MATLAB-Simulink. A constant load torque is applied to the induction motor and get the desired waveforms of phase voltage in fig5.9a, Three phase stator current fig in 5.9b, desired motor speed fig in 5.9c and the desire torque in fig5.9d as shown in the below figure.

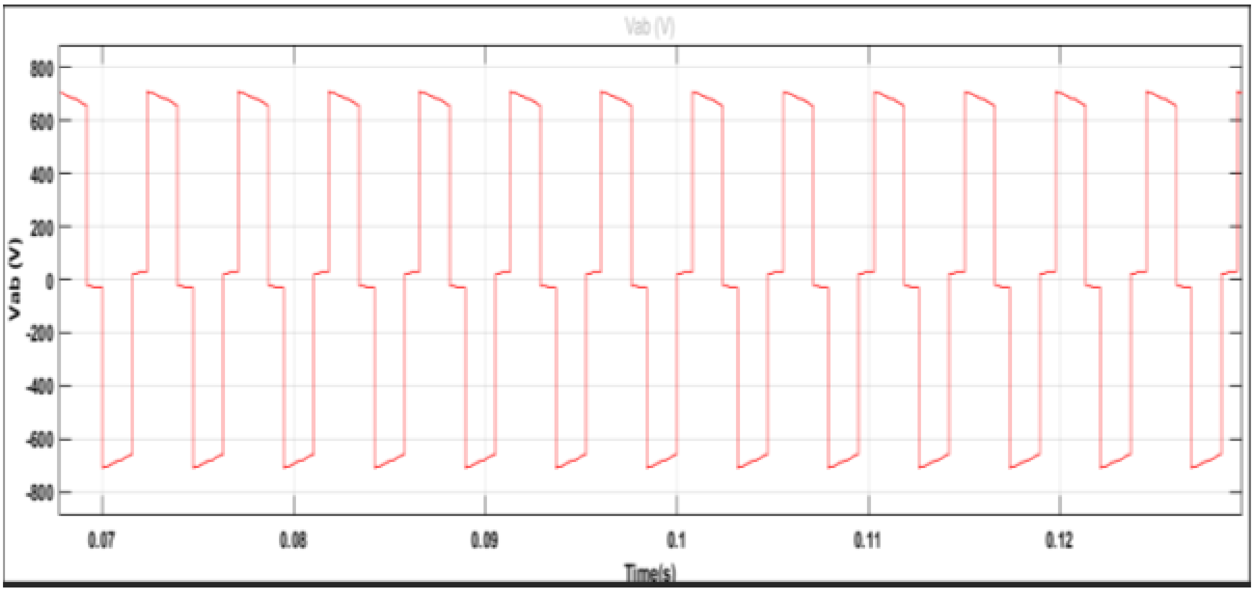


Figure 5.9a Phase voltage

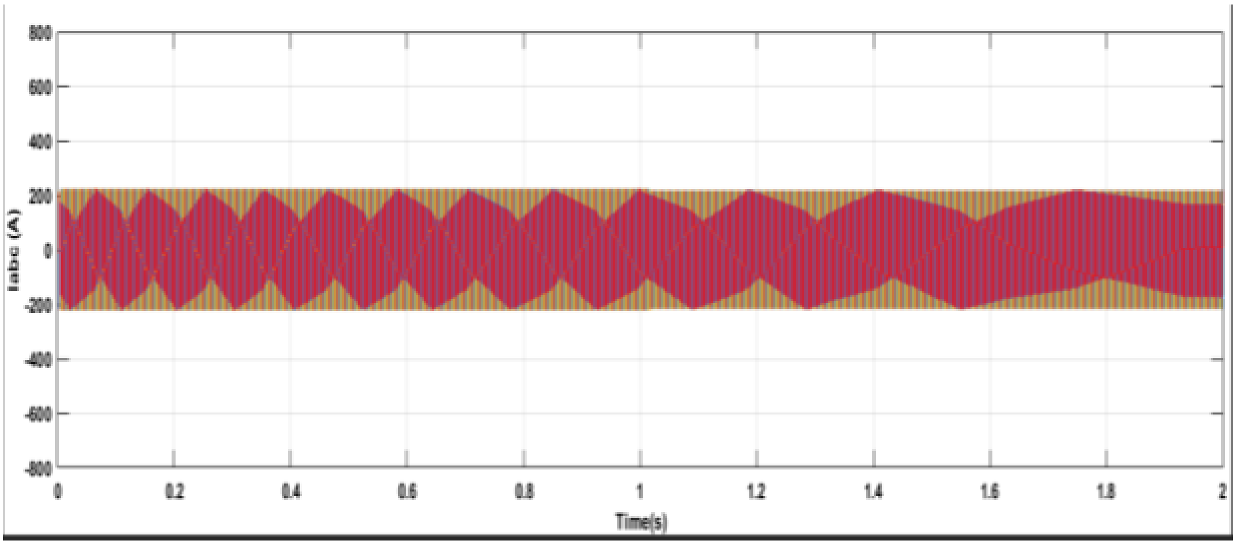


Figure 5.9b Three Phase Stator currents

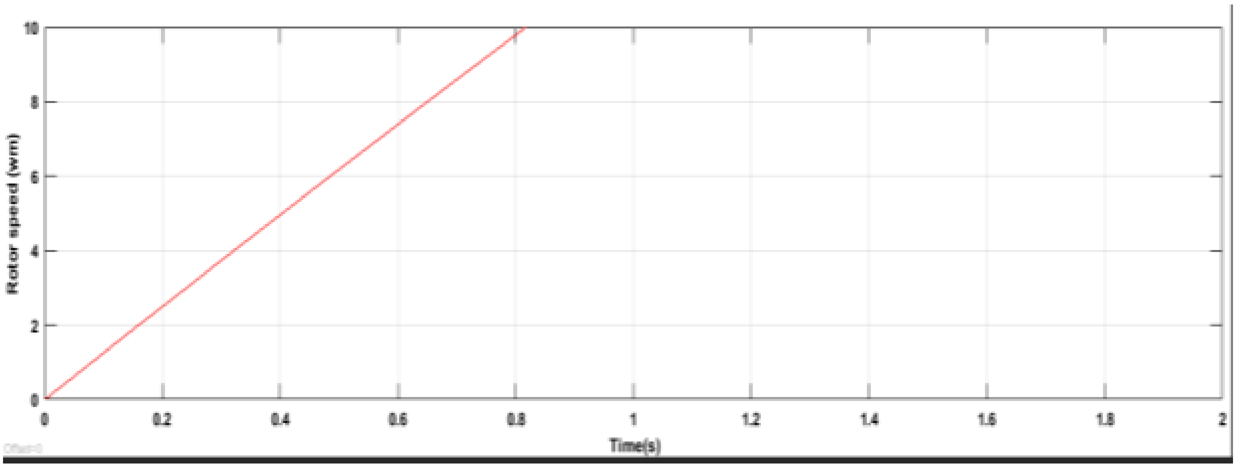


Figure 5.9c Under Transient Motor Speed

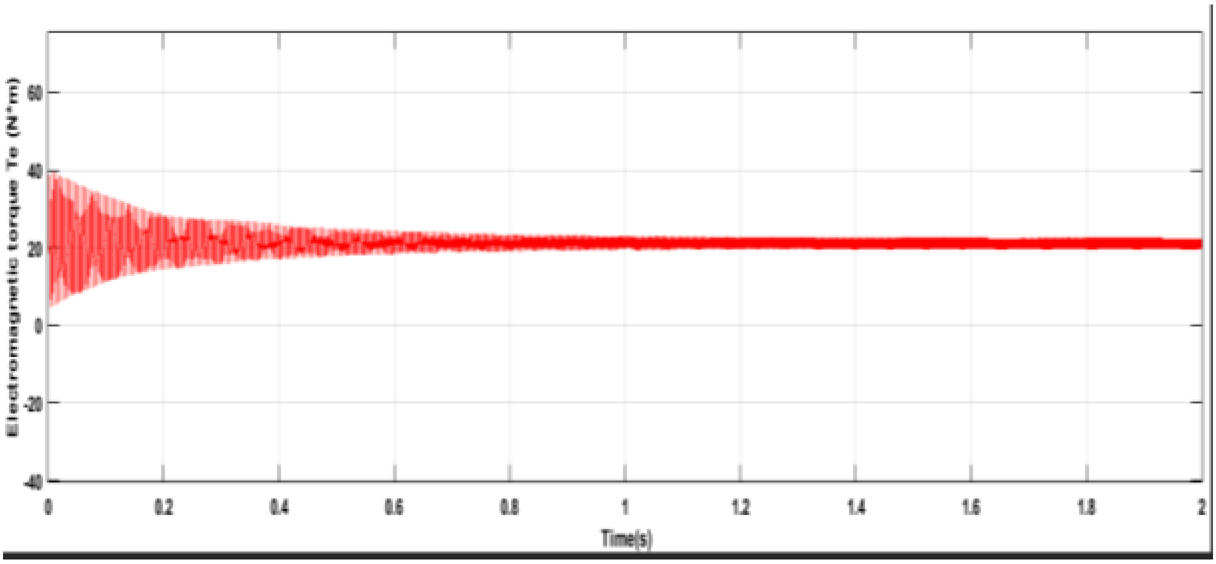


Figure 5.9d The Developed Torque.

5.10 when fault is occurred in phase A or 1st leg

A fault tolerance inverter fed vector control of three phase induction motor drive system has been simulated in MATLAB-Simulink. A constant load torque is applied to the induction motor and the fault occurred in phase A or 1st leg in the time period from 0.42 to 0.82 sec and get the desired waveforms of phase voltage in fig5.10a, Three phase stator current fig in 5.10b, desired motor speed fig in 5.10c and the desire torque in fig5.11d as shown in the below figure.

