Induction Motor Steady-State Performance under Varying Quality of Supply and Stator Winding Short Circuit Location Using Negative Sequence Current

By

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ABSTRACT

Virtually 35% of stator related faults on three phase induction motors are a direct result of stator short circuit. Thus, online fault diagnostic techniques are preferred in particular for critical machines that are critical to the process due to technique’s quick reaction time essential to fault and it robustness. A breakdown on a critical machine may lead to catastrophic failure causing loss in downtime and unscheduled maintenance. It is essential to continually monitor the condition of the machine’s health not only the frame but also the winding condition to predict any developing failures and be rectified before the fault propagates to a catastrophic state. Various techniques have been used in the study to monitor the condition of an induction machine stator winding; these techniques are classified as offline and online monitoring techniques.

This thesis focuses on the turn-turn insulation monitoring on three-phase low voltage induction machine in steady state. When the winding begins to deteriorate, the machine currents become magnetically unbalance, which gives rise to negative, and positive sequence components of current. In the event of a short circuit between the turns in the winding, negative sequence current offers a fast, reliable and robust monitoring technique. The limitation of this technique is that, it is sensitive to external disturbances such as variation in Quality of Supply (QoS) parameters. This can be a change in magnitude of supply voltage and frequency (voltage swell, voltage dip and voltage unbalance) which has a direct impact on the negative sequence component of current. The research emancipation reveals the impact of these external influences when there is an incipient of short circuit and when there is no short circuit. Limitations of such a technique are evaluated by means of subjecting the machine to various external effects using a dynamic model on Simulink and the simulated results are verified by an experimental study. The simulated results and experimental results have a correlation, which supports the negative sequence current monitoring as an indicator of incipient fault in a stator winding of a three-phase induction motor.

List of Abbreviations

A	Ampere
AC	Alternating Current
DC	Direct Current
IEEE	Institute of Electrical and Electronics Engineers
kV	Kilo Volt
kW	Kilo Watts
LV	Low Voltage
MV	Medium Voltage
MVA	Mega Volts Ampere
MW	Mega Watts
V	Voltage
QoS	Quality of Supply
MCSA	Motor Current Signature Analysis
NSC	Negative Sequence Current
MMF	Magneto motive Force
DMM	Digital Multi Meter
W	Watts

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1. Introduction

The attractiveness of the induction motors comes from their simplicity in structure, robustness and reliability. Initial costs and maintenance costs of induction motors is also less in comparison with other types of motors [1]. Due to these features, induction motors are applied in most industrial processes such pumps, conveyors, fans under normal operation conditions, the components of induction machine are subjected to thermal, mechanical and electrical stress. The stress is increased during transients, such as load and supply variations, and many causes mechanical and insulation failure of the induction machines [2].

The vast majority of the motors used in industry are squirrel-cage induction motors due to their low cost, high reliability and high efficiency. There are no electrical connections to the rotor, which means that there are no brushes, commutator or slip rings to maintain and replace. The speed of an induction motor is essentially determined by the frequency of the power supply and by the number of poles of the motor. However, the speed decreases a few percent when the motor goes from no-load to full load operation. The dimensional of energy saving in the industry is on the rise, induction motors are an integral part of drive systems, not only is condition monitoring necessary for keeping the process running but also to ensure cost reduction and energy consumption reduction [3]. This paper focuses on robust method for early detection of anomalies due to short circuit between turns in stator winding of induction machine, where an anomaly is defined as a deviation from the nominal expected behaviour of machine dynamics.

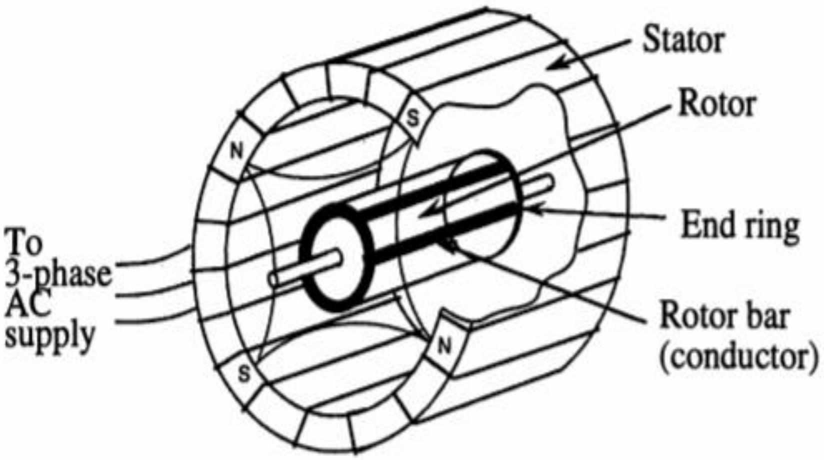

Figure 1-1 Diagram of Squirrel Cage induction motor [4]

1.1 Background

Induction motors come in various sizes, from single phase motors usually called fractional horsepower machines to large 3 phase motors rated up to hundreds of kilowatts. The architecture of these machines regardless of the size is the same. The stator is made of 3 phase windings to which electrical power is connected [5]. The rotor configuration of induction motors may vary from wound rotor, salient pole rotor and squirrel cage rotor.

The stator of a squirrel cage induction motor comprises of laminated stator core that is made up of sheet steel punching with inner slots that the winding is fits in, for higher rating motors the stator slots are open type to allow for the insertion of pre-shaped insulated coils that are laid out in the same fashion forming stator poles [6].

The cage rotor of a three-phase motor consists of a shaft that is pushed through iron core and bearing landings to support the drive end and non-drive end bearings. The common rotor construction is that with rotor bars in the lamination slots with no winding [6]. The rotor bars of a squirrel cage motor are embedded deeper into the rotor and have an increased inductance to ensure lower starting currents and lower pull-out torque on the motor.

There is no electrical connection to the rotor, current flowing in the rotor is due to the voltage induced by the rotating magnetic field applied in the stator and hence the name induction motor. The magnetic field rotates at synchronous speed, which depends on the frequency of the supply and the number of poles of the machine according to equation 1 below:

$$\omega_s = \frac{120f}{P} \tag{1-1}$$

Where: ω_s is the synchronous speed

f is the frequency of the supply and

P is the number of poles of the motor

The speed of the rotor is slightly lower than the synchronous speed. The difference between the two speeds is called slip. The slip is different from machine to machine and depends on the load. Equation 2 below describes slip of an induction motor

$$S = \frac{\omega_s + \omega_r}{\omega_s} \tag{1-2}$$

Where: ω_s is the synchronous speed

ω_r Is the rotor speed

S is the slip

One important point to be noted is that the end rings and the rotor conducting bars are permanently short-circuited, thus it is not possible to add any external resistance in series with the rotor circuit for starting purpose [7]. The rotor conducting bars are usually not parallel to the shaft, but are purposely given slight skew. In small motors, the rotor is fabricated in a different way. The entire rotor core is placed in a mould and the rotor bars and end-rings are cast into one piece. The metal commonly used is aluminium alloy. Some very small rotors, which operate, based on eddy current, have their rotor as solid steel without any conductors.

1.2 Principle of operation

When three phase stator winding of an induction motor is energized from a 3 phase supply assuming that the quality of supply is healthy and free from voltage unbalance, voltage dip, voltage swell and fault harmonic content, a rotating magnetic field is set up which rotates round the stator at synchronous speed [8]. The rotating field passes through the air gap and cuts the rotor conductors, which yet, are stationary. Due to the relative speed between the rotating flux and the stationary rotor, electromotive forces (EMFs) are induced in the rotor conductors. Since the rotor circuit is short-circuited, currents start flowing in the rotor conductors [9]. This induced current circulating in the rotor bars interact with the air gap flux to produce torque.

The current-carrying rotor conductors are placed in the magnetic field produced by the stator. Consequently, mechanical force acts on the rotor conductors. The sum of the mechanical forces on all the rotor conductors produces a torque, which tends to move the rotor in the same direction as the rotating field [9]. The resultant torque produced is maintained as long as the rotating flux and rotor current is present. The fact that rotor is urged to follow the stator field can be explained by Lenz’s law. According to this law, the direction of rotor currents will be such that they tend to oppose the cause producing them [8].

Now, the cause producing the rotor currents is the relative speed between the rotating field and the stationary rotor conductors. Hence, to reduce this relative speed, the rotor starts running in the same direction as that of stator field and tries to catch it. An induction motor can operate in different modes governed by the slip of the machine.

1.3 Machine inter turn short

The different stator related faults on an induction motors may yield catastrophic consequences for an industrial process. The causes of stator related faults may vary from machine design flaws, improper use, cooling method deficiencies and extreme power quality parameters; the varying quality of supply from the utilities put stress on the machine winding and bearings, which may lead to premature failures [10]. The stator related faults manifest themselves gradually over time, the winding insulation resistance deteriorate over time as the extreme conditions worsen so is the winding condition, which eventually fails if not detected at an early stage and rectified.

Based on the findings on failure survey over the past decades have reported that almost 40 % of the motor failures were caused by bearing related issues which includes under greasing or over greasing the rolling elements. Almost 38 % of these faults are attributed to stator winding faults, 10 % is contributed by rotor related faults, which include broken rotor bars. A mixture of faults, which affect other parts of an induction motor, contributes the remaining 12 % of these failures. From the survey findings, it is evident that stator winding related faults are prevalent which gives rise to turn-turn faults and phase-phase faults [11], [12]. Factors such as harmonics, supply voltage irregularities, thermal and mechanical stresses lead to insulation degradation in the stator winding which eventually manifest as a winding failure.

Early detection of stator winding related faults is a very important part of condition monitoring of induction motors [11]. Failures such as inter-turn short circuit which occurs when the insulation deteriorate and eventually breaking down between two or more adjacent turns of the same coil and the turns short against each other which reduces the effective resistance of the faulted phase [12]. Inter-turn faults constitute the most common causes of failures in three-phase induction motors and they are more prevalent as their occurrence is catastrophic [10].

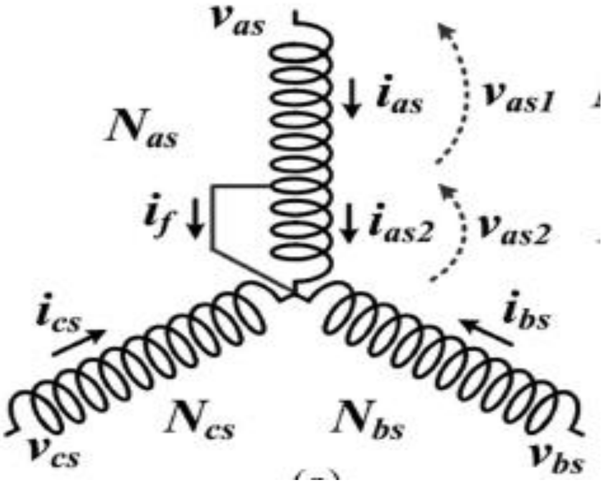

Figure 1-2 Induction motor star-connected stator winding - inter-turn short circuit on phase "a" [1]

1.4 Feasibility study

Winding faults are one of the most typical failures in three-phase squirrel-cage induction machine (IM) applications. These faults are caused by the combination of various internal and external stresses acting on the stator [9]. The internal stresses in IM are thermal, electrical, and mechanical. The external ones are due to environmental conditions such as high ambient temperatures, high moisture, corrosive environments, dusty medium, and oil surroundings. The objective of the thesis is to simulate and measure the winding faults in an induction machine in case there is an occurrence of fault in the induction motor it needs to be seen and be attended immediately to avoid the catastrophic failure in the line. The prompt fault detection and identification of these types of faults can avoid costly repairs, significant financial losses, and safety problems.

1.5 . Project description and research questions

Condition monitoring means the continuous evaluation of the health of plant and equipment throughout its serviceable life. Idea of planned shutdown can be possible due to introduction of condition monitoring. Monitoring should be designed to pre-empt faults, whereas protection is essentially retroactive [13]. Condition monitoring can, in many cases, be extended to provide primary protection, but its real function is always being to attempt to recognize the development of faults at an early stage. Schedule Outages in the most convenient manner, resulting in lower down time and lower Capitalized losses. Expenses occurred due to forced outage can be minimized by condition monitoring.

Condition monitoring of electric machinery can significantly reduce the cost of maintenance and the risk of unexpected failures by allowing the early detection of potentially catastrophic faults. Online condition monitoring uses measurements taken while a machine is operating, to determine if a fault exists [13].Based on studies according to Motor Reliability Working Group (MRWG) and the investigation carried out by Electric Power Research Institute (EPRI), a common mode of failure of an induction motor is the bearing failure followed by stator winding and rotor bar failures. The bearing failure increases the rotational friction of the rotor [14].

Condition monitoring forms an integral part of production and plant health, contributes to cost reduction in the form of planned maintenance and reduction of downtime. The research will cover the following questions:

1) Which motor parameters are affected during stator winding short circuit fault condition?
2) What is the effect of excessive fault harmonics on the supply driving an induction motor?
3) What is an effectiveness of using negative sequence current as a stator winding short circuit indicator for small-to- large induction motors?
4) What is the effect of single phasing an induction motor while under load, while running at no load and at start up?
5) What is the effect of voltage swell, voltage sag as well as voltage imbalance on the operational parameters of an induction motor?

A set range has to be defined where condition monitoring can be employed, ideally big and critical motors are selected for condition monitoring as the small motors are easily disposable and are available off the shelf at a cheaper price.

1.6. Research aim and objectives

In recent decades, many researches have been made to detect the stator turn fault in induction motors. Stator turn fault makes the motor asymmetry; several parameters in the motor will change due to the asymmetry and become the fault indicator. The purpose of this research is to investigate and an attempt be made to detect the location of the shorted coil in the stator winding and the influence of poor quality of supply on an induction motor. Negative sequence current analysis will be used for this in Matlab necessary measures should be taken to avoid catastrophic failure that may take place in the motor.

The main aim is to deduce a low cost and effective method for condition monitoring of induction motors, which does not affect the operation of the machine as it is desired to be an online test. The objectives include but not limited to:

1) Mathematical model and simulation of induction motor.
2) Investigate the effect of fault on the motor parameters such as voltages and currents.

3) Model a machine with varying quality of supply conditions
4) Model a machine with undesired harmonic content on the supply voltage and current
5) Simulate the motor model with faults, with a specific focus on winding and bearing failures.
6) Compare simulated results and practical results to draw a meaningful conclusion.

1.7. Research methodology

A mathematical model of an induction motor is developed and the model will define the transient and steady state parameters of the motor and how they change when a fault is introduced either to a winding or in the supply voltage parameters. A change in the mathematical model will signal a fault or error that needs to be attended to. From the mathematical model, a simulink model will be developed to further study the behaviour of the induction motor with and without faults and plot graphs and current trends.

The second step is to translate the simulation into a practical experiment, taking a healthy stator of an induction motor and do the necessary tests, subjecting the machine to different supply conditions and winding short circuit conditions the verify the effectiveness of the method of negative sequence current and the validity of such an approach. Any deviations would be analysed thoroughly and observe the effectiveness of the method applied. It would be ideal to get results from a new motor and another set from an old motor so that the new motor data can be used as a benchmark and any deviation from new motor data would be a signal of a fault present on the old motor.

2. Literature review

Motors form a very critical component in the electric utility, rolling mills and other process industries, induction motor failures could result in a catastrophic shutdown of a production line and loss of production due to downtime, which can lead to compromised product quality and reduced profit returns. Studies have shown that stator-winding breakdown is one of the major causes of machine failures. Stator related failures in industrial induction motors are mainly caused by the combination of many factors such as a poor quality of supply from the utility, thermal stress and mechanical stresses as well as the environment at which these machines operate [15]. Poor maintenance plan can add unto the stresses that shorten the life span of the induction motors.

Several simulations and model studies have been published related to the analysis of the stator winding faults and several techniques can be used to diagnose stator-winding faults. These published models continuously monitor the induction motor parameters as a baseline; any deviation observed during the real time monitoring is used as a fault indicator indicating the localized fault present in the stator winding of an induction motor [16]. These techniques include partial discharge, vibration monitoring, current monitoring and the analysis of the axial flux.

Condition monitoring methods are divided into two groups namely the online diagnostic methods where the motor condition is monitored while the machine is live and running. Offline diagnostic methods monitor the motor parameters while the motor is not running. Machine parameters such as motor current, motor flux, motor voltage and frequency are extracted through a sophisticated methodology for processing, analysis and comparison against a baseline so that any deviations are used as a fault indicator.

2.1. Motor Current Signature Analysis (MCSA)

Motor current signature analysis (MCSA) based approach is applied to perform short circuit fault detection in a three-phase induction motor. MCSA is a noninvasive fault detection technique; this method is performed by monitoring and extracting motor parameters that trigger a short circuit fault condition as well as harmonic related fault condition. This method is a frequency-based technique that extracts frequency information where one or more specific frequencies of current are used as fault indication.

For an induction motor fed from a healthy supply that is balanced and the voltages are sinusoidal. An occurrence of a stator winding fault which can be classified as inter-turn short-circuit, phase-to-phase short-circuit and phase-to-ground short circuit leads to an asymmetry between the three-phases of the motor. This asymmetry in the three-phases produces a change in the harmonic components of the rotor and stator currents of the induction motor. The line currents spectrum will somehow have side band currents. These side band currents are a function of the minimum value of the supply current lower sideband and the maximum value of the supply current upper sideband. Thus, the method of MCSA is effective when there is an occurrence of stator short circuit which increases specific frequencies which are characterized by Kf_s, which is an integer multiple of the fundamental frequency [17].

A Welch spectrum is necessary for frequency analysis. At no load conditions, the current spectral component resonates at 540 Hz among all the fault frequencies possibilities within the range of 500Hz-600Hz. At 75% of load, the fault detectability based on the proposed technique under coupled load the 540Hz spectral amplitude shows consistent behaviour under the load condition. As the load increases with the number of shorted turns being kept constant, the frequency variation reflects across nonrelated frequency components and the sensitivity of the technique is inconclusive [18]. Increasing the load on the motor affects the amplitude of the Welch frequency spectrum making it complex to achieve accurate monitoring and fault detection. MCSA is directly affected by an increase in load on the faulted motor altering the amplitude of the fault indicator.