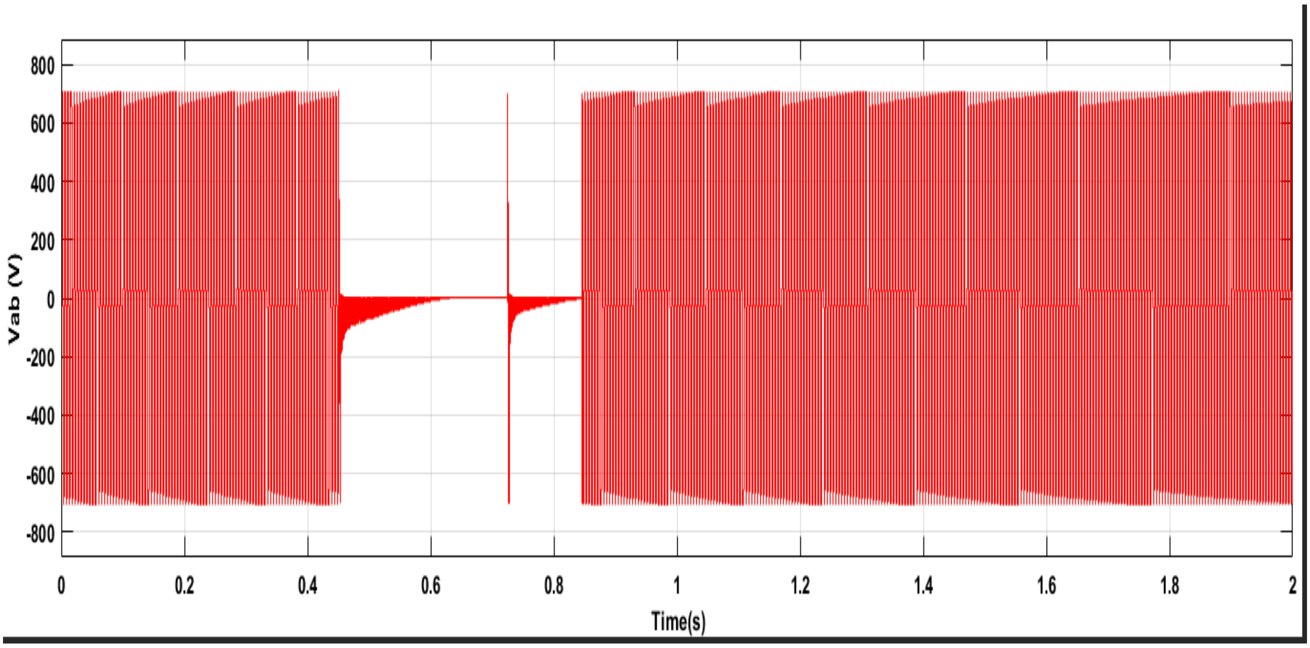


Figure 5.10a Phase voltage

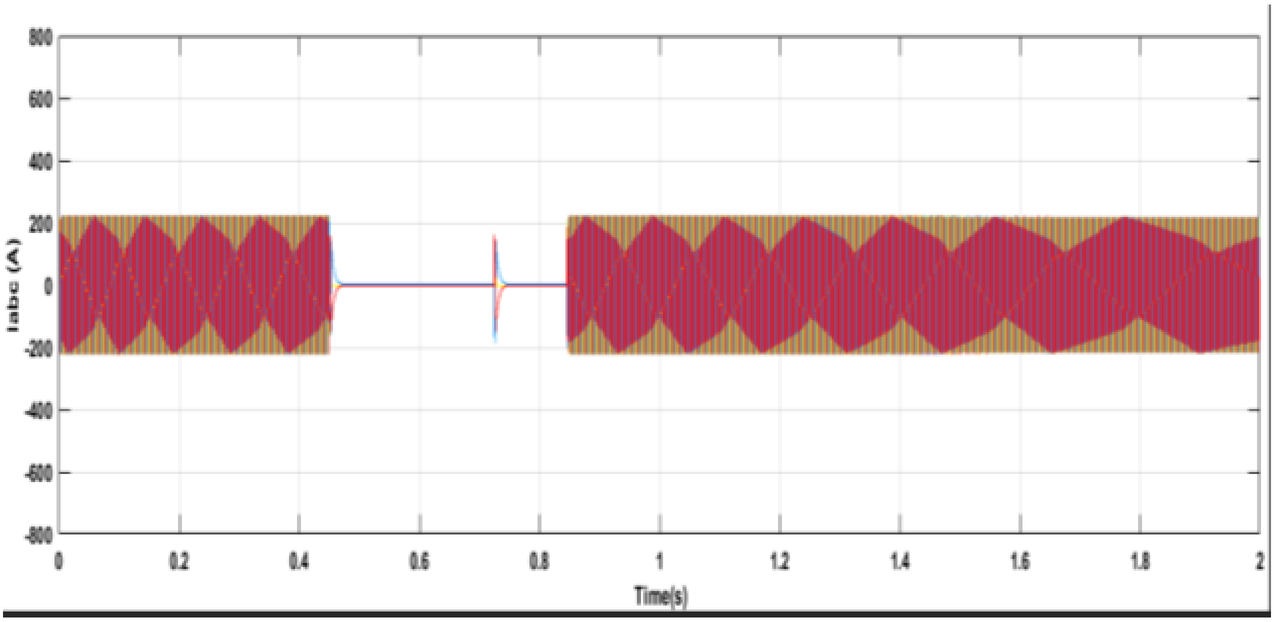


Figure 5.10b Three Phase Stator currents

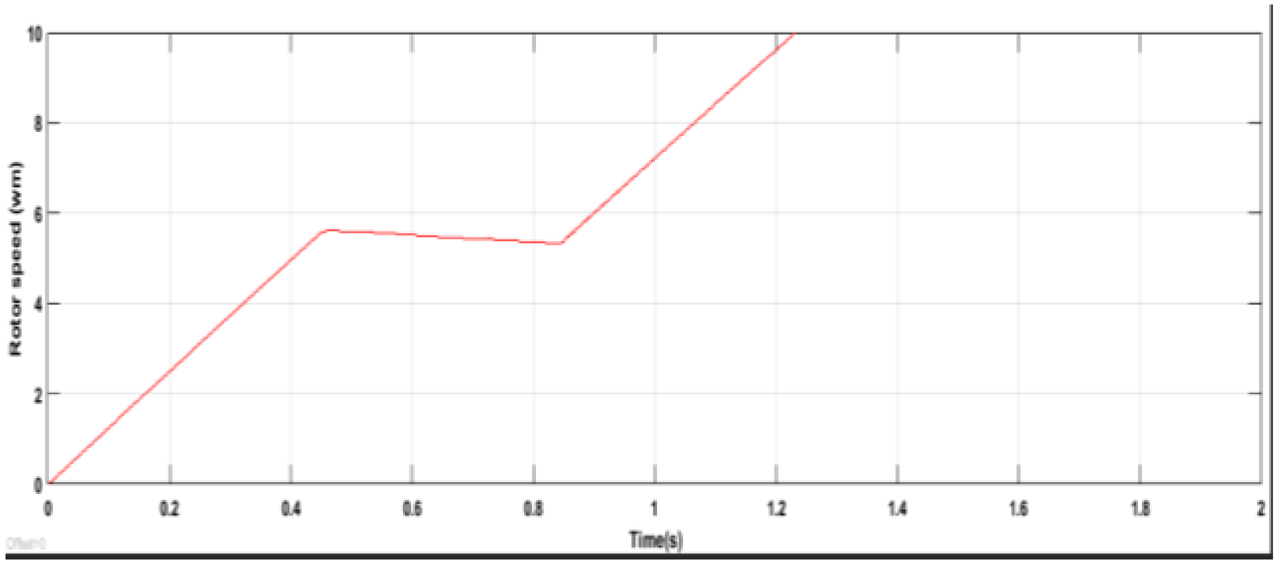


Figure 5.10c Under Transient Motor Speed

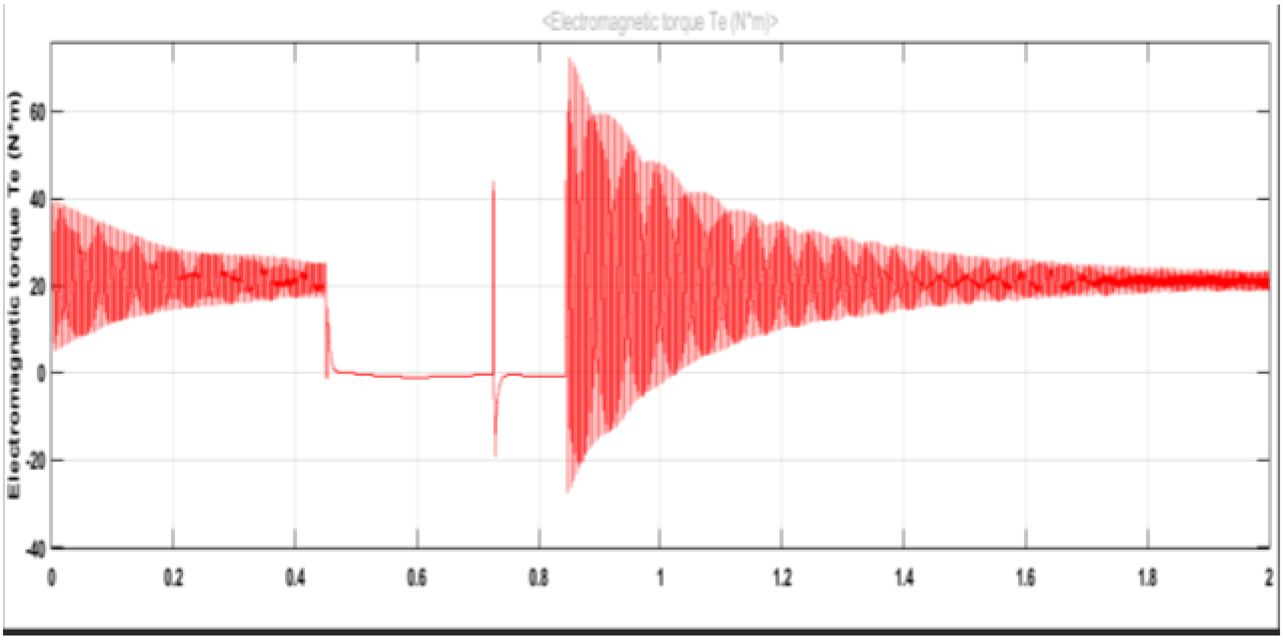


Figure 5.10d The Developed Torque

5.11 when fault is occurred in phase B or 2nd leg

A fault tolerance inverter fed vector control of three phase induction motor drive system has been simulated in MATLAB-Simulink. A constant load torque is applied to the induction motor and the fault occurred in phase B or 2nd leg in the time period from 0.42 to 1.18 sec and get the desired waveforms of phase voltage in fig5.11a, Three phase stator current fig in 5.11b, desired motor speed fig in 5.11c and the desire torque in fig5.11d as shown in the below figure.

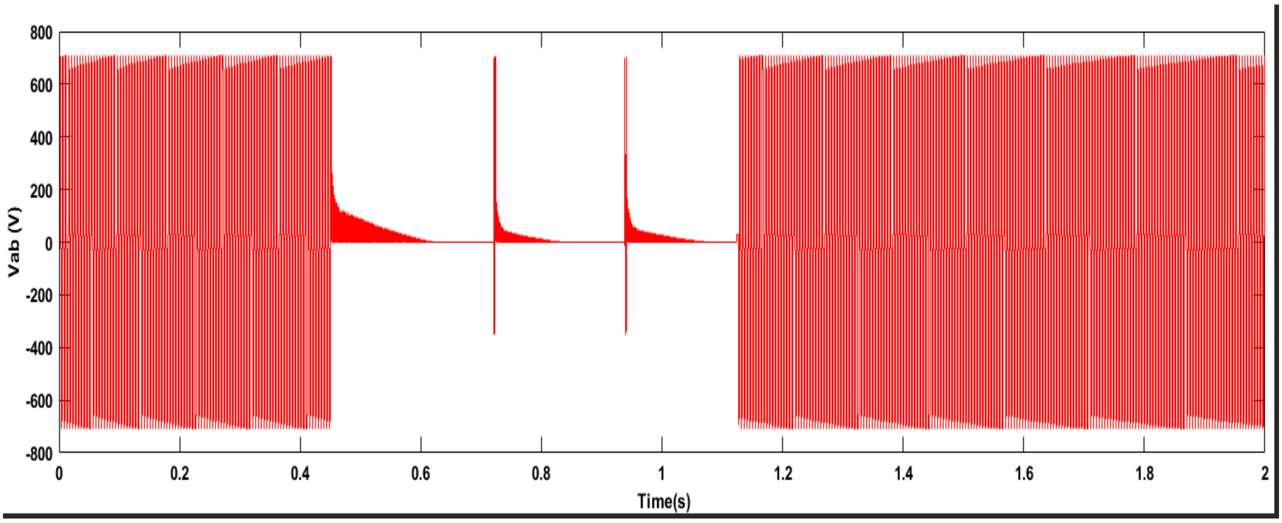


Figure 5.11a Phase voltage

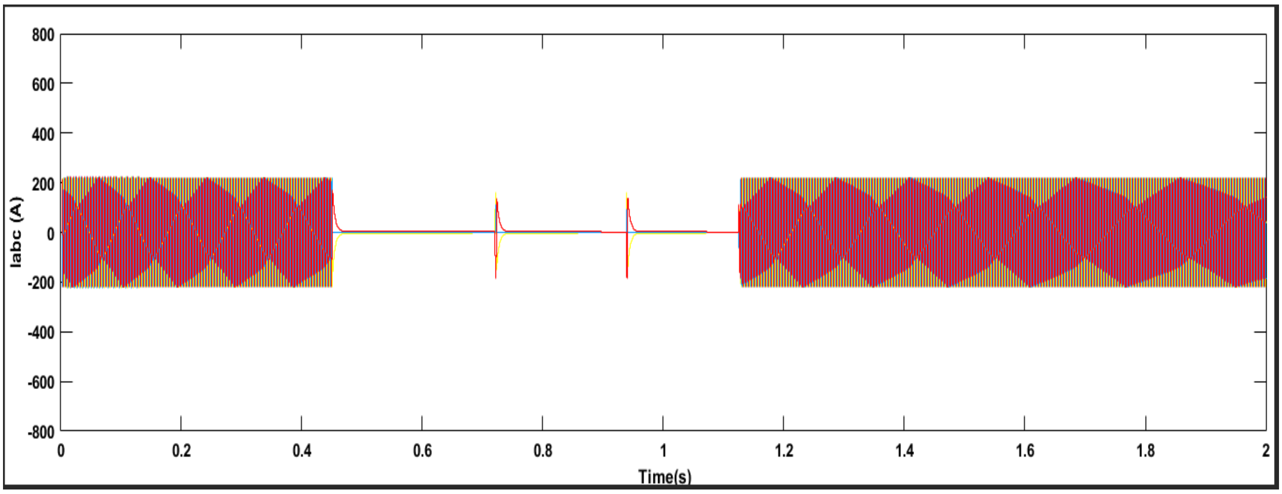


Figure 5.11b Three Phase Stator currents

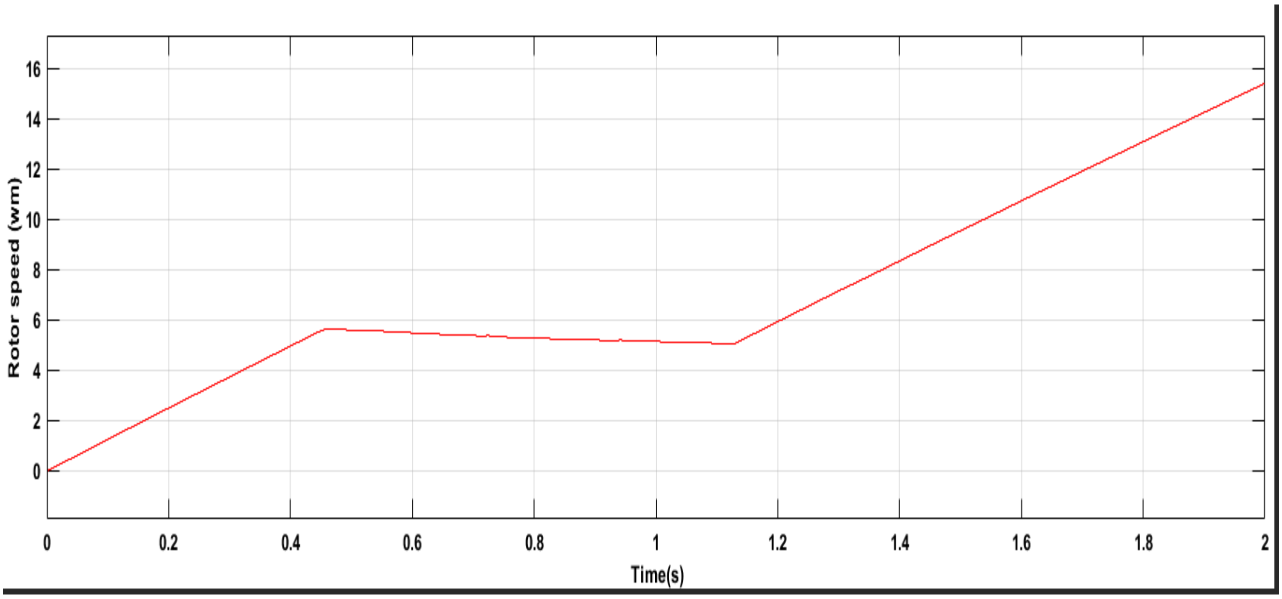


Figure 5.11c Under Transient Motor Speed

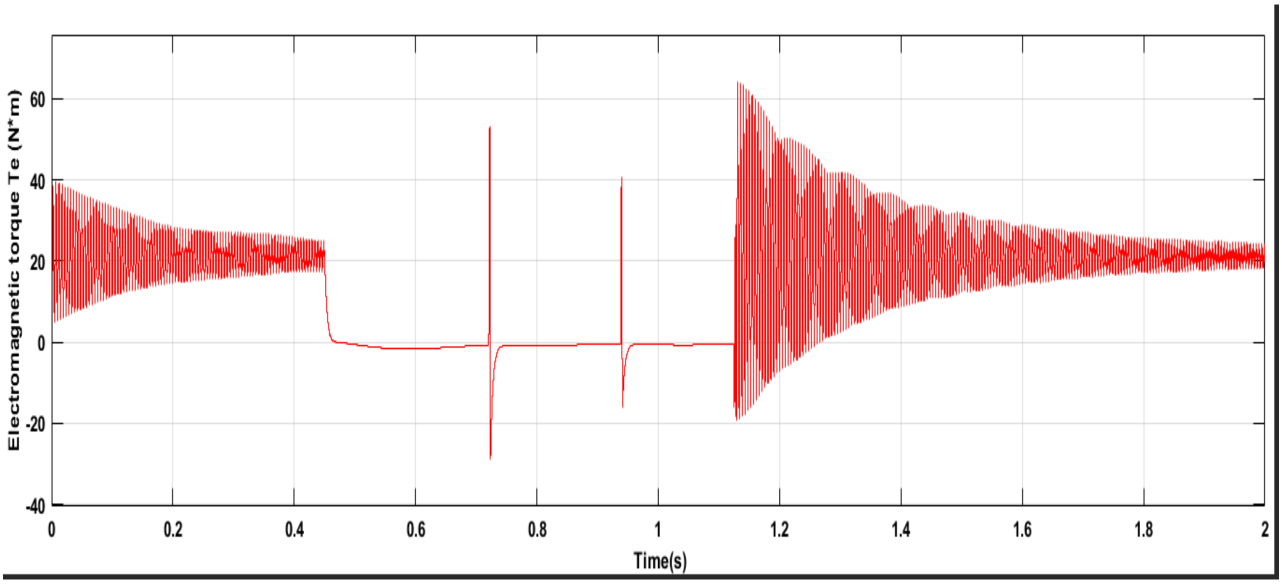


Figure 5.11d The Developed Torque

5.12 when fault is occurred in phase C or 1st leg

A fault tolerance inverter fed vector control of three phase induction motor drive system has been simulated in MATLAB-Simulink. A constant load torque is applied to the induction motor and the fault occurred in phase C or 3rd leg in the time period from 0.42 to 1.72 sec and get the desired waveforms of phase voltage in fig 5.12a, Three phase stator current fig in 5.12b, desired motor speed fig in 5.12c and the desire torque in fig5.12d as shown in the below figure.