2.2. Assessment of Fault Harmonics

An ideal induction motors are built with a field distributed stator winding and it operates in a uniform magnetic field, these motor under these conditions will produce a perfect and true sinusoidal voltage with no noise. Since these ideal conditions do not exist in real life as there are impurities and non-idealities in the utility network [19]. Distortions in current and voltage waveforms are created causing these signals to deviate from a pure sine wave created by a fundamental frequency of 50Hz.

These distortions, described in the form of a periodic function forming harmonics, which form part of the wave and superimposed onto the fundamental sine wave. These harmonics are signals that are an integral multiple of a fundamental frequency. According to the Fourier theorem, any periodic function with a period of T generally continuous and limited may be represented by an infinite series of sinusoidal terms [20]. These terms are odd function of the series, which denote and express the odd harmonics as being the contributor to harmonics being harmful in induction motors as well as other equipment connected to the contaminated network.

Each harmonic component contribution in a network varies, the higher the harmonic order the lesser the contribution to the net sine wave of either current or voltage. The presence of both lower order and higher order harmonic distortion in a network has negative effects on induction motors such as the speed reduction of the motor and the net torque reduction. These harmonics are classified to either being the forward or reverse component or the zero sequence component, this determines the direction of flow of the harmonic content as well as the effect it has on the motor parameters [21]. Even harmonics have a frequency that is an even multiple of the fundamental frequency and odd harmonics have a frequency that is an odd multiple of a fundamental frequency. Odd harmonics have a greater effect on induction motors.

Magnetic fields are set up in the motor core by the supplied voltage to the motor; these magnetic fields create iron losses in the magnetic frame of the motor. These iron losses that are created by a rotating magnetic field produce a two-component loss, which are namely, eddy current losses, and hysteresis losses. Eddy current losses vary as the square of the frequency supplied to the motor and hysteresis losses are proportional to the supplied frequency. The additional losses increases the motor operating temperature to a value higher than the motor's rated temperature which results in premature winding faults.

The fifth order harmonic has a negative sequence rotation, which means it rotates in the direction that opposes the motor rotation. It has a higher voltage as compared to the seventh and third order harmonics respectively. These odd harmonics produce a counterclockwise rotating torque, which reduces the net motor torque [21]. The presence of harmonics also affects the motor efficiency as it decreases by 10% and causes pulsation in torque because of negative sequence harmonics.

2.3. Effects of Quality of Supply on Induction Motors

The increasing stress and widening gap between the power supplied and the power demanded from the utility by domestic, commercial and industrial loads gives rise to power quality issues as the utility cannot keep up with the loads [22]. The sudden rise in inductive loads or unnotified load variation in industries disturb the quality of supply, which has negative implications on the performance of equipment inclusive of induction motors. The main concern of power quality is focused on the deviation of power quality parameters such as voltage and current from the set of defined values. Voltage magnitude variation and voltage unbalance seem to be most common occurring power quality problems, over the years the increasing use of variable seed drives for electric motor application has introduced harmful harmonic content in the quality of supply [22]. Three-phase induction motors are widely used in industrial systems whose working principle and performance is greatly affected when driven by unsymmetrical voltage.

2.3.1. Under Voltage/ Voltage dip

Voltage dip is a shortly reduction in the distribution network's declared voltage dropping below the equipment rated voltage for a defined period. The threshold of the equipment immunity of the voltage dip is 90% of it rated voltage for a range of 10milliseconds to 1 minute [22]. These voltage dips influence the functionality and performance of equipment connected to the electric network such as variable speed drives, transformers and electric motors. They can be classified as either balanced or non-balanced voltage dip depending on the direction of flow of reactive power and the location of the short circuit fault being either downstream, customer side or upstream being the utility side [23].

A three-phase short circuit condition where all three phases short against each other which can be caused by extreme weather conditions such as wind can produce a balanced voltage dip. Starting up larger balanced loads or larger motors can causes the balanced voltage dips. For unbalanced voltage dips, they are caused by single line to earth faults due to lighting or phase-to-phase faults where two phases short against each other. Unbalanced voltage dips are characterized by the individual phase voltage being different to each other with respect to the phase angle, voltage magnitude as well as the direction of the voltage dip per phase.

The net torque of an induction motor is directly proportional to the square of the supplied voltage driving the motor. Any deviations in the supply voltage affects the motor net torque.

As the motor supplied voltage drops, because of a voltage dip, the motor net torque also decreases as a square of the voltage. A decrease in torque also decreases the motor speed, depending on the dip duration the speed may recover to it rated value as the voltage magnitude recovers to it declared value. The worst case the motor may not be able to accelerate its load upon the restoration of supply voltage and the motor ends up stalling. The decrease in voltage presents spikes in current during the dip period a decrease in voltage requires an increase in current to counteract the effect of changing voltage [24]; these current spikes can damage the motor insulation resistance over time, which can lead to premature stator short circuit caused by the deteriorating winding insulation. The present current spikes also have a negative implication on the motor protection system, the modern variable speed drives tend to trip as the voltage drops below 80% of the motor voltage, so the dip contributes to longer downtime and loss of production.

2.3.2. Over-Voltage/ Voltage swell

Voltage variations in a network can range from small voltage fluctuations of shorter duration to fluctuations of longer duration some may lead to complete outage. Voltage swell (over voltage) is regarded as a power quality parameter that is critical to the operational of an induction motor as it alters the motor characteristics if not kept within required compatibility limits [25]. Voltage swell is a sudden increase in the voltage across the network that is out of the rated tolerance and immunity level of the connected equipment. These swells may be a direct result of the upstream faults on the feeder line due to lightning that causes the voltage to rise shortly.

Voltage swells are usually associated with system fault conditions, any deviation on the system from declared values - just like voltage sags but are much less common their occurrence is not often on the power system. This is particularly true for ungrounded or floating delta systems, where the sudden change in ground reference result in a voltage rise on the ungrounded phases. In the case of a voltage swell due to a single line-to-ground fault on the system, the result is a temporary voltage rise on the unfaulted phases, which last for the duration of the fault. Voltage swells can also be caused by the deenergization of a very large load. The abrupt interruption of current can generate a large voltage, per the formula:

$$V = L\frac{di}{dt} \tag{2-1}$$

Where L is the inductance of the line and $\frac{di}{dt}$, is the change in current flow [26]. Moreover, the energization of a large capacitor bank can also cause a voltage swell, though it more often causes an oscillatory transient.

Although the effects of a sag are more noticeable, the effects of a voltage swell are often more destructive. It may cause breakdown of components on the power supplies of the equipment, though the effect may be a gradual, accumulative effect. It can cause control problems and hardware failure in the equipment such as induction motors connected on the load side, due to overheating that could eventually result to shut down, which manifest as stator winding short circuit. In addition, electronics and other sensitive equipment are prone to damage due to voltage swell [27].

The net torque of an induction motor is directly proportional to the square of the supplied voltage driving the motor as indicated earlier on the paper. Any sudden changes that occur in a short period in the supply voltage affects the motor net torque, motor torque is relative to the speed at which the rotor turns to drive the load. As the supplied voltage to the motor sudden rises in the absence of voltage suppressing equipment, because of a voltage swell, the motor net torque also increases as a square of the voltage. A sudden increasing torque causes a pulsation on the motor speed as the motor tries to maintain its rated speed.

2.3.3. Voltage Unbalance and or Single-phasing

Voltage unbalance can be best defined as a ration of the negative sequence voltage component to the positive sequence voltage component supplied to any equipment connected to the three-phase supply. Voltage unbalance is given in terms of a percentage value, the higher the percentage value the greater the existence of unbalance between the three-phases of the supply. The zero sequence voltage is omitted on the basis that it has no influence on the behaviour of the rotor of an induction motor nor any other equipment. The output power and torque of the rotor are not related to the zero sequence component, thus the contribution remains zero [28].

By applying the method of analysing the complex voltage unbalance factor (CVUF) which is a segregation losses approach to analyse the stator core, friction and stray load of an induction motor [29]. When a typical induction motor runs at no load conditions; the unbalance factor greater than 3% is regarded as a severe power quality issue which needs urgent attention and rectification to ensure that no damage is done to the equipment connected to the supply especially induction motors, which are sensitive to an increasing voltage unbalance [22]. The presence of negative sequence voltage component gives rise to core losses, which include losses in the rotor bars, higher losses, increases the operational cost of an induction motor.

A small fraction of change in the voltage causes larger deviations in the motor current; this increasing motor current can cause trips on motor overload protection equipment and generates losses in the form of heat. The change in unbalance factor produces torque oscillations and ripples in the torque; the average torque is reduced considerably [30]. The unbalance in supply voltage has other adverse effects on induction motors like excessive heat, for induction motors of lower insulation class typically class F the presence of excessive heat the stator winding can degrade the insulation and eventually damage the insulation leading to stator short circuit. The other effect is vibration, which can lead to premature bearing failures due to bearing frequencies exceeding the maximum allowable limits causing bearings to collapse and damage the stator core laminations. Increased core losses due to unbalance can damage the stator core and lead to high operational costs.

Operating principle of an induction motor is such that the spatial distribution of the stator winding and the phase distribution of the three-phase input supply ensures the generation of the three-phase synchronous rotational electromagnetic field [31]. The introduction of the single phasing phenomenon on induction motors has negative implications such as a sudden rise in current and excessive overheating. Single phasing is the sudden loss or disconnection of one phase leaving the motor to operate in the two-phase region. The single phasing condition in induction motors can be as a direct result of three possible disturbances on the utility network [32]:

- Open phase on the terminals of the motor
- Open phase on the substation transformer primary
- Open phase on the primary of the distribution transformer bank

The characteristic behaviour of an induction motor under single phasing condition depends on the stator-winding configuration, whether it is star connected or delta connected. The stator current of the induction motor is governed also by the connection of the stator winding, when single phasing occurs the motor remains with two phases connected to the grid while the third phase falls away to a zero volt value [32] [24]. Different stator connections influence the phase current, in the case of a star connected stator winding the phase and the line current are the same, but may be 1.7 times higher than during single phasing. For delta connected stator the two remaining phases during the single phasing do not change the initial value, only the affected phases doubles the current due to resistance drop being twice less than the remaining phases [32].

In the condition where the single phasing of an induction motor occurs while the motor is rotating, the torque produced by the other two remaining phases produces a positive rotating magnetic field that will keep the motor rotating and produce the necessary torque to drive the load. The lost phase will produce a negative rotating magnetic field, which tends to oppose the motor rotation. During the occurrence of single phasing, the motor will produce excessive heat on the two remaining phases, which could result in stator winding burnout [33]. The presence of heat can be transferred to the rotor component of the motor heating up the rotor bars, which lead to vibration, and ultimately resulting in lubrication overheating and premature bearing failure due to vibrating shaft [31].

2.4. Negative Sequence Current Component

The method of negative sequence current elaborates the use of the current to detect short circuit in an induction motor winding. The temporary fault is defined as an instantaneous fault in the machine winding which over time disappears, the occurrence of the short circuit is not permanent [34]. In the context of the analysis the model is governed by cycles, the machine starts as healthy winding and after some time the fault occurs, one cycle later it disappears. During fault transition, motor currents are evaluated as fault indicator by comparing the change in negative, positive and zero sequence components of current. The machine is studied under different load conditions keeping the supply constant with the changing load and increasing number of shorted turns in the stator winding. The negative sequence current is chosen as the most effective fault indicator as the magnitude of the current is linear with an increase in shorted turn and it is not affected by load variation. Under healthy conditions, the negative sequence current is zero; it increases as the fault occurs.

Stator winding faults in an induction machine often develops from undetected insulation breakdown between two or more adjacent turns within a winding, which can be caused by factors such as overheating and voltage fast transient or voltage surge present in the stator winding. The undetected winding deterioration leads to high current flow in the weak fraction of the insulator eventually causing a short circuit [35].

For a balanced machine, the three phase currents are displaced by 120 degrees away from each other in a network and the magnitude of the phasors are equal. These currents contain only the positive sequence current, negative sequence current is the measure of the degree of unbalance in the network while the zero sequence component measures the magnitude of the current that does not complete the loop through the phase [34]. Experimental results prove the negative sequence current to be not immune to load variation and it is most effective in fault detection.

For reliable and robust fault detection by means of negative sequence current, the supply parameters such as voltage magnitude, phase sequence and frequency must be kept within an acceptable range and be controlled to ensure that there are no deviations from set values. Any deviation in the supply parameters will reflect on the negative sequence component and the method will interpret the power quality variation as a short circuit occurrence.

3. Mathematical Model of an Induction Motor

Various methods can be used to detect the turn-to-turn stator winding short circuit faults in an induction machine. Finite element methods (FEM), which is a computer, based numeric technique for calculating parameters of electromagnetic devices. It can be used to calculate the stator flux density, inductances and induced electromotive force etc. the behaviour of each element can be described with relatively simple set of equations. The finite element method has a capacity to provide detailed information about the machine nonlinear effects, which in this case are stator-winding short circuit faults. The disadvantage of such an approach is the time required calculating the field distribution may be very long; this time depends on the number of finite elements considered which makes it not ideal for this problem. It can only be applicable for new motor designs as their winding integrity is still much intact, however, long time simulation requirements are what makes it unattractive.

Another possible method that could be implemented is the one based on monitoring an off diagonal of the sequence component of impedance matrix, which is a resistance-based model; this method takes into consideration the motor non-idealities such as variation in supply voltage unbalance. This method is an on-line detection method for turn fault that considers the negative sequence current I_n. The method monitors the value of Z_{np} which is an impedance parameter as a fault indicator, when fault occurs in the motor the value of Z_{np} varies since the motor becomes asymmetrical. The advantage of this method is that none of the motor parameters is required; on the other hand, the challenge with this method is the difficulty of calculating ΔZ_{np}, which is a change in the diagonals of the impedance matrix on-line. Two sets of data points of I_p, V_n and I_n must be obtained as a function of slip when the supply is unbalanced, this is complex as the voltage changes very slowly in the by a small amount. It is for this reason the method was not chosen due to its complexity to implement.

Finally, a method of monitoring a negative and positive sequence current components of the machine in steady state operation was chosen as a turn fault indicator for this task, having to also know the severity factor related to the faulted fraction in the stator winding. The expectations as well as specifications were defined above in order to serve as the guideline in achieving the desired outcomes through the technique in trying to simulate and measure the severity of the short circuit being phase-phase or phase-earth fault in the stator of the induction machine. It is therefore imperative to evaluate the fault under varying quality of supply, that is non-ideal supply, which entails a sag, swell, and unbalance in supply voltage, coupling such an effect with a shorted fraction of the induction machine. The above method was chosen on the basis that it has a low cost system and it simplicity.

The approach that was implemented was based on certain steps, which are:

- Transformation of voltage and current equations from *abc* to *d-q* axis to obtain the plots for healthy coils as well as faulty coils.
- Obtaining the three phase voltages and currents from the source and calculating other motor parameters in steady state operation.
- Assuming nonidealities in the supplied voltage that feeds the DOL induction motor.

3.1. Linear Transformation in Induction Machines

The dynamic performance of an alternating current (ac) machine is somewhat complex because the three phase rotor windings move with respect to the three phase stator windings. Thus, the windings of such induction machines need to be transformed into an equivalent winding with d-q axis analysis. It can be looked on as a transformer with a moving secondary, where the coupling coefficient between the stator and the rotor position is θ_r. The machine model can be described by differential equations with the varying mutual inductances. It is important to note that a three-phase machine can be represented by an equivalent two phase machine with d^s - q^s corresponding to stator direct and quadrature axis and d^r-q^r corresponding to rotor direct and quadrature axis [36].

3.1.1 Invariance of power

When the transformation has been done, the power developed must be the same for both three and two phase models. The principle of achieving the power through the transformation is referred to as invariance of power. The analysis the magneto motive force produced in the equivalent two-phase winding must be the same as the original three-phase winding.

3.1.2. Three-phase machine.

ABC are rotating coils with reference to the d-q axes, which are locked to the reference frame. They are alternating currents i_a, i_b , i_c which create a resulting MMF which rotates in the counter clockwise direction at the same rotational velocity as the rotor and mains frequency ώ=w_r for a two-pole machine. Therefore, QR and DR are quasi-stationary coils, which must create the same MMF to maintain the same power throughout the system [36] [37].

The d and q currents in the generalized model can be calculated using the Park's transformation vector [37].

For a healthy induction machine, the three phase currents are displaced by 120° to each other as expressed in the form of the equations 1-3:

$$i_a(t) = I_{max} \sin(\omega t - \theta) \qquad (3-1)$$

$$i_b(t) = I_{max} \sin(\omega t - \theta - {}^{2\pi}/_{3}) \qquad (3-2)$$

$$i_c(t) = I_{max} \sin(\omega t - \theta + {}^{2\pi}/_{3}) \qquad (3-3)$$

Moreover, the voltage equations for a healthy machine are given by:

$$V_{as}(t) = V_{max} \cos(\omega t) \qquad (3-4)$$

$$V_{bs}(t) = V_{max} \cos\left(\omega t - {}^{2\pi}/_{3}\right) \qquad (3-5)$$

$$V_{cs}(t) = V_{max}\cos(\omega t + {}^{2\pi}/_{3}) \qquad (3-6)$$

In the generalized theory of machine, it enables the transformation of the three phase currents into an equivalent two-phase system through the park vector as explained above. Considering a machine to be rotating in a synchronous rotating frame, the ABC-DQ transform can be used to transform three phase quantities to two-phase. The three phase current are measured and represented in the synchronous rotating frame on the basis of invariant power Clarke transform as expressed in the matrix below:

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos(\theta - 120) & \cos(\theta - 240) \\ \sin\theta & \sin(\theta - 120) & \sin(\theta - 240) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (3-7)$$

The transformation matrix of the currents is the same:

$$[i_{dq0}] = \sqrt{\frac{2}{3}}[C][i_{abc}] \qquad (3-8)$$

Current i_d and i_q create the required MMF for the machine to run while i_0 is the equivalent of a neutral current. It does not flow in any winding and does not create MMF i_0 is therefore zero under balanced conditions but it is used to keep the matrix square. The entire transformation is referred to as Park’s vector transformation.

In addition, to move from the qd axes another transformation yields the αβ axis.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} cos\omega t & sin\omega t \\ -sin\omega t & cos\omega t \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad (3-9)$$

3.1.3. Voltage equations of an induction machine.

For an ideal induction motor that is symmetrical, free of faults and no idealities the rotor and stator voltage equations are dependent on the flux linkage, which are defined by:

$$V_{s,abc} = (r_s i_s)_{abc} + \frac{d\lambda_{s,abc}}{dt} \qquad (3-10)$$

$$V_{r,abc} = (r_r i_r)_{abc} + \frac{d\lambda_{r,abc}}{dt} \qquad (3-11)$$

In the case where a cage induction motor is used where slip rings are said to be short-circuited it is deduced that the terminal voltage in the rotor is zero thus:

$$0 = (\mathrm{r_r i_r})_{\mathrm{abc}} + \frac{\mathrm{d}\lambda_{\mathrm{r,abc}}}{\mathrm{dt}} \qquad (3-12)$$

3.2. Mathematical model of an induction motor with stator shorted turns

The transient model of an induction motor should cover both the normal that is healthy and faulty conditions. It is rather difficult and tedious to model an induction motor in a 3-phase rotating *abc* reference frame so the transformed equations in a d-q reference frame are summarized below. Stator winding faults can be classified into either turn-turn fault or turn to earth fault, in this project the focus is in the turn-turn fault. It is then assumed that the turn-turn fault covers percentage of μ of the motor winding. In such a case the transformer action between the healthy and fault, winding is adopted such that the healthy winding represents the primary side and the shorted winding along with the rotor bars is regarded as a secondary side.

In order to represent the change in turns ratio between the windings, a change in self and mutual inductances due to inter-turn fault is considered

Consequently, the stator flux linkages equations in the d-q reference frame become:

$$\frac{d\lambda_{qs}}{dt} = (V_{qs} - i_{qs}\ r_s) \tag{3-13}$$

$$\frac{d\lambda_{ds}}{dt} = (V_{ds} - i_{ds}\ r_s) \tag{3-14}$$

Moreover, it is necessary to model the motor inclusive of the fault current:

$$\frac{\mathrm{d}\lambda_{\mathrm{qr}}}{\mathrm{dt}} = -\mathrm{i}_{\mathrm{qs}}\mathrm{r}_{\mathrm{r}} + \omega_{\mathrm{r}}\ \lambda_{\mathrm{ds}} \tag{3-15}$$

$$\frac{\mathrm{d}\lambda_{\mathrm{dr}}}{\mathrm{dt}} = -\mathrm{i}_{\mathrm{ds}}\mathrm{r}_{\mathrm{r}} + \omega_{\mathrm{r}}\lambda_{\mathrm{qs}} \tag{3-16}$$

$$\frac{\mathrm{d}\lambda_{\mathrm{dq}}}{\mathrm{dt}} = \mu_{\mathrm{dq}}^{\mathrm{s}} - \frac{\mathrm{d}\lambda_{\mathrm{dr}}}{\mathrm{dt}}\mathrm{r}_{\mathrm{s}}\left(\mathrm{i}_{\mathrm{dq}}^{\mathrm{s}} - \mathrm{T}_{\mathrm{dq}}\mu_{\mathrm{dq}}\mathrm{i}_{\mathrm{f}}\right) \tag{3-17}$$

$$\frac{\mathrm{d}\lambda_{\mathrm{qsf}}}{\mathrm{dt}} = \frac{-\mu}{(1-\mu)}\frac{\mathrm{d}\lambda_{\mathrm{qs}}}{\mathrm{dt}} + \mu(\mathrm{r}_{\mathrm{s}} + \mathrm{r}_{\mathrm{f}})\mathrm{i}_{\mathrm{qsf}} \tag{3-18}$$

$$0 = R_f\mu_{dq}i_f + \frac{d\lambda_{fq}}{dt} \tag{3-19}$$

So that the total stator current in the q-axis is given by:

$$\mathrm{i}_{\mathrm{qst}} = \frac{\mathrm{i}_{\mathrm{qs}}+\mu}{(1-\mu)\mathrm{i}_{\mathrm{qsf}}} \tag{3-20}$$

Considering a short circuit current, flowing in the fault loop through a resistor:

$$\mathrm{r}_{\mathrm{f}} = \mu_{\mathrm{f}}\mathrm{r}_{\mathrm{s}} \tag{3-21}$$

μ_f Is the severity factor, which indicates the fraction of a short-circuited turns in the stator winding of the machine.

$$\mu_f = \frac{n_f}{n_s} \qquad (3-22)$$

$$0 = r_f i_f + \frac{d\lambda_f}{dt} \qquad (3-23)$$

Where r_f and i_f are the short circuit resistance and the short circuit current respectively and the factor λ_f represents the short circuit flux linkage on the faulted branch.

3.2.1. Negative sequence current

Consider the transformation matrix of d-q currents to the $\propto - \beta$ axis to obtain the forward and reverse rotating stator currents for short circuit fault diagnostics.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} cos\omega t & sin\omega t \\ -sin\omega t & cos\omega t \end{bmatrix} \begin{bmatrix} i_\propto \\ i_\beta \end{bmatrix} \qquad (3-24)$$

Converting further to α-β axis using matrix to calculate the forward and reverse components of current, which is fixed with respect to the stator in the q-axis.

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{3} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (3-25)$$

$$i_\propto = i_a - \frac{1}{2} i_b - \frac{1}{2} i_c \qquad (3-26)$$

$$i_\beta = -\frac{\sqrt{3}}{2} i_b - \frac{\sqrt{3}}{2} i_c \qquad (3-27)$$

$$i_n = \frac{1}{2}[(i_\propto - i_\beta)cos\omega t - (i_\alpha - i_\beta)sin\omega t] \qquad (3-28)$$

$$i_p = \frac{1}{2}[(i_\propto + i_\beta)cos\omega t + (i_\alpha - i_\beta)sin\omega t] \qquad (3-29)$$

Under healthy condition $i_\propto = 0$

Under healthy conditions with all machine parameters being symmetric and ideal quality of supply the alpha current is zero, a sudden incipient of short circuit in the winding the alpha current increases which gives rise to the negative sequence current used as a fault indicator. For healthy windings, the negative sequence current is zero, the positive sequence current is 100%, and these components are inversely proportional to each other.

Finally, the torque developed can be expressed as a function of stator current and flux linkage as:

$$T_e = \frac{3P}{4}(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \qquad (3-30)$$

Hence, giving the rotational speed of:

$$\frac{d\omega_r}{dt} = \frac{P}{2J}(T_e - T_L) \qquad (3-31)$$

T_{em} – Electromechanical torque and T_L – Load torque

3.3. Harmonic Distortion supplied to the stator of a healthy induction motor

Power systems are designed such that their operational frequency should be 50Hz or 60Hz, However certain loads produce currents and voltages that are an integer multiple of the fundamental frequency of 50Hz or 60Hz. These integer multiple of fundamental frequency form an electrical pollution known as harmonics. Nonlinear loads or the connected devices that draw nonsinusodial currents from a power system produce harmonics. Nonlinear load current wave shape vary with the applied voltage wave shape, that is any distortion in the voltage wave shape with influence the current wave shape. The current distortion of nonlinear load decreases with an increase in the applied voltage distortion as a compensating effect [38].

Harmonic sequence components also adversely affect induction motors. Positive sequence components (i.e., 7th, 13th, 19th…) will assist torque production, whereas the negative sequence components (5th, 11th, 17th…) will act against the direction of rotation resulting in torque pulsations. Zero sequence components (i.e., triplen harmonics) are stationary and do not rotate, therefore, any harmonic energy associated with them is dissipated as heat. The magnitude of torque pulsations generated due to these harmonic sequence components can be significant and cause shaft torsional vibration problems.

3.3.1. Fourier Transform of harmonics

Any periodic waveform can be decomposed into a components being the DC, Harmonic and fundamental frequency components. For a given function with period of T it can be expressed as a Fourier series comprising of fundamental frequency and harmonic components

$$u(t+T) = u(t) \qquad (3-32)$$

Then the series can be expressed as the into a series of sine and cosine components representing the even and odd harmonic components as a function of a fundamental frequency

$$u(t) = \bar{u}_0 + u_{11}\cos(\omega t) + u_{12}\cos(2\omega t) + u_{13}\cos(3\omega t) + +u_{1n}\cos(n\omega t) + \\ \dots u_{21}\sin(\omega t) + u_{22}\sin(2\omega t) + u_{23}\sin(3\omega t) + +u_{2m}(m\omega t) \qquad (3-33)$$

Where:

Fundamental frequency: $\omega = 2\pi f$

DC Voltage component: $\bar{u}_0$

Harmonic component: u_{1n}, u_{2m}

The presence of unwanted harmonics will give rise to a total harmonic distortion (THD) in the signal. The THD is the summation of all the voltage harmonic components present in the signal compared to the fundamental voltage component [39].

$$THD_v = \frac{\sqrt{V_2^2+V_3^2+V_4^2+\cdots+V_n^2}}{V_1} \times 100\% \qquad (3-34)$$

The higher the percentage of THD the more distortion that is present on the signal.

3.4. Machine Data.

3.4.1. Per Phase Equivalent circuit.

In order to carry out the complete computer simulation of the cage induction machine, it becomes necessary to acquire the machine data through experimental work. Tests had to be conducted which are running light test (no load test) as well as the locked rotor test as well as the measurement of the DC resistances of the stator windings the aim is to get the better understanding of the induction machines that have stator winding faults. To achieve this it is important to recognize that these motors are generally modelled as per phase induction circuits, which makes it easy to determine the parameters. The underlying principle in determining the parameters is to refer all the calculations of the rotor to the primary side winding which is the stator, for the machines that operate at a region that is two times bigger than the rated power, normally the magnetizing component is shifted to the input.

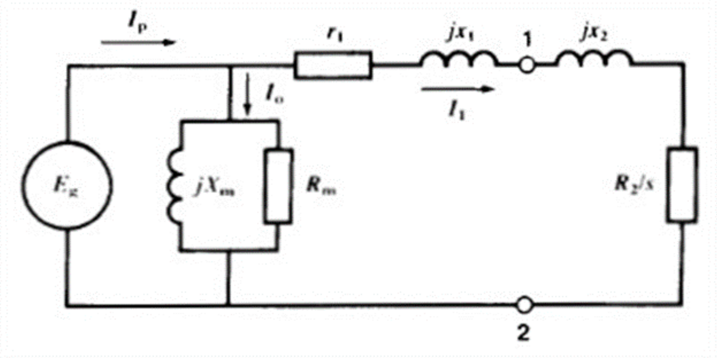

Figure 3-1 Induction Motor per-phase equivalent circuit referred to the stator

Where:

R_1 and X_1 Are stator impedances

R_2 and X_2 Are the rotor impedances that are referred to the stator

3.4.2. Locked Rotor Test.

The locked rotor test provided the information that is necessary to determine:

- The leakage reactance
- The winding resistances

In this test, the rotor will be locked by external means to prevent rotation. In this test, the slip is unity and the mechanical load resistance, which is Rm, is zero, thereby resulting in a very low input impedance of the equivalent circuit. The machine will be run at rated voltage which is a line voltage with the rotor locked it is expected that the phase current $\mathrm{I_{ph}}$ will be much higher compared to the rated value of the line current. As the rotor is locked it suggests that the slip of the machine will equal one (S=1) which implies that $\mathrm{R_2}'/_{S}$ will be equal to $\mathrm{R_2}$. As the phase current being higher it is also greater than $\mathrm{I_0}$ it is advisable to ignore the magnetizing component at this point, which will subsequently, simplify and reduce the equivalent circuit.

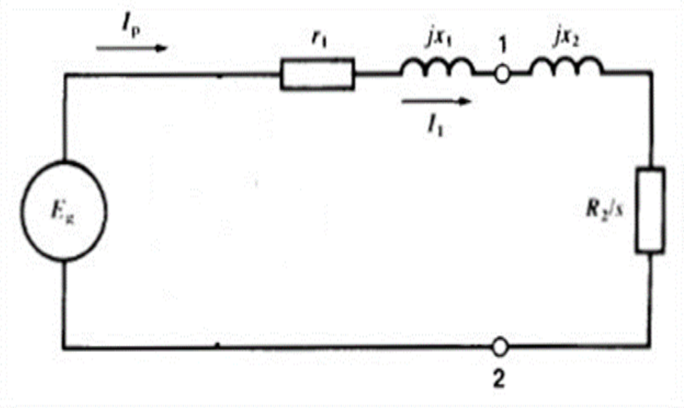

Figure 3-2 Reduced Equivalent Circuit of Locked Rotor Test [17]

From the values of the current, power as well as the line voltage of the induction motor other parameters can then be extracted which are the impedances of the locked rotor test and are expressed as:

$$X_1 + X_2' = \frac{Q_{ph}}{{I_{ph}}^2} \qquad (3-35)$$

$$R_1 + R_2' = \frac{P_{ph}}{{I_{ph}}^2} \qquad (3-36)$$

3.4.3. Running light Test.

The objective of the running light test is to determine:

- Stator ohmic losses, Pr
- Stator core losses due to hysteresis and \Eddy current, Pc
- Magnetizing inductance, Xm
- Rotational losses due to friction and windage, Prot

The test is carried out at rated frequency and with balanced three phase voltages applied to the stator terminals. At no load the machine slip is said to be zero and the rotor current are very small thereby resulting to a negligible no load rotor loss. To obtain the stator resistance per phase of the machine R_1 it is necessary to measure first the stator resistance between two terminals R_{LL} this would mean that

$$R_1 = R_{LL}/2 \qquad (3-37)$$

Assuming a star connected stator. Using the line-to-line voltage this suggests that the value of ${R_2}'/_S$ is high thus the current I_1 is small and can be ignored compared to the magnetizing current I_m which is across the magnetizing component. The values of the magnetizing reactance X_m as well as the core resistance R_C are determined by measuring the line voltage and the current at no load conditions.

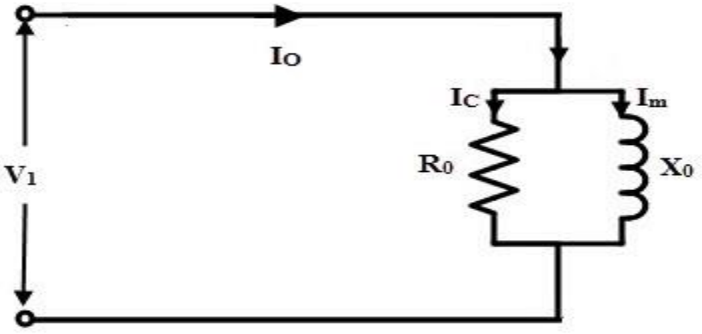

Figure 3-3 Running light test equivalent circuit [40]

Core resistance as well as the magnetizing reactance are calculated based on the following:

$$X_o = \frac{{V_{PH}}^2}{Q_{PH}} \qquad (3-38)$$

$$R_o = \frac{{V_{PH}}^2}{P_{PH}} \qquad (3-39)$$

Both the running light and the locked rotor test were conducted on the test machine, induction motor and the results were obtained as a function of per phase values, the table below shows the results of the tests conducted.

Table 3-1 Running light test and locked rotor test values

Running light test			
Description	**Symbol**	**Value**	**Units**
Phase Current	I_{PH}	1.89	A
Active Power	P_{PH}	50	W
Stator Resistance	R_{PH-PH}	5	Ω
Phase Voltage	V_{PH}	110	V
Locked rotor test			
Phase Voltage	V_{PH}	36	V
Phase Current	I_{PH}	5.1	A
Active Power	P_{PH}	86.67	W

From the values in the table 1 above it is possible to calculate the stator resistance as well as the stator reactance based on the following equations.

$$R_1 = \frac{R_{PH-PH}}{2} \qquad (3-40)$$

$$X_1 = \frac{X_1 + X_2}{2} \qquad (3-41)$$

Table 3-2 Equivalent circuit parameters

Description	**Symbol**	**Value**	**Units**
Stator resistance	R_1	2.85	Ω
Stator reactance	X_1	1.653	Ω
Stator inductance	L_{1s}	5.262	mH
Rotor resistance	R_2	0.482	Ω
Rotor reactance	X_2	1.653	Ω
Rotor Inductance	L_{1r}	5.262	mH
Core resistance	R_C	222.78	Ω
Magnetizing reactance	X_m	56.206	Ω
Magnetizing inductance	L_m	178.91	mH
Number of poles	p	4	
Rated stator voltage	V_{RATED}	220	V
Rated rotor speed	N_{RATED}	1135	rpm
Supply frequency	f	50	Hz
Inertia constant	J	0.012	
Total Number of stator coils per phase	N_s	16	

4. Simulink model of an induction motor

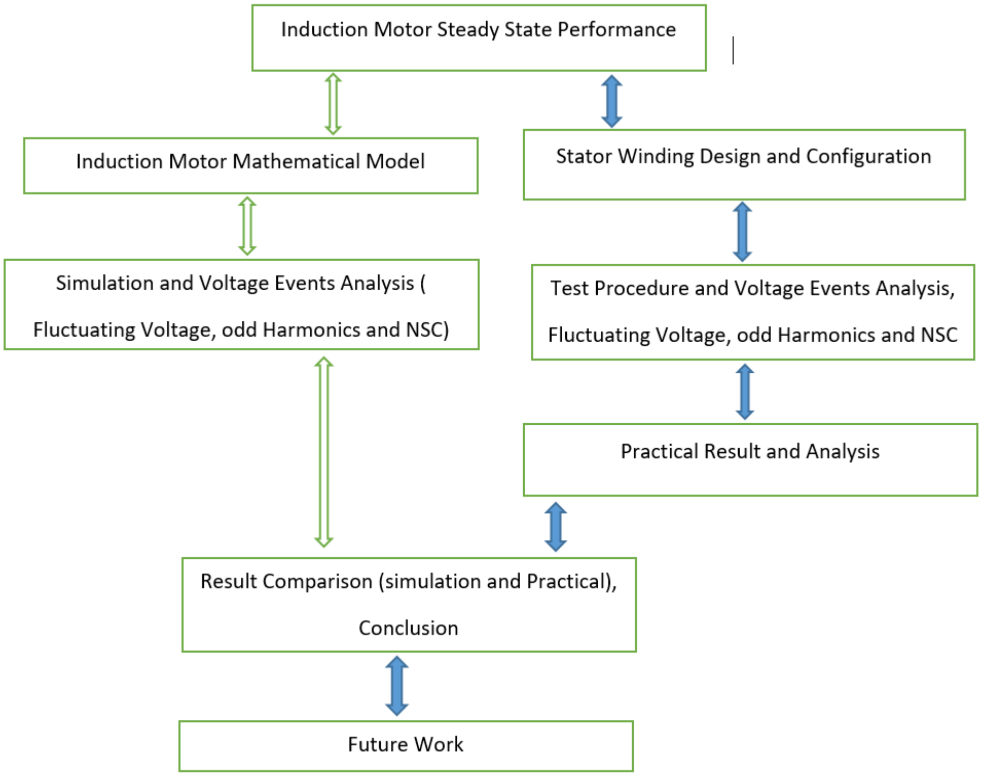

Figure 4-1 Simulink process flow chart

4.1 Healthy machine-healthy quality of supply (QoS)

For healthy coils with the winding intact motor voltage declared as 380 V pick voltage balanced supplied to the induction motor terminals. The winding of the motor is a star connected configuration, these results reflect a motor running as free wheel that is, no load conditions, for the purpose of this simulation the focus is on steady state condition using a dynamic model on Simulink blocks. Transient behaviour of the machine is ignored as the parameters are time changing.