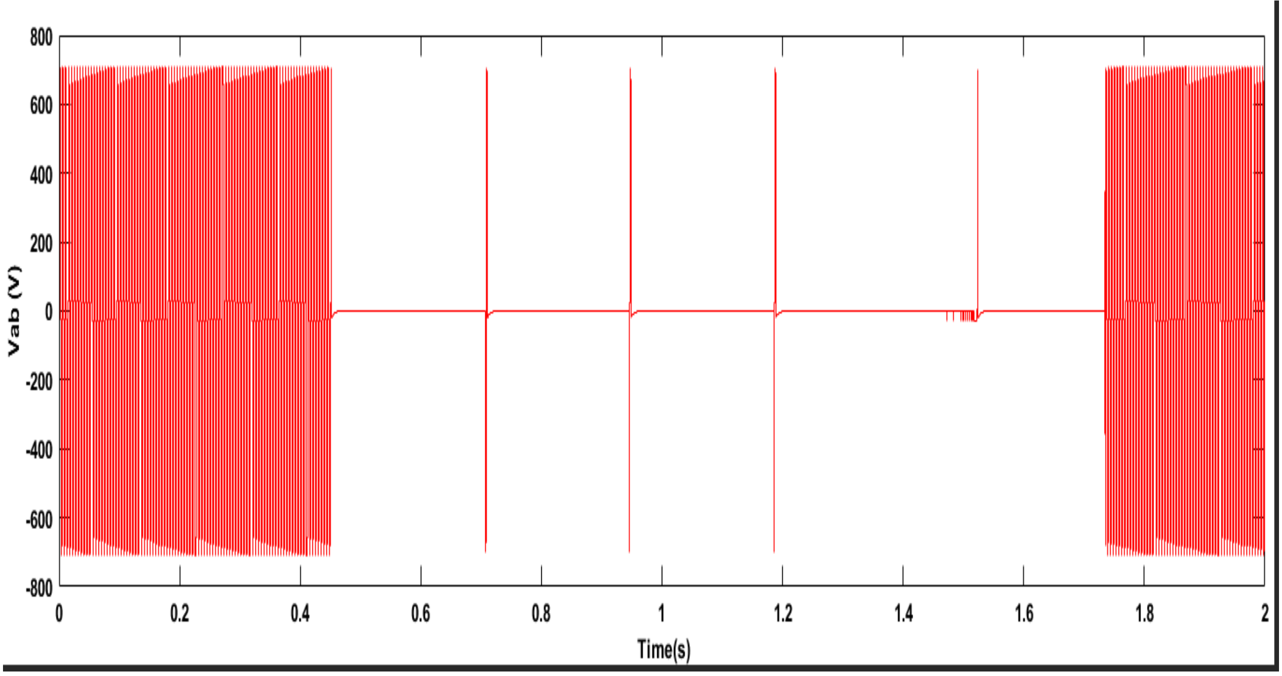


Figure 5.12a Phase voltage

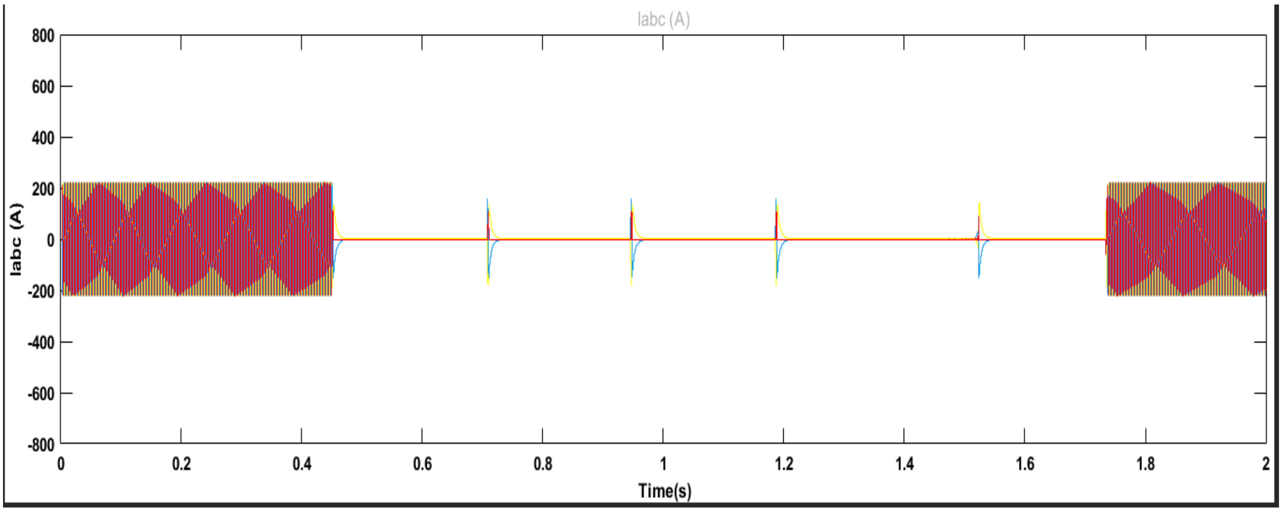


Figure 5.12b Three Phase Stator currents

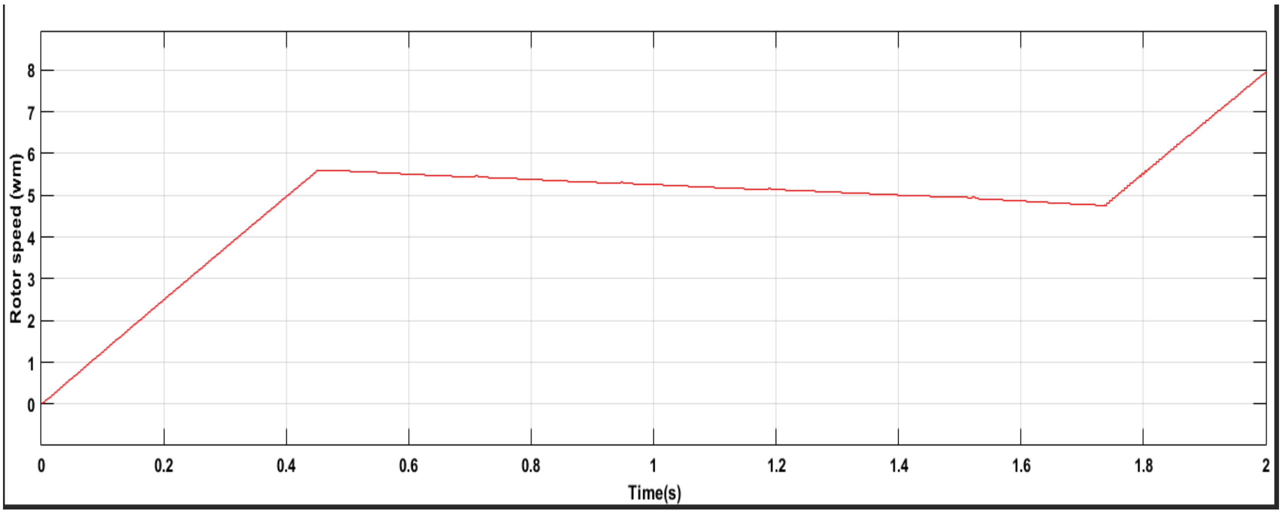


Figure 5.12c Under Transient Motor Speed

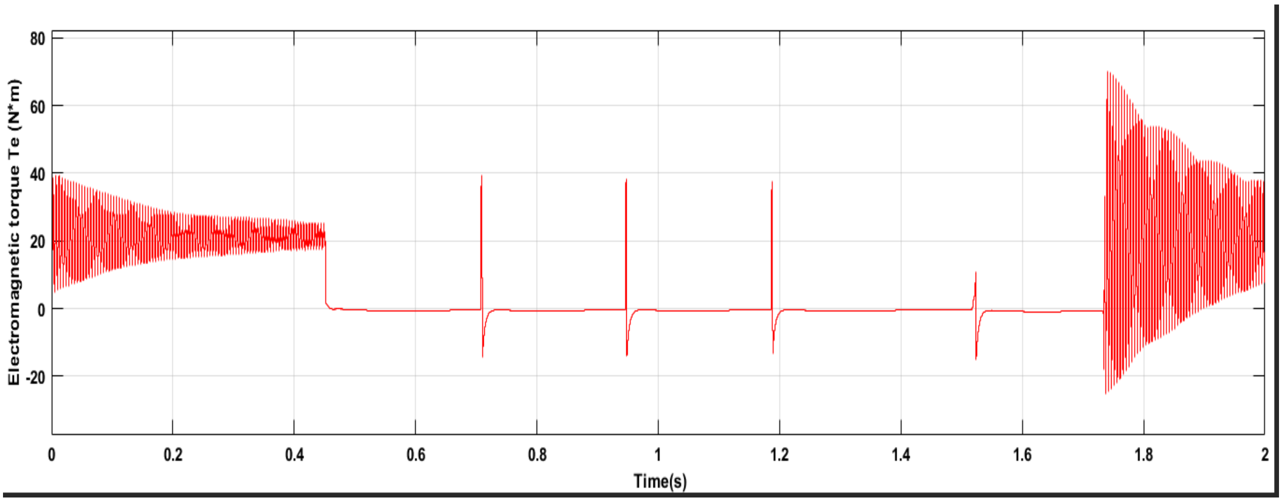


Figure 5.12d The Developed Torque

CONCLUSION

In this thesis, modelling and simulation of fault tolerant topology and a system reconfiguration scheme for the high speed induction motor drive is proposed. The method can achieve safe post-fault isolation and reconfiguration to avoid the secondary fault caused by direct switch of the redundant or extra switch and the faulty switch after the fault diagnosis process. The system reconfiguration can be implemented rapidly and effectively after the open circuit or short circuit switch fault by the proposed method. Simulated result verify the validity of the proposed fault tolerant method.

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