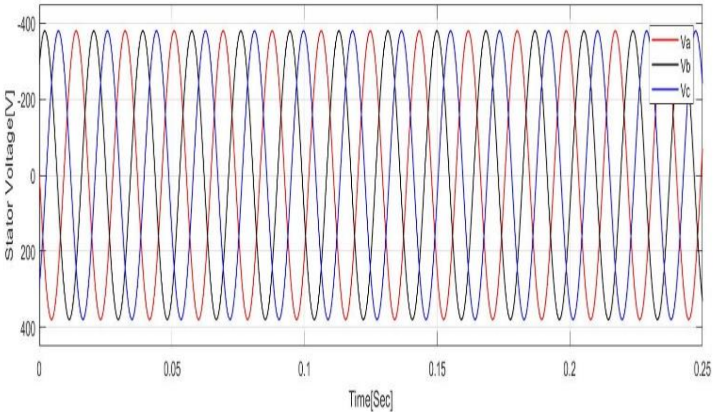

Figure 4-2 Stator voltage for healthy machine under balanced supply voltage

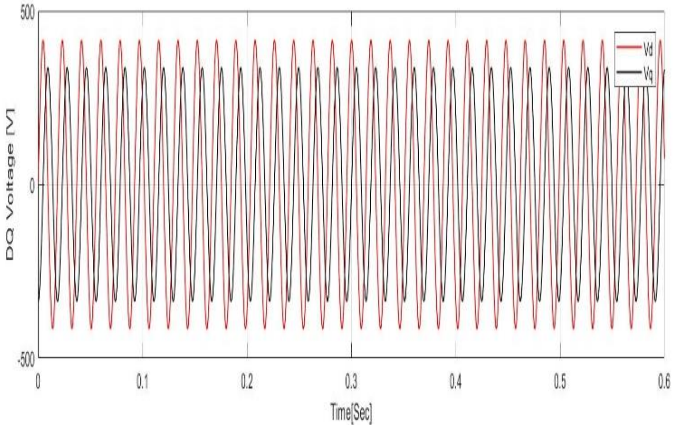

Figure 4-3 Two Phase D-Q voltage for an induction motor with balance supply voltage

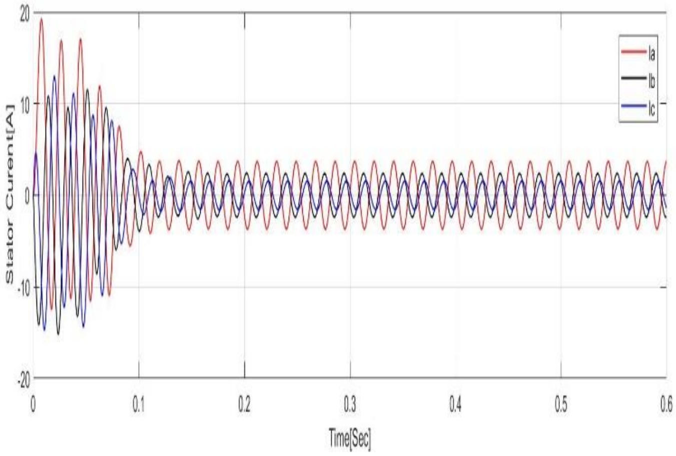

Figure 4-4 Three-Phase stator currents of an induction motor - healthy coils and balanced supply voltage

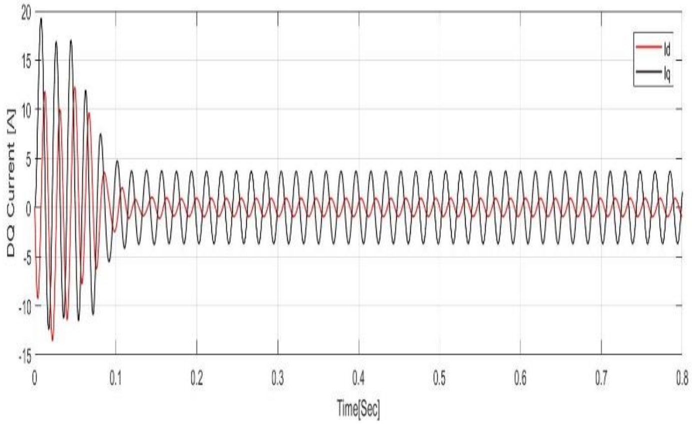

Figure 4-5 Two phase D-Q Current of an induction motor

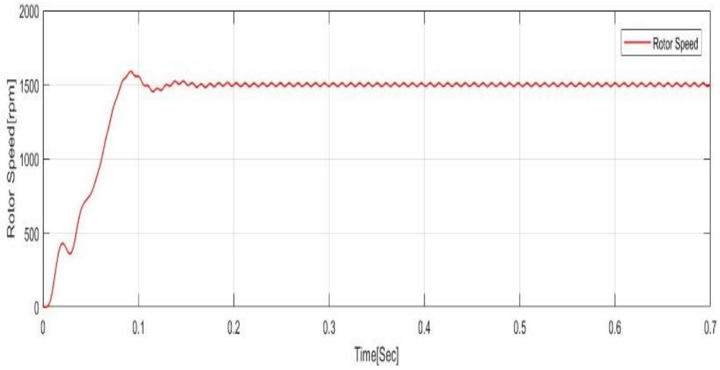

Figure 4-6 Rotor Speed of an induction motor

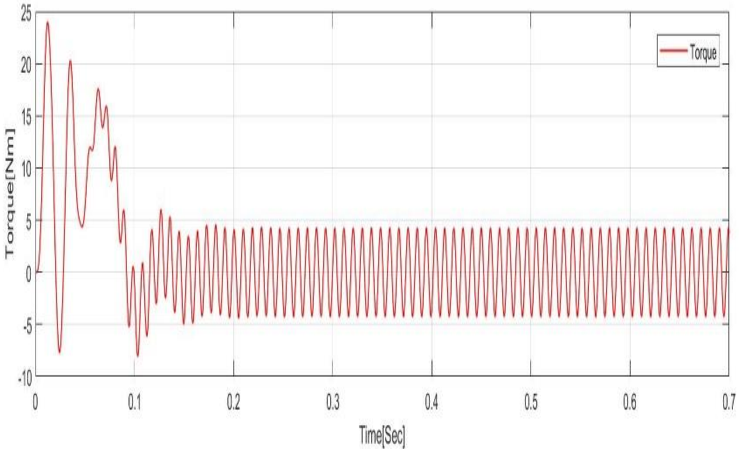

Figure 4-7 Motor torque of an induction motor with healthy coils

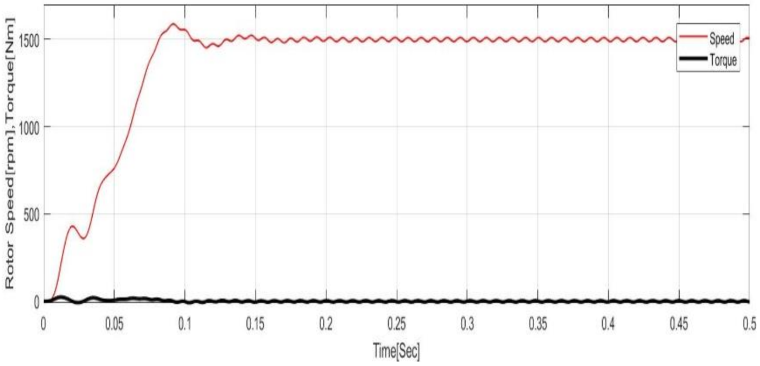

Figure 4-8 Speed and torque curves for an induction motor with healthy coils

The starting behaviour and performance of an induction motor depends on the nature of the supply fed to the motor by the utility or network, which the motor is connected to.by design from original machine manufacturer a set defined running parameters are given that will enable the motor to perform to design specifications. In the condition where an induction motor is running at no load, applications such as fans circulating thin air. The speed is at rated and the torque at high speeds is zero as the load is negligible as in figure 4-6 to figure 4-8. In cases where the motor is driven by a variable speed drive, the status and performance of the drive will determine the performance of the motor [41]. With desired (ideal) supply conditions, the motor draws three-phase current which set up a magnetic field in the stator, this magnetic field is symmetric and the motor ramps up to speed and settles at rated speed determined by frequency of supply and pairs of poles in the stator.

In the on load condition, with quality of supply within compatibility limits, the three-phase current set up a rotating magnetic field and the rotor will ramp up to speed in the direction of the magnetic field. Depending on the torque required to drive the load, at low speed the motor will be delivering high torque and a gradual increase in speed reduces the torque. In induction motors, torque and speed are inversely proportional. The torque is maximum at zero rpm and minimum at rated speed. Sinusoidal waveform of voltage and current that are 120 degrees out of phase are maintained.

4.2. Under voltage (Voltage Dip):

Voltage Dip is the shortly disturbance that occurs across the induction motor terminals that drop the declared voltage level to a lower voltage for a short period. This sudden voltage change has an impact on the motor operational parameters that are dependent on input voltage. The reduced stator voltage across the motor terminals result in increased current drawn by the motor which gives rise to increased temperature rise and increase in both stator and rotor losses in induction motors.

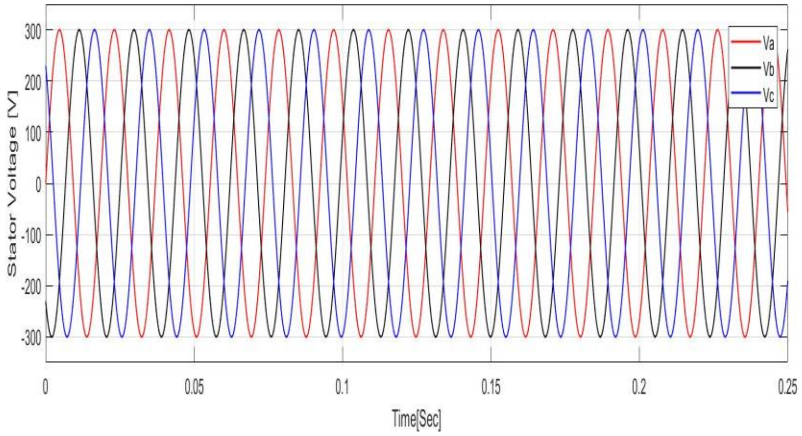

Figure 4-9 Stator voltage when a sudden dip occurs upstream which affects the motor voltage

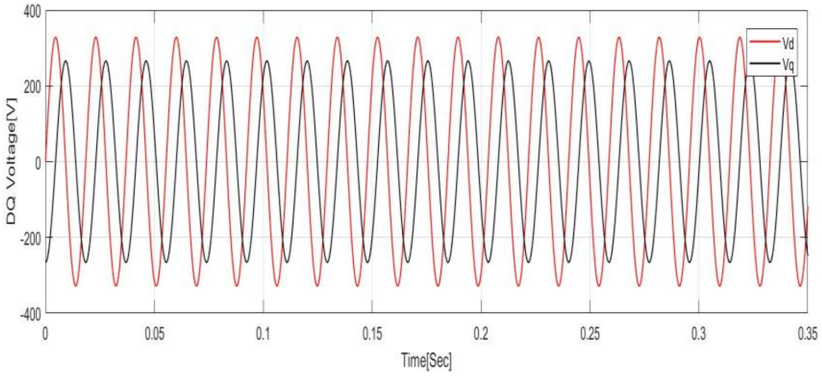

Figure 4-10 Two phase D-Q voltage with a sudden occurrence of voltage dip

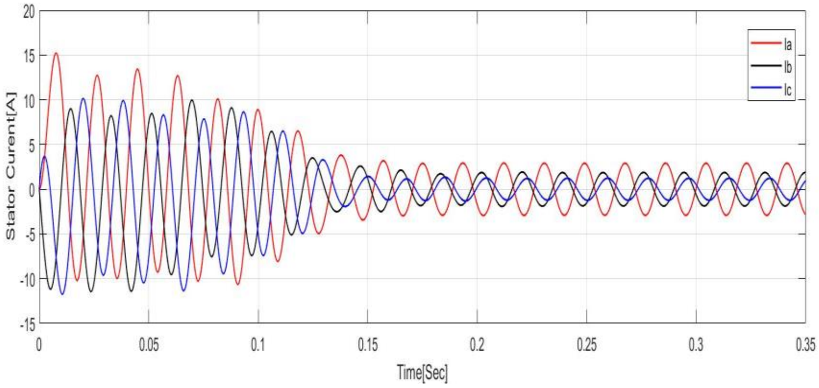

Figure 4-11 Stator current behavior for a no load induction motor which reacts to compensate the effect of voltage dip

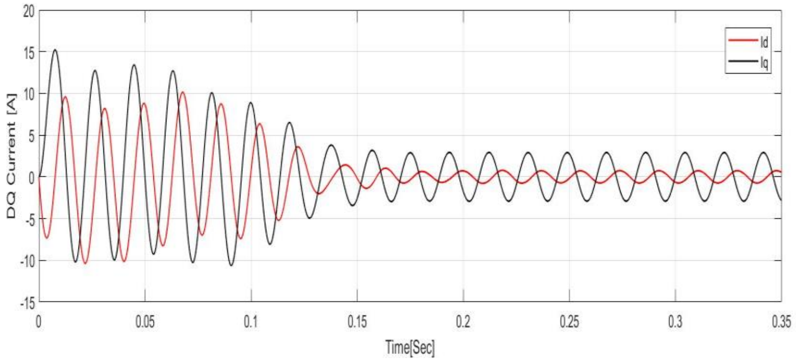

Figure 4-12 Two Phase D_Q current under voltage dip condition

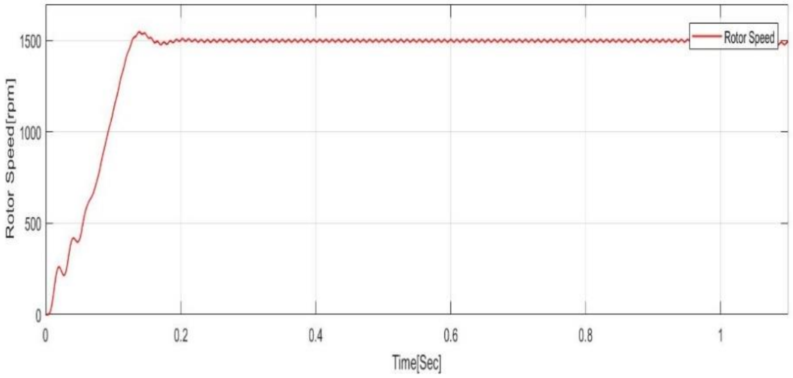

Figure 4-13 Behavior of the rotor speed under-voltage dip condition

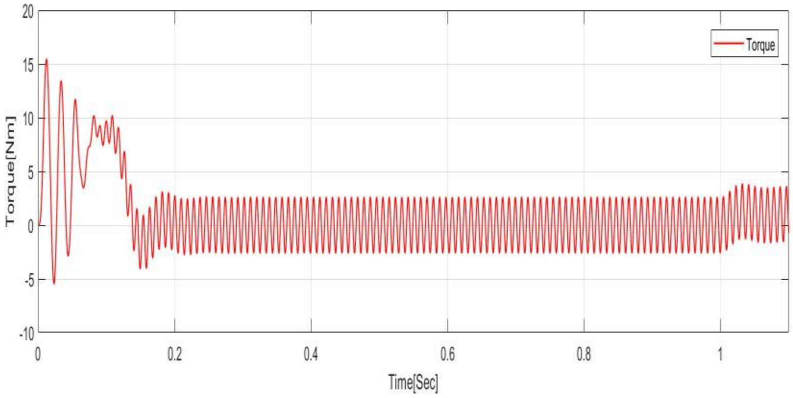

Figure 4-14 Motor torque behavior when the voltage dips

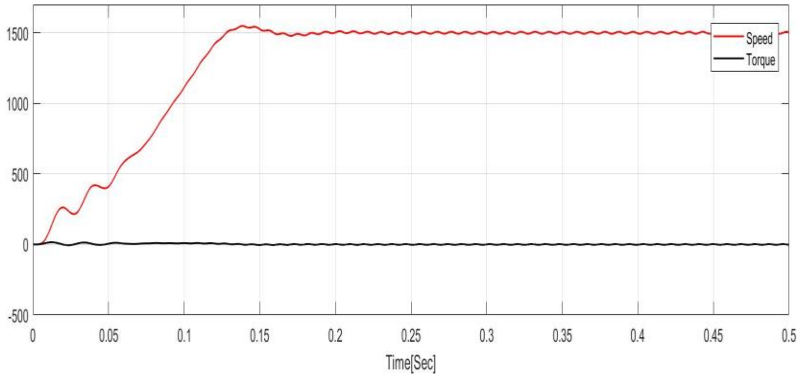

Figure 4-15 Motor torque and rotor speed behavior of an induction motor with voltage dip condition

If an induction motor is supplied with a voltage less than rated value of voltage as per nameplate, at rated frequency, the magnitude of magnetizing air gap flux decreases, as flux=V/f. Therefore, the magnitude of net air gap vector will decrease. Torque is directly proportional to the air gap, so a reduction in the air gap density will reduce the motor torque. So, the effective torque decreases and so it runs with less speeds [41]. A reduction in rotor speed in reverse slip increases & hence motor should accelerate.

With relation to figure 4-11 to figure 4-15 it is apparent that the relationship between current and voltage for an induction motor are ohmic, that is a change in voltage supplied to the motor affects the phase current depending on the severity of change in each parameter. Under voltage dip condition, the current across three-phase increases to reduce the effect of changing voltage. The total power delivered to the drive shaft will be affected, as the power is the function of supplied voltage in turn changing the speed and torque, this hold at no behaviour. The motor torque is zero over the whole speed range, as the shaft is not driving load so the torque requirement is zero over the speed range.

However, as voltage supply to stator is of less magnitude in relation to the nameplate rated voltage, the length of rotating stator flux vector also reduces, but the synchronous speed is same, which is proportional to the frequency. So the rotor will try to accelerate (due to high slip), but due to lesser magnitudes of both the fluxes, it cannot and so the motor runs at speeds less than the case when rated supply is given to it [41]. In the case where a motor is coupled to a mechanical load, it must draw fixed amount of power from the line; any reduction in voltage will demand the motor to draw more current in order to maintain the desired output power. The more the supplied voltage lowers, is the more current is drawn and when this current exceeds the name plate rated current the motor begins to build up heat which damages the stator winding and eventually the machine fails on insulation breakdown.

4.3 Over-voltage (Voltage Swell)

Overvoltage condition refers to the shortly rise in voltage magnitude observed from the motor terminals from upstream. This current rise exceeds the motor nameplate rating. This overvoltage may be a result of lightning striking the network at a given time and appear as a transient or capacitor discharging back to the network, which gives rise to the voltage spikes, which can have negative impact on the winding of an induction motor and other operational parameters.

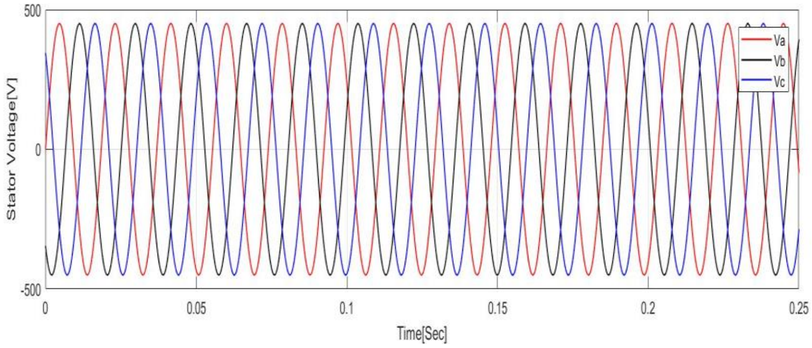

Figure 4-16 Shortly stator voltage with voltage swell

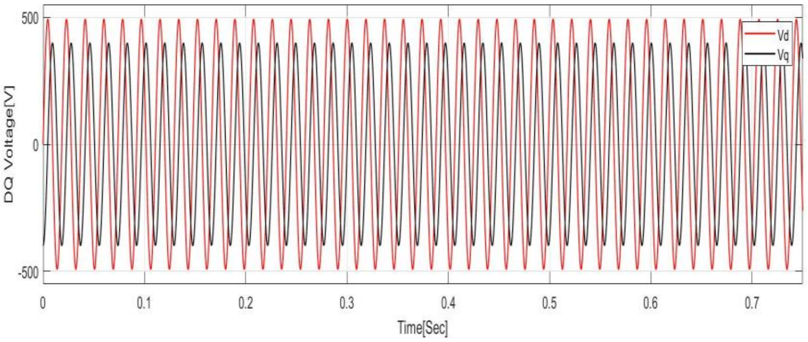

Figure 4-17 Two Phase D-Q stator voltage with voltage swell

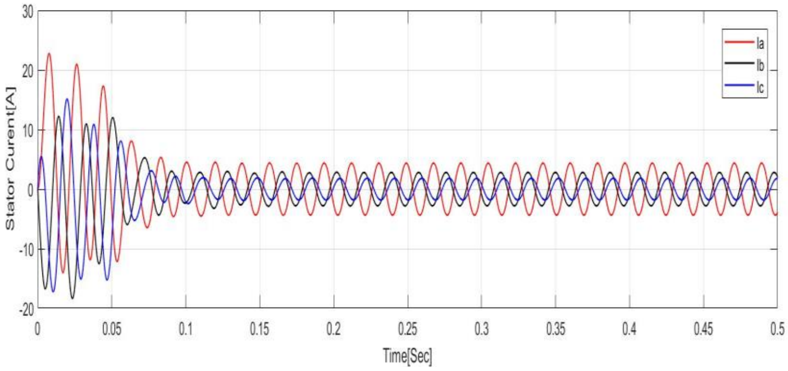

Figure 4-18 Three-phase stator current behavior compensating the effect of swelling voltage

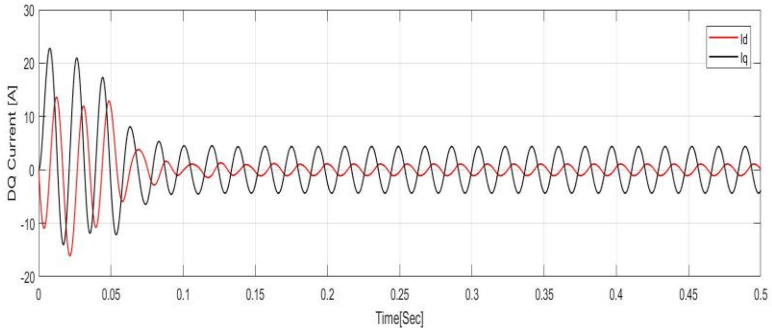

Figure 4-19 Two phase D-Q stator current translated from three-phase current

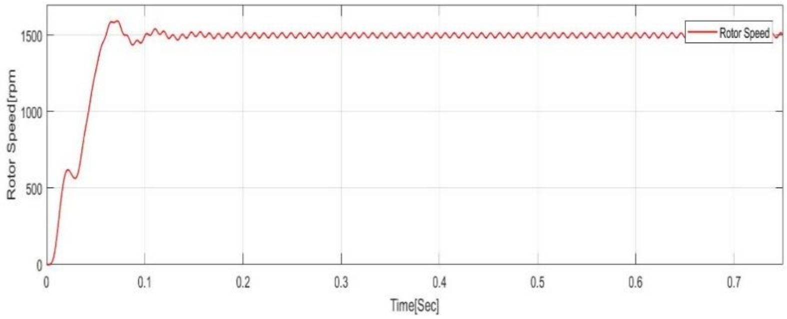

Figure 4-20 Induction motor rotor speed because of pulsating torque and voltage

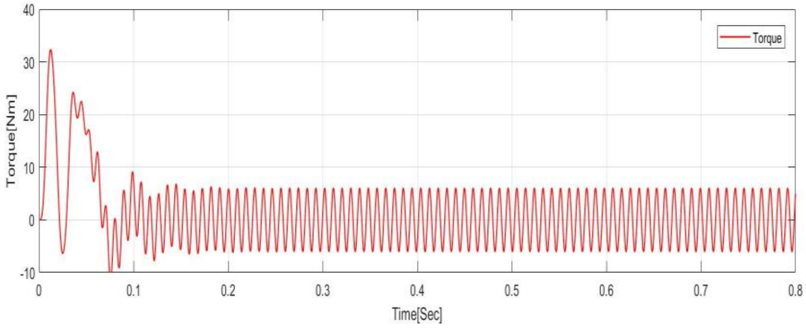

Figure 4-21 Induction motor torque responding to a change in voltage magnitude

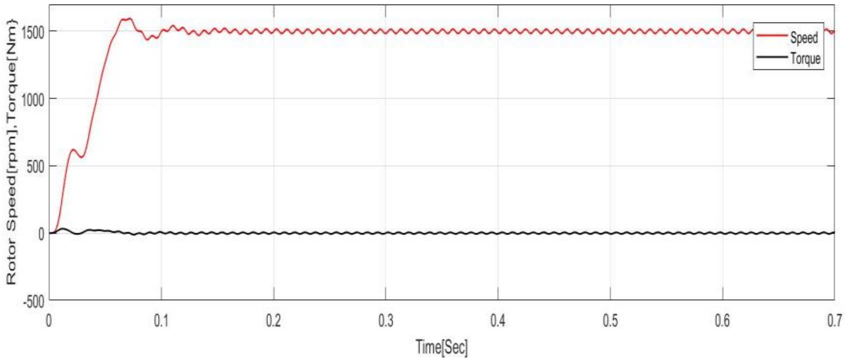

Figure 4-22 Torque and rotor Speed characteristics of an induction motor under swell conditions

Over voltage across the motor terminals pushes the magnetic components of the motor to saturation region [42]. This kind of behaviour across an induction motor forces the machine to draw more current in an effort to magnetize the iron beyond the point where magnetizing is practical. Flux density of an induction motor is directly proportional to supply voltage, if the motor run above its rated voltage; it is going to magnetically saturate the steel in the motor core. This increases the current drawn causing the motor to run hotter and shorten the motor lifespan. The motor starting current, sometimes referred to as an inrush current figure 3-23 is directly proportional to the supply voltage; an increase in the voltage will increase the magnitude of the inrush current drawn by the motor at starting for a short while before it settles at a finite value. This increase in inrush current may lead to unpleasant motor trips at starting and may require multiple restarting [42].

4.4 Voltage Unbalance- Single Phasing

When there is a sudden fault in the three-phase network from the utility side or the secondary side of the transformer that feeds the induction motor, the fault occurs such that one phase goes to zero volts while the other two maintain their magnitude this is a phenomenon of single phasing which introduces a degree in voltage unbalance [43].

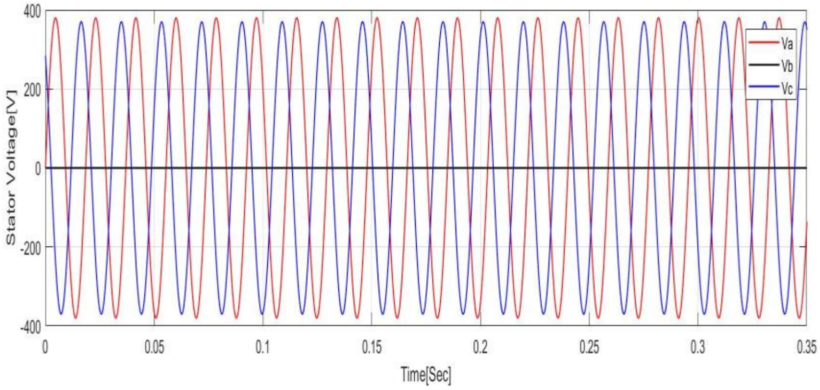

Figure 4-23 Three Phase stator voltage under single-phasing

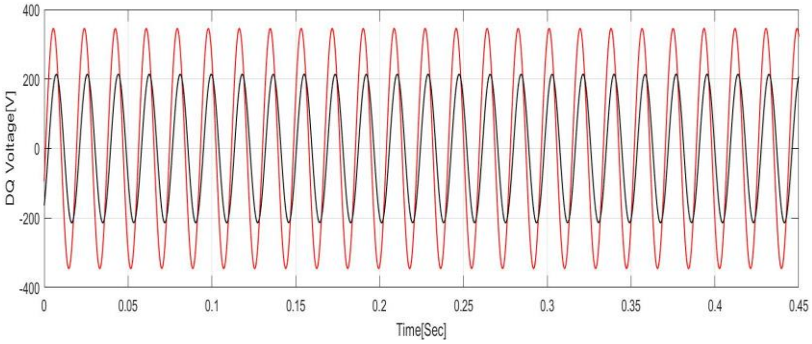

Figure 4-24 Two phase D-Q voltage behavior when single phasing condition occurs

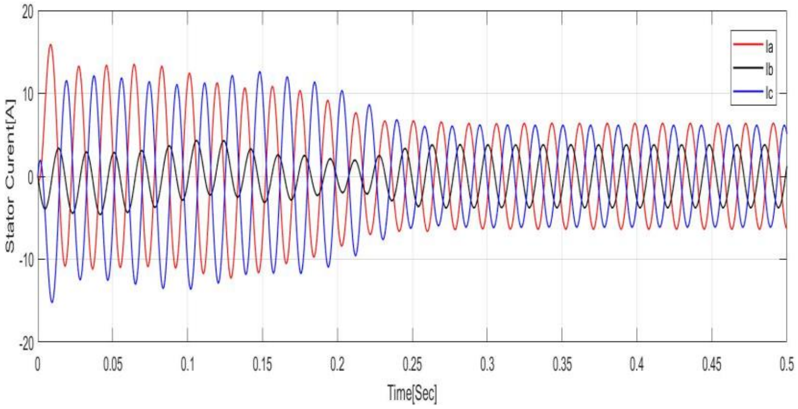

Figure 4-25 Three phase stator current with unbalance

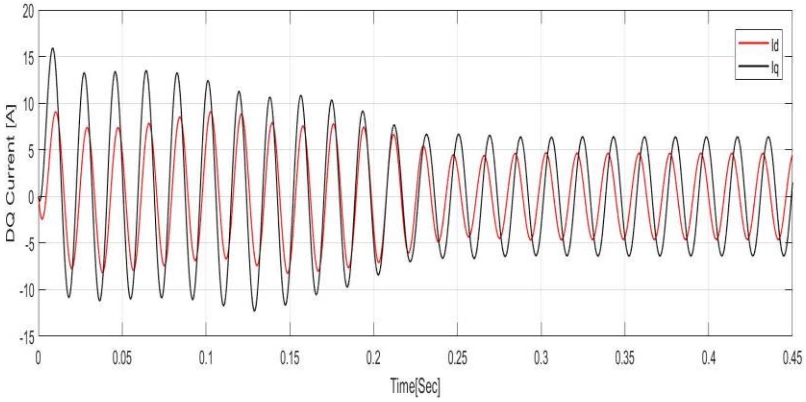

Figure 4-26 Two Phase D-Q Current response to single phasing on the motor voltage

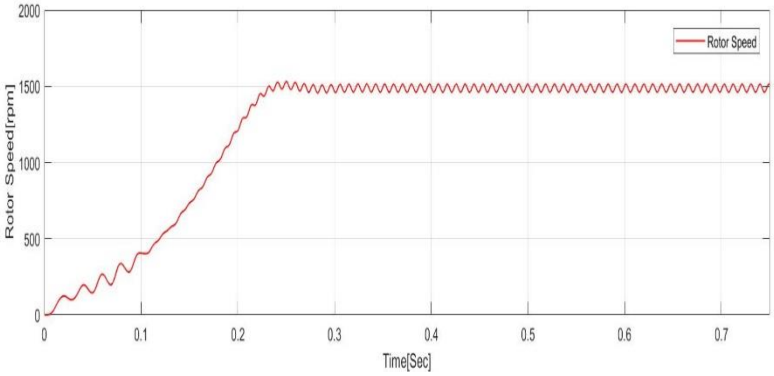

Figure 4-27 Pulsating Rotor Speed response to single phasing

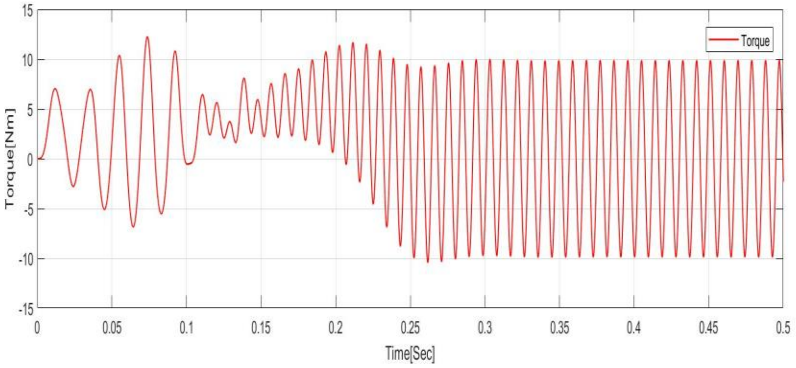

Figure 4-28 Induction motor Torque single phasing

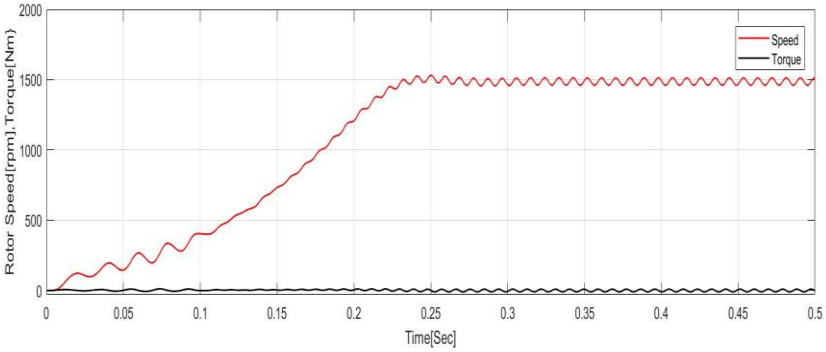

Figure 4-29 Pulsating rotor speed and motor torque of an induction motor

The motor cannot start under the single phasing condition as there is no phase shift between the voltages as one phase is zero in magnitude, in the condition where the single phasing occurs while the motor is running, it will continue to run and drive the load until the motor burns out [43]. When the single phasing occurs the motor slip increases but the motor does not stall unless if the load is close to 80% of full load. The phase current figure 3-29 increases and circulating current may damage the motor winding by increasing the heat on the motor winding. Current on the remaining two phases increase to 170% of the rated current which may damage the cables due to excessive over heating creating a higher potential for stator winding short circuit [40].

4.5 Effects of odd Harmonics on Induction Motors

The motor stator voltage supplied to an induction motor set up magnetic field in the stator core, which creates losses in the magnetic field frame of the motor. If the supplied voltage to the stator component of an induction motor contains higher frequencies, it produces additional losses in the core of the motor, which increases operating temperature of the core and stator winding [44]. These nonsinusodial voltages supplied to the stator create harmonic current that circulate in the motor winding. Eddy and hysteresis losses in an induction motor are part of the iron losses that are produced in the core when rotating magnetic fields are created. Eddy losses vary with a square of the applied frequency and hysteresis are proportional to the frequency.

Through application of Fourier analysis, the effect of even harmonics is negligible thus in this analysis the even harmonics would be ignored. As most of the waveforms in a power system have half-wave symmetry, thus even harmonics are cancelled. The classification of harmonics can be extended to either negative or positive harmonics. Negative sequence harmonics circulate between the three phases of the motor creating additional problems with motors as the opposite phasor rotation weakens the rotating magnetic field that is required by the motor, especially induction motors, causing them to produce less mechanical torque, the lesser the mechanical torque produced means the motor cannot drive the load as desired.

4.5.1 Third (3^{rd}) harmonic distortion

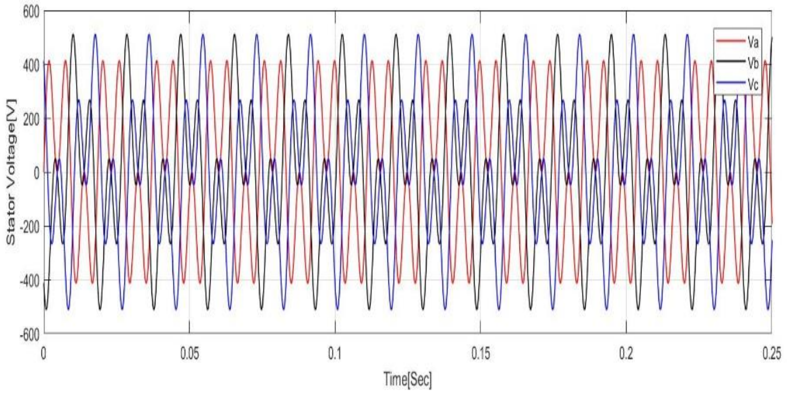

Figure 4-30 Stator voltage with harmonic context casing a phase shift in voltage magnitude

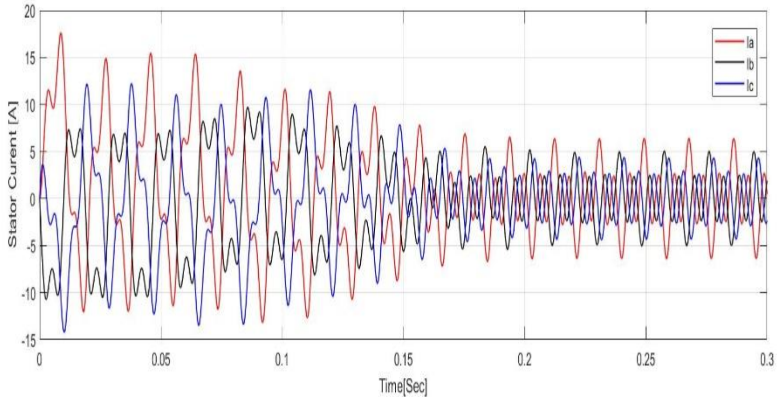

Figure 4-31 Stator current with current phase of third order harmonic frequency

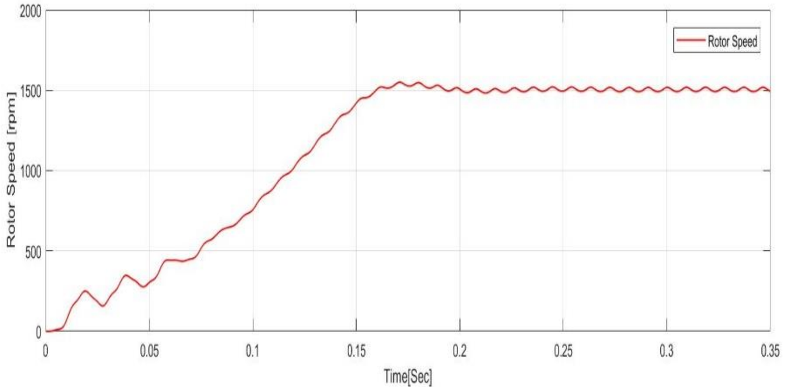

Figure 4-32 Pulsating rotor speed of an induction motor

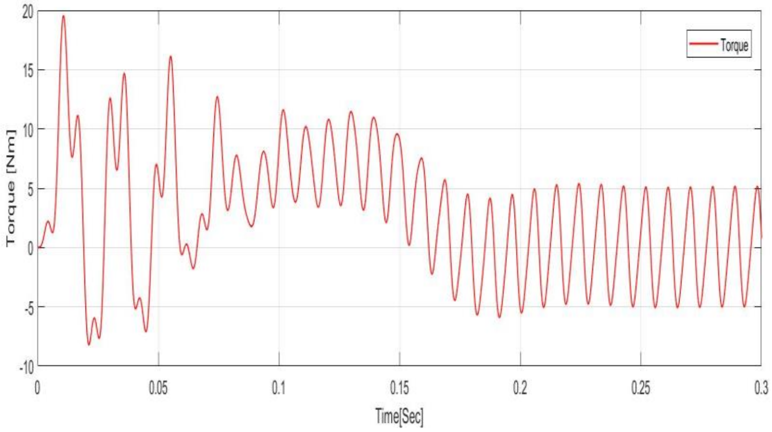

Figure 4-33 Clockwise rotating motor torque that adds up to the net torque of an induction motor

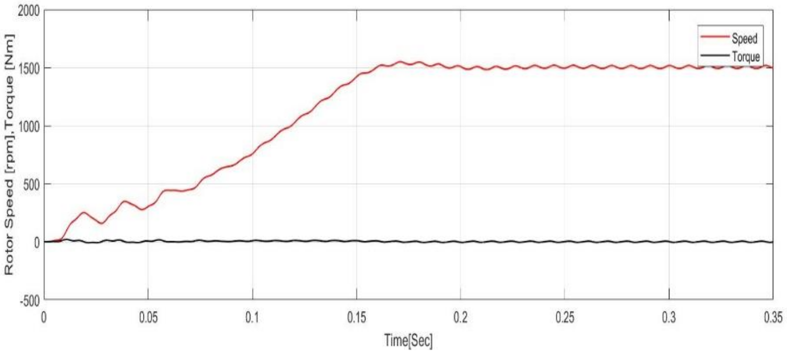

Figure 4-34 Motor torque plotted against rotor speed for an induction motor at start up

4.5.2 Fifth (5^{th}) harmonic distortion

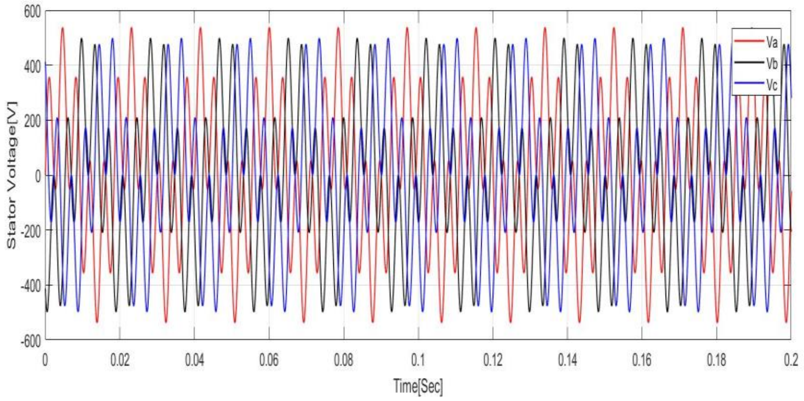

Figure 4-35 Stator voltage of an induction motor with fifth order harmonic

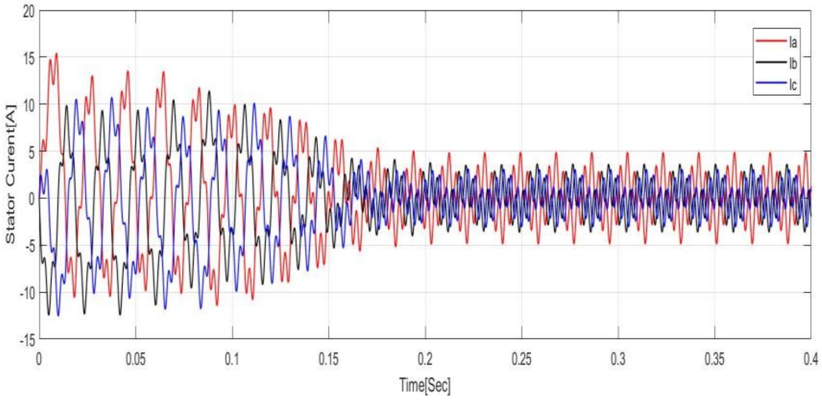

Figure 4-36 Transient behavior of stator current with fifth order frequency harmonic

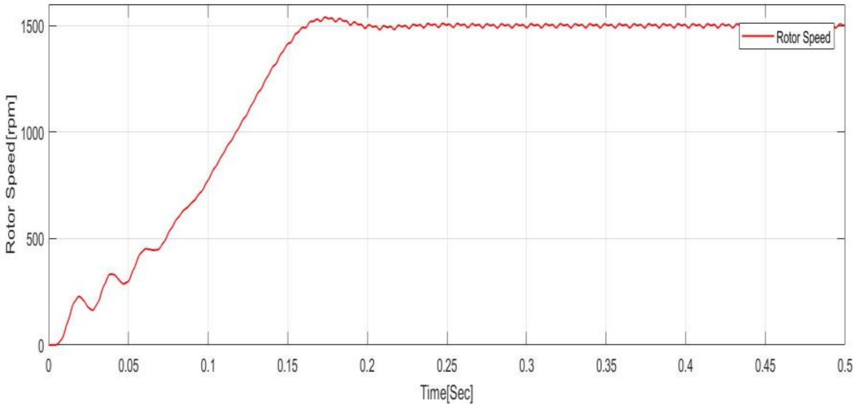

Figure 4-37 Pulsating rotor speed as the motor ramps up the pulsating torque affects the speed

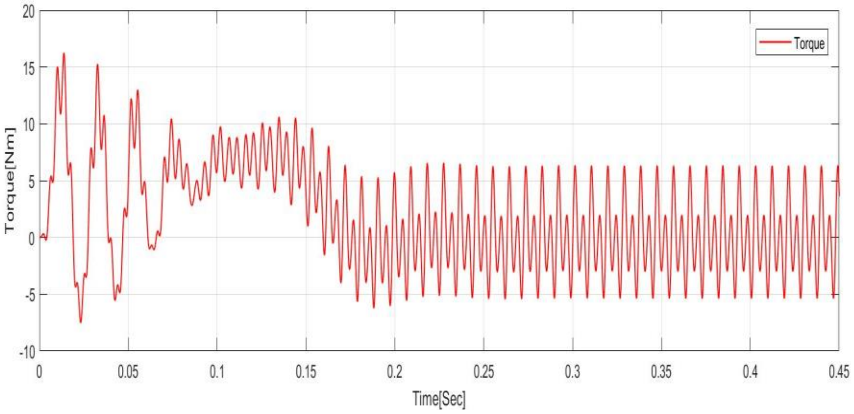

Figure 4-38 Counterclockwise motor torque produced by the motor

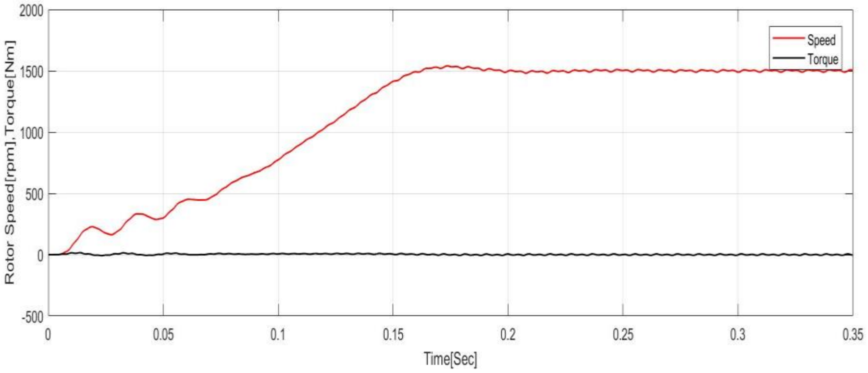

Figure 4-39 Rotor speed and motor torque at start up.

4.5.3 Seventh (7th) harmonic distortion

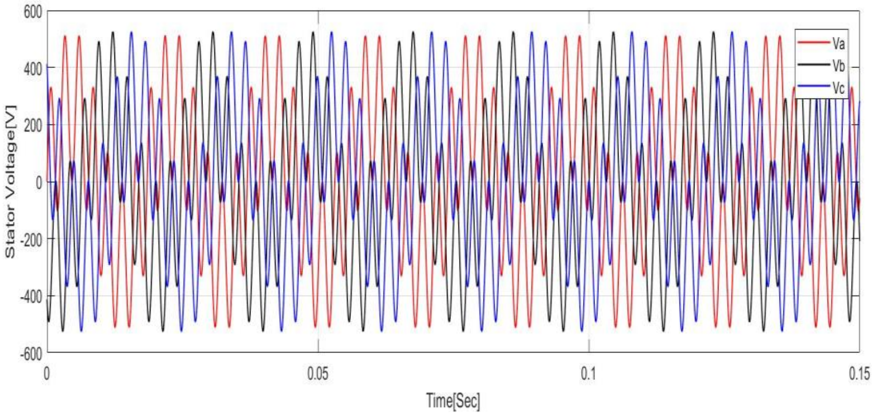

Figure 4-40 Stator voltage with uneven magnitude due to higher order frequency

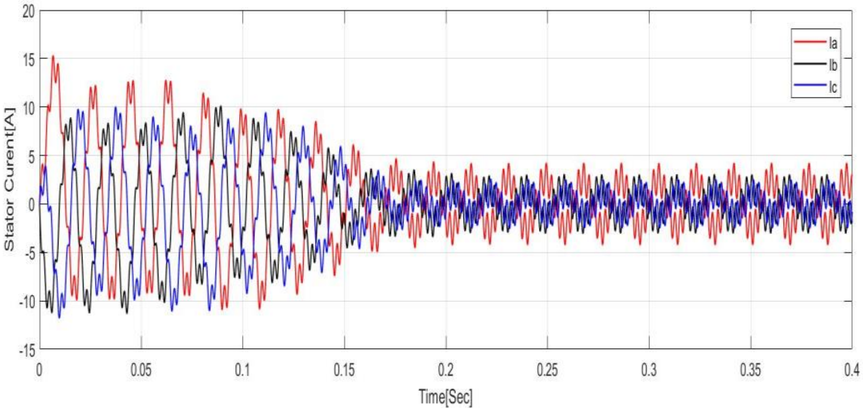

Figure 4-41 Effects of seventh order frequency on stator current

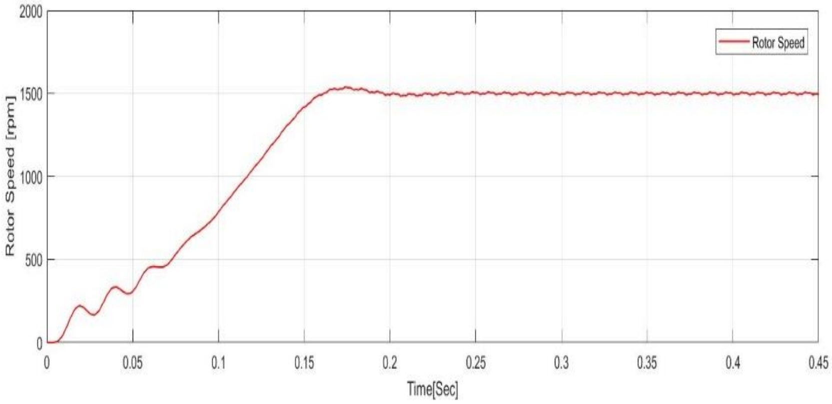

Figure 4-42 Rotor speed pulsation due to higher order frequency harmonic

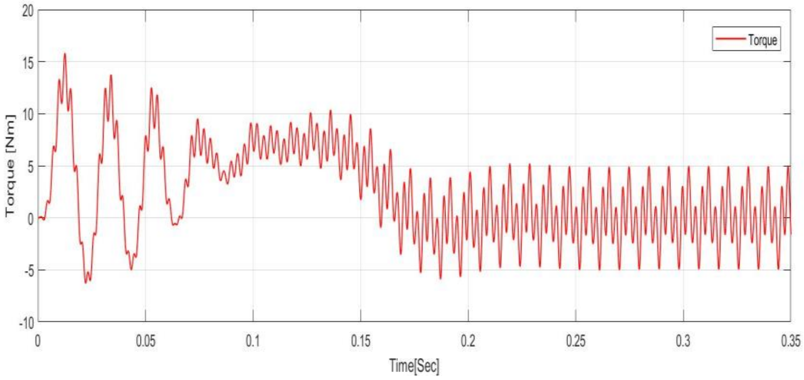

Figure 4-43 Counter clockwise torque produced by the seventh order harmonic which impedes the net motor torque

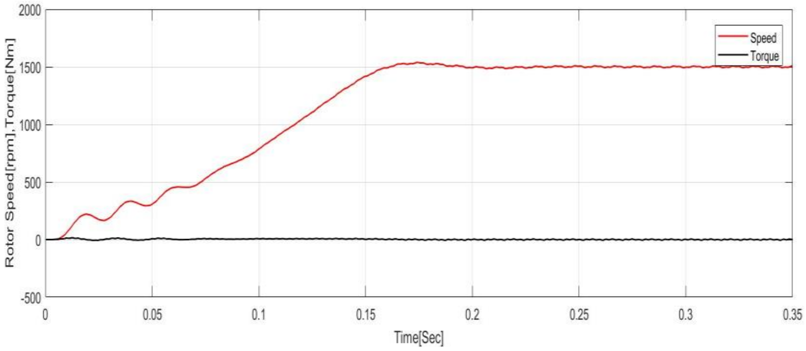

Figure 4-44 Net counter clockwise torque against the rotor speed of an induction motor

4.5.3.1 Ninth (9th) harmonic distortion

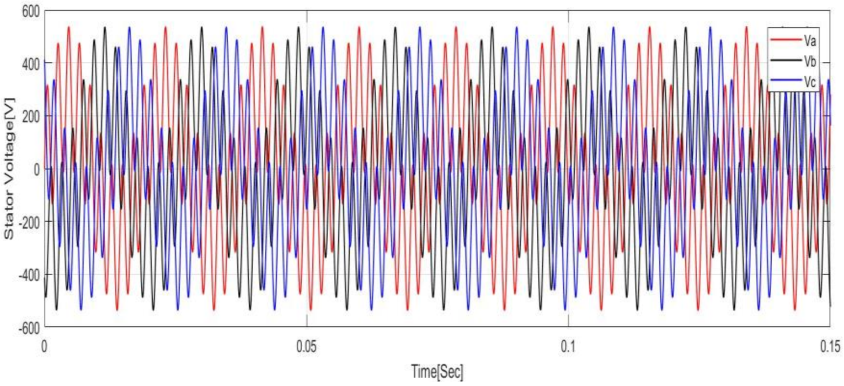

Figure 4-45 Effect of triplen harmonic on the stator voltage

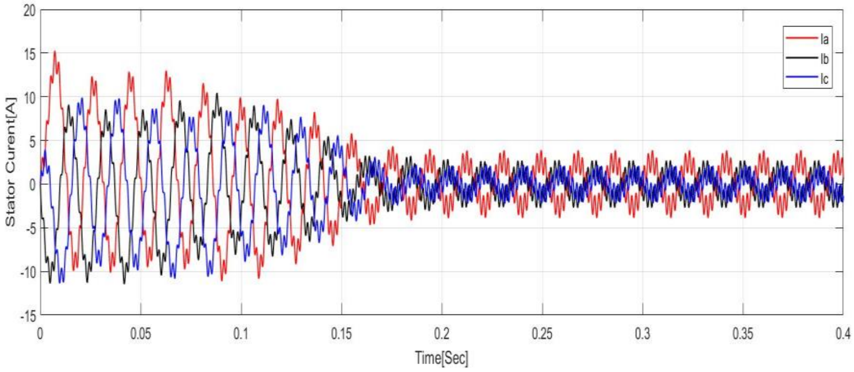

Figure 4-46 Stator current with an insertion of triplen harmonic

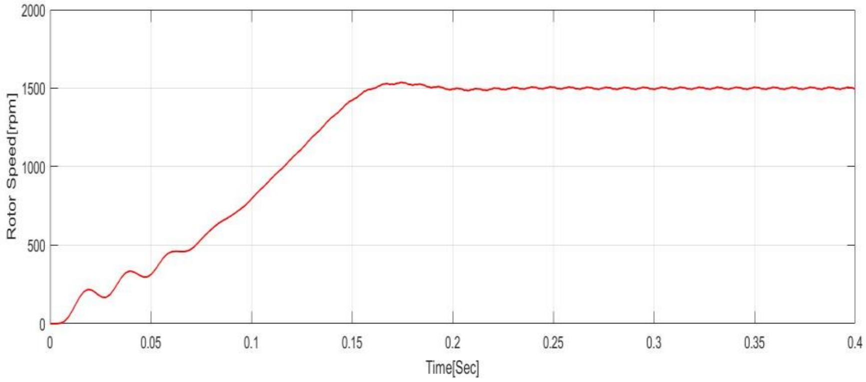

Figure 4-47 Effect of zero sequence harmonic on rotor speed over time as the speed ramps to rated speed

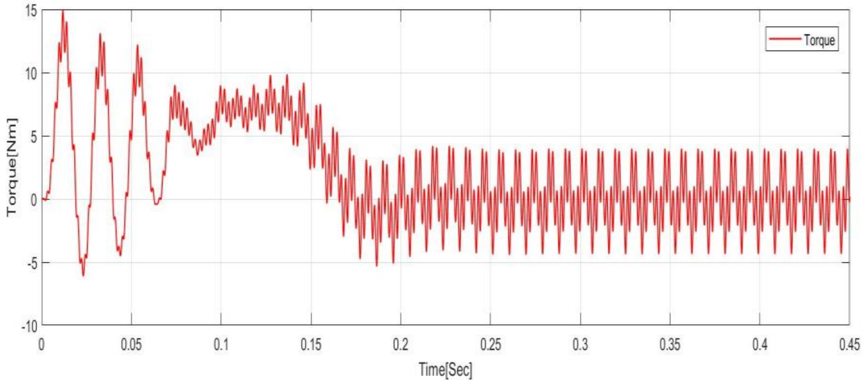

Figure 4-48 11th Harmonic Torque of an induction motor

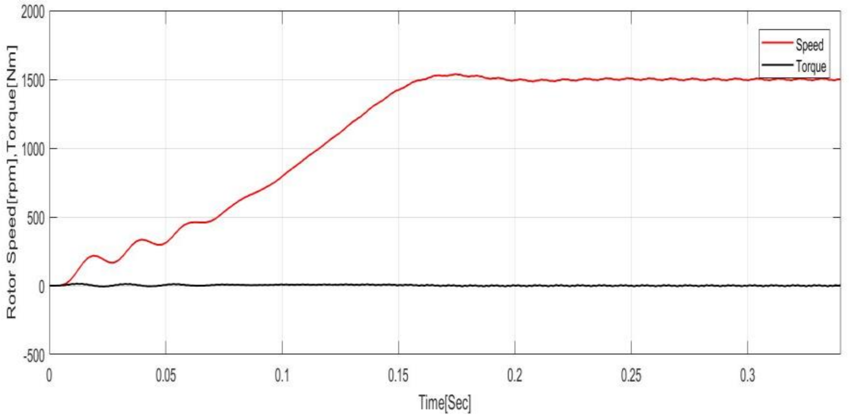

Figure 4-49 Speed and torque behavior of stationary magnetic field produced by the ninth harmonic

4.5.4 Eleventh (11^{th}) harmonic distortion

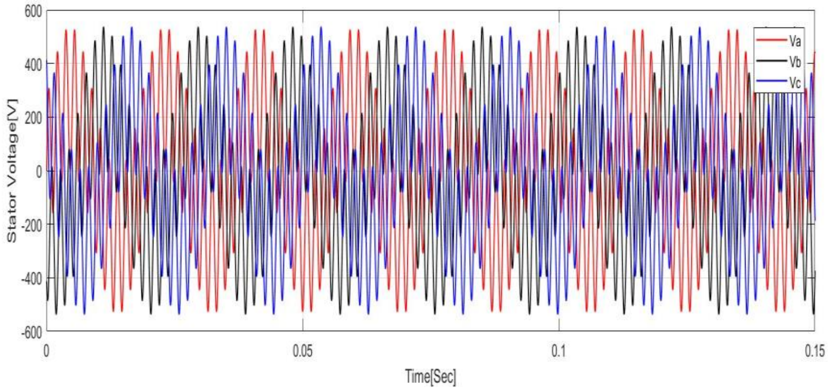

Figure 4-50 Stator Voltage with 11th harmonic distortion,

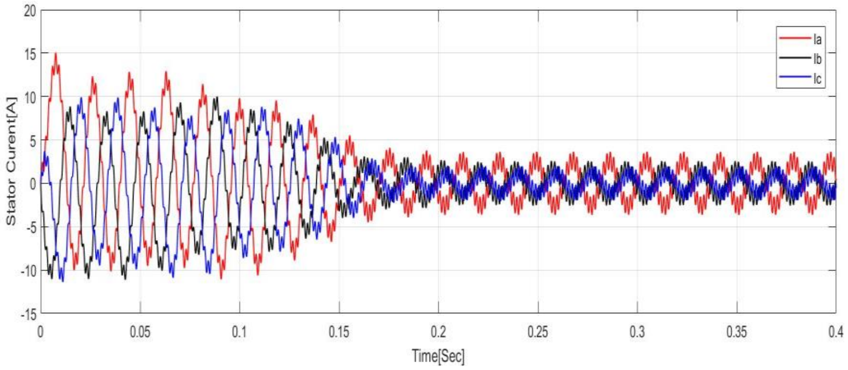

Figure 4-51 11th order harmonic current on the motor winding

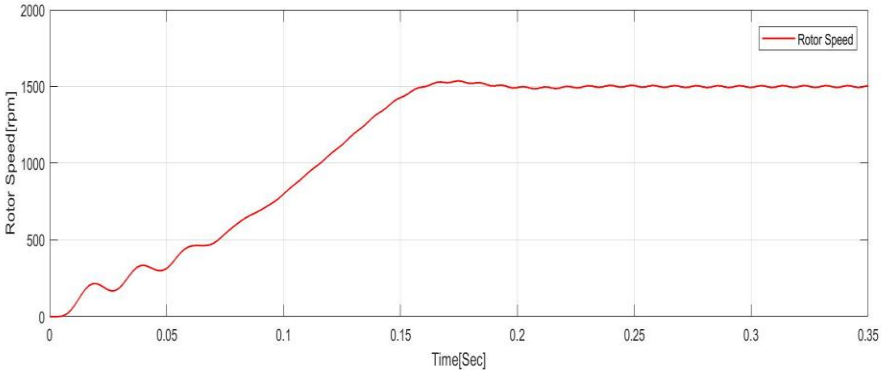

Figure 4-52 Rotor speed pulsation caused by the torque pulsation

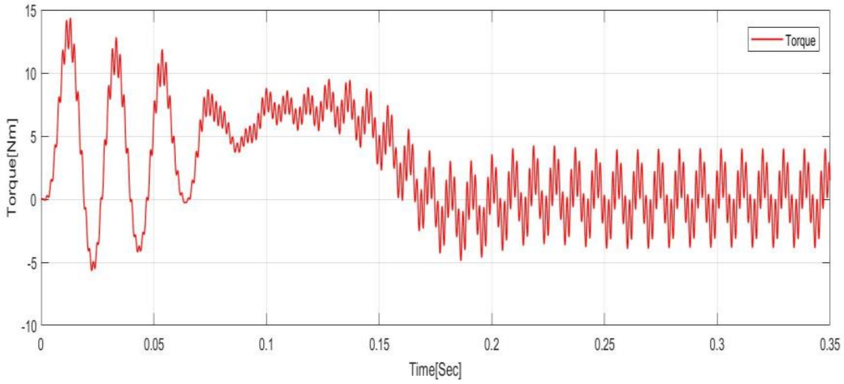

Figure 4-53 Motor torque pulsation the torque

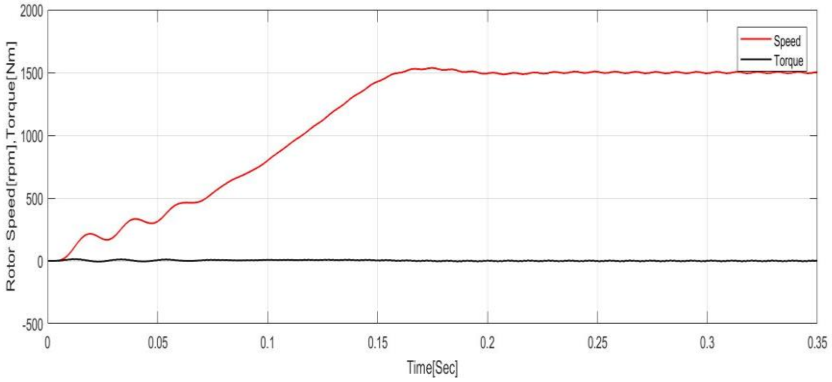

Figure 4-55 Motor torque and rotor speed when the stator voltage has 11th harmonic content

4.6 Analysis of harmonic distortion

Higher order frequency voltages, which are unpleasant to an induction motor due to their negative effect, give rise to harmonic currents. These harmonic currents give rise to vibration by affecting the lubrication quality causing bearings on the motor to collapse. Harmonics produce a resultant flux across an air gap. This resultant flux distribution can cause to crawl, which is a tendency of an induction motor to run at very slow speed, or cogging, which occurs when the harmonic frequencies coincide with the slot frequency due to the harmonics present in the supply voltage, then it causes torque modulation at start up [45].

As reflected by the results and mathematical model, harmonics can be divided into two types mainly the odd harmonics and even harmonics. The average of the even harmonics is zero over a half cycle so their contribution has no effect. Odd harmonics are grouped into third order harmonic, fifth order harmonic and seventh order harmonics; the ninth order harmonic is the same as the third order harmonic with reduced magnitude but same phase rotation. The 11^{th} order harmonic is the same as the fifth order harmonic and seventh order harmonic [46].

The presence harmonics tend to increase the heat dissipation across an induction motor due to the additional iron losses and copper losses that are present in the stator winding and rotor circuit [45]. Furthermore, the harmonic currents and voltage create leakage magnetic field in the stator and rotor end, which produces an additional stray dependent losses, which are high frequency rotor and stator surface losses.

An excessive temperature rise in induction motor can cause premature bearing mature due to the bearing lubrication being subjected to excessive heat. For motor with low winding insulation and temperature class B or lower excessive heat can lead to inter turn short circuit or phase-to-earth short circuit in the stator winding. A sudden change in voltage $\frac{dv}{dt}$ can damage winding insulation over time. For every 10 degrees Celsius temperature rise above rated temperature of the motor, the lifespan reduces by half, which imposes shorter life span of an induction motor [47]. Third harmonic can bearing currents, which causes arcing between the bearing raceway or rolling elements creating a rougher surface and increases the bearing friction.

Triplen harmonics which are an integer multiple of the third harmonic are classified as zero sequence harmonics being the 3rd and 9th harmonics produces a stationary field. Magnetic losses increases since the harmonic field frequencies are higher, harmonic energy is the dissipated as heat [48]. Positive sequence harmonics produce a clockwise rotating magnetic field, which add to the motor torque. The magnitude of the triplen harmonic current are additive in the neutral leading to larger current circulating in the neutral, which can be a hazard.

Phase sequence rotation of odd harmonics need to be taken into consideration as it has negative impacts. Fifth order harmonic current rotates in the negative phase sequence and produces a counter clockwise torque and this torque produced reduces the motor net torque. Harmonic order eleven produces torque pulsation with frequency 12 times the fundamental frequency; this torque causes pulsation in rotor speed [49].

4.7 Stator short circuit with unbalance supply voltage

Unbalance voltage have significant effect on motor parameters, these voltage transients will make the motor run at higher temperatures. Voltage transients can interrupt the normal timing of a motor, speed variation, and result in micro-jogging state. These interruptions may cause excessive vibration which give rise to bearing failures and winding short circuit as well as noise. The voltage variation also produces hysteresis losses in motors that increase the amount of current necessary for operation, which in reverse has an effect on energy consumption. Motor winding insulation is degraded and eventually fails when the insulation resistance is below the required limits; the phenomenon of stator short circuit is introduced. The failure can be either inter-turn or phase to ground short circuit. Below is the effect of short circuit and voltage unbalance on negative sequence current, as well as the relationship between the shorted turns and fault current. Fault current is the current that will be flowing in the short-circuited branch of the winding.

4.7.1 Two Shorted Stator Turns

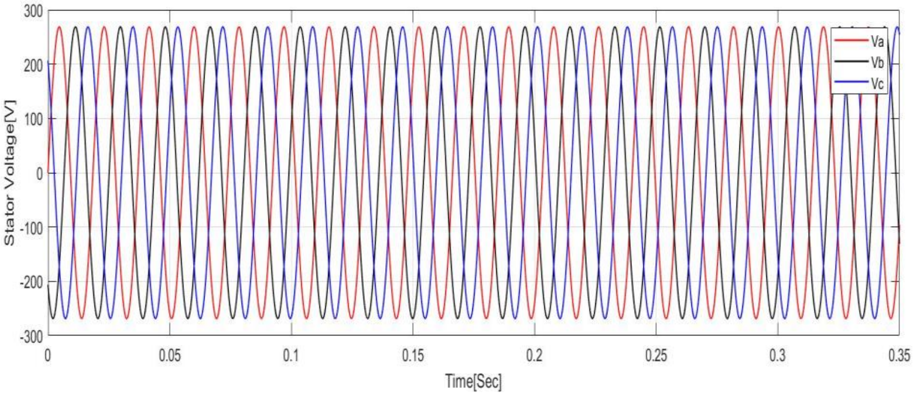

Figure 4-56 Stator voltage of an induction machine exhibiting two-shorted stator turns

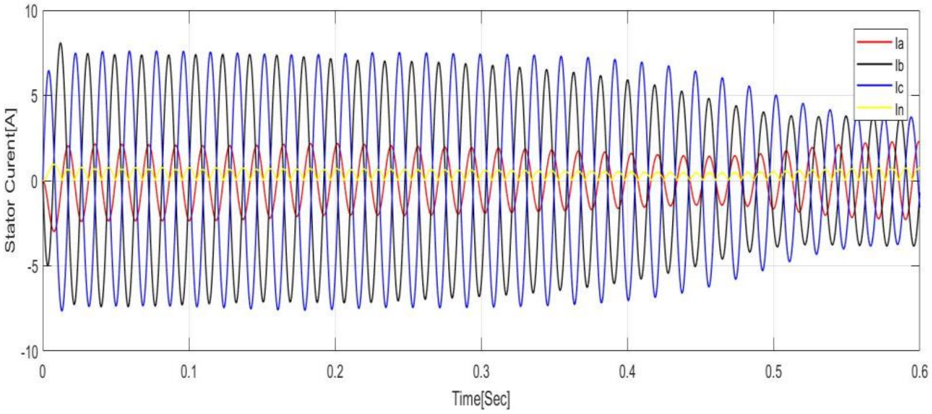

Figure 4-57 Stator current with negative sequence current for two-shorted stator turns

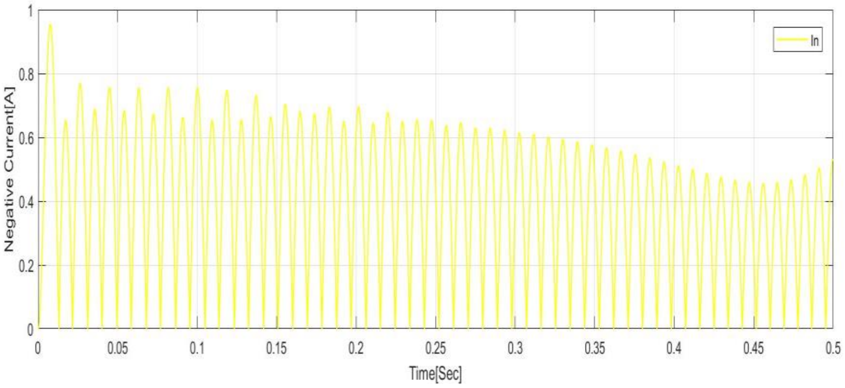

Figure 4-58 Negative sequence current when the stator has two turns shorting against each other

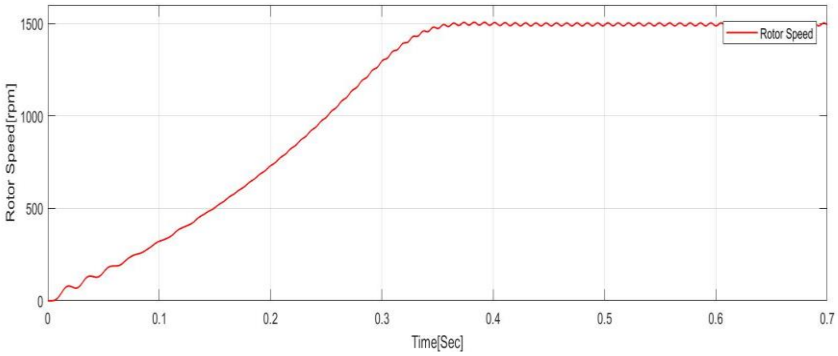

Figure 4-59 Steady state response of the rotor speed with stator shorted turns

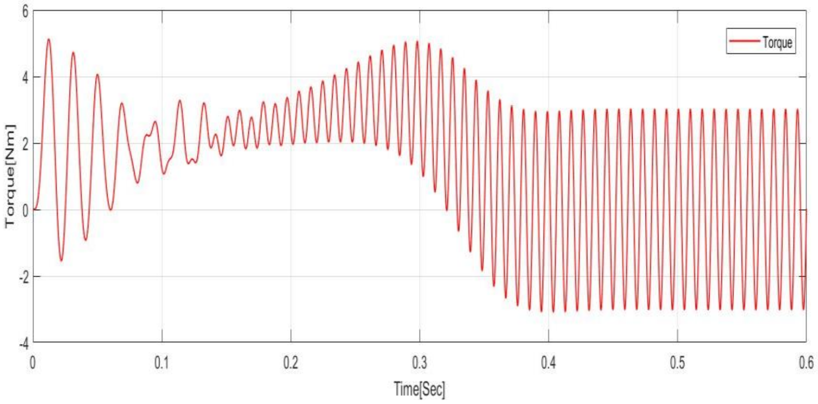

Figure 4-60 Pulsating net motor torque

4.7.2 Four Sorted Stator Turns

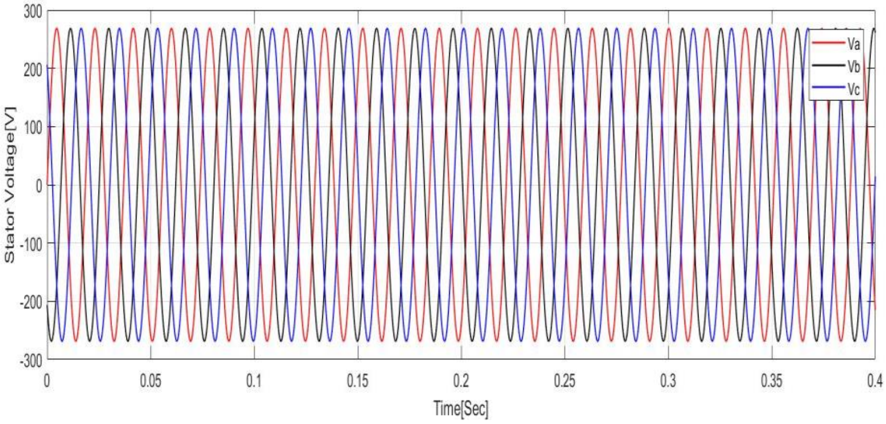

Figure 4-61 Stator voltage response of an induction motor with four shorted coils

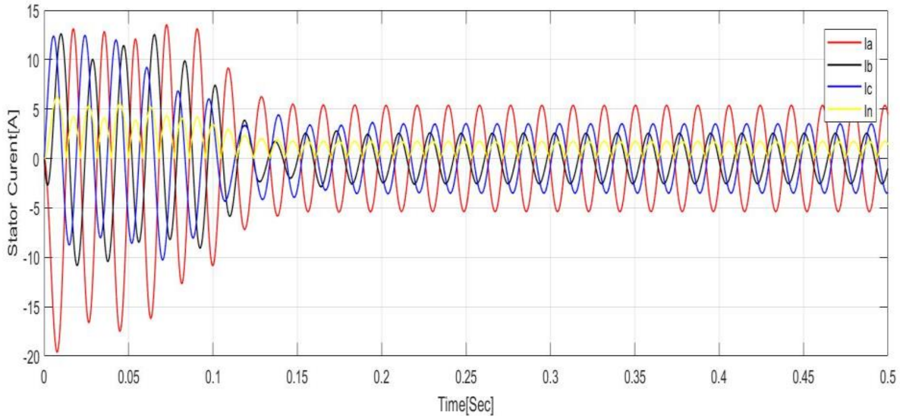

Figure 4-62: Stator current with negative sequence response for shorted coils in the stator winding

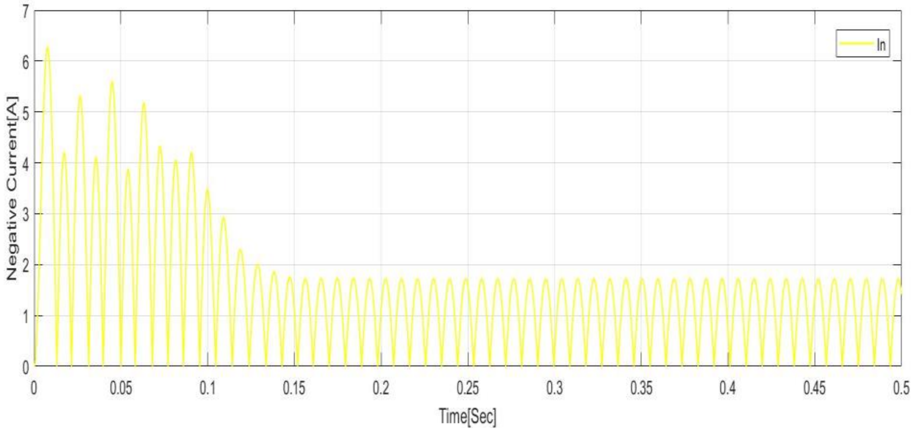

Figure 4-63: Negative sequence current for a faulted stator winding

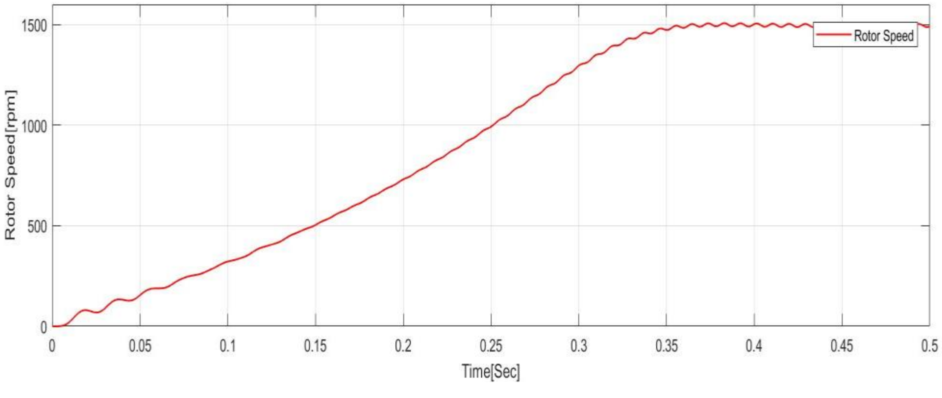

Figure 4-64: Rotor speed of an induction motor with four stator-shorted turns

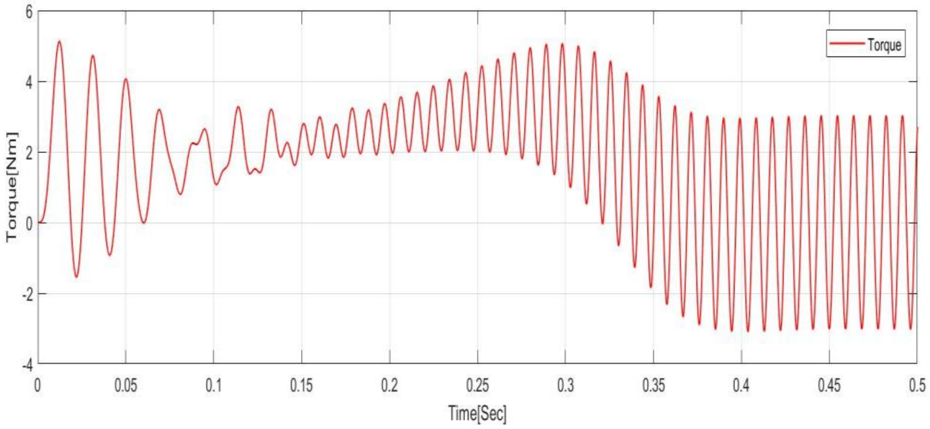

Figure 4-65: net torque response of an induction motor with four shorted stator turns

4.7.2.1 Six Shorted Stator Turns

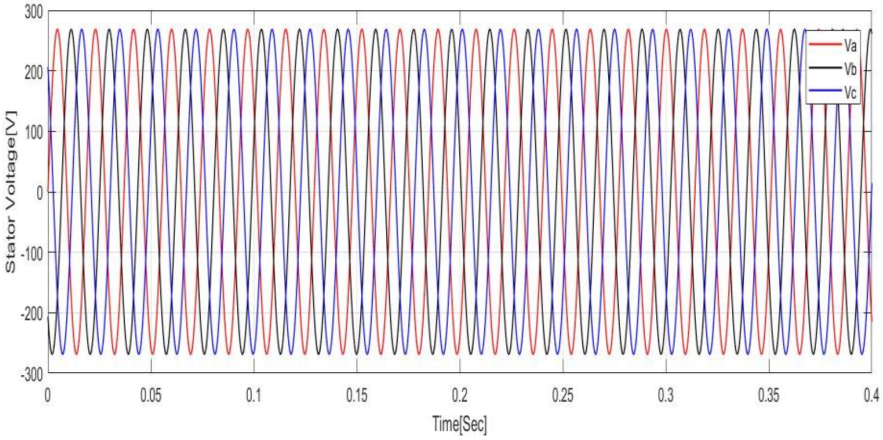

Figure 4-66: Stator voltage of an induction motor with six shorted turns on the stator winding

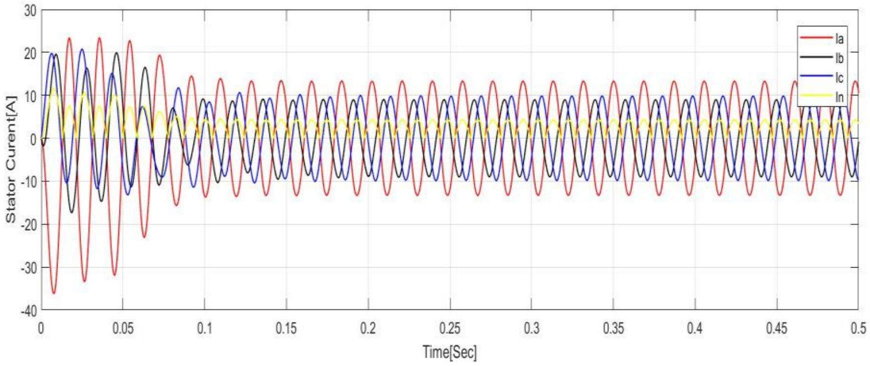

Figure 4-67: Stator current with negative sequence current for an induction motor

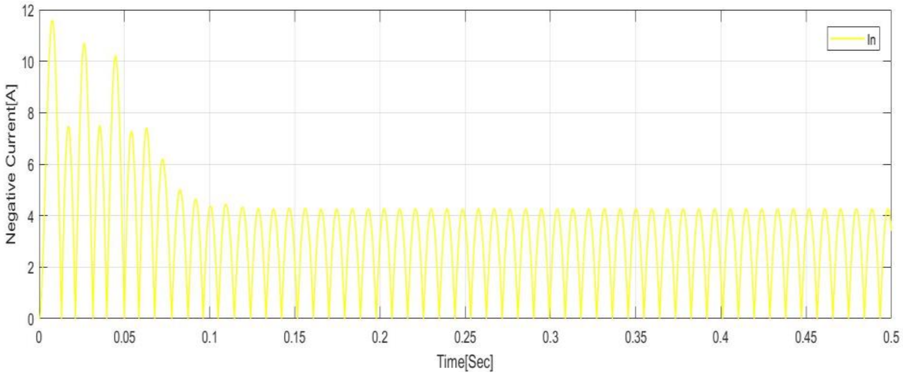

Figure 4-69 Negative sequence current of an induction motor for six turns on the stator shorted

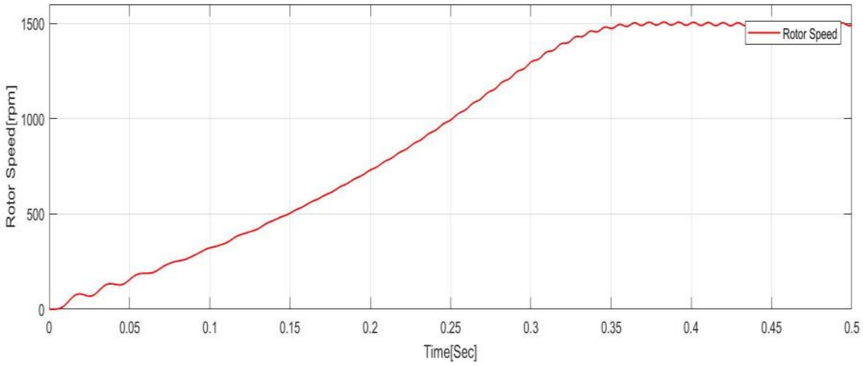

Figure 4-70 Rotor speed of an induction motor with six shorted turns on the stator winding

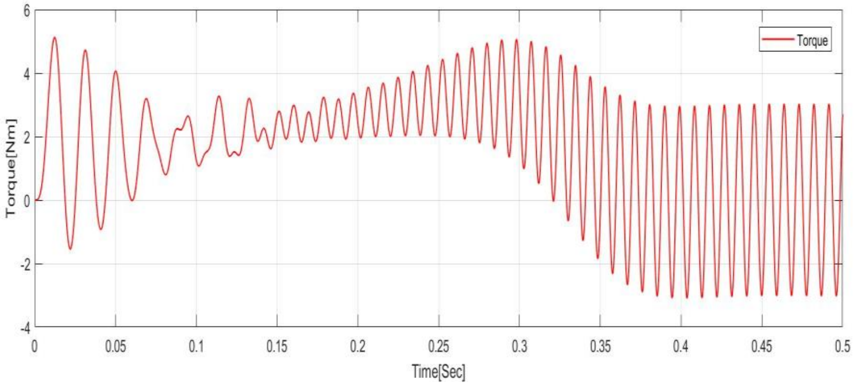

Figure 4-71 Net pulsating torque of an induction motor with shorted stator turns

Chapter 4 has demonstrated the influence of unstable quality of supply on the dynamic model of an induction motor. A change in supply voltage has negative implication on motor operational parameters such as torque and speed. Excessive heat is developed in the stator winding during a period of changing voltage, which gives rise to short circuit condition in the winding, and further deteriorating the winding integrity.

5 Practical Setup and Testing of a Three-Phase Induction Motor

Various methods are deployed to detect the short circuit occurring in the stator winding of the induction motor, if these faults go on unattended for a long period they may lead to machine failure and may stop the line from running. A negative sequence current phenomenon in this paper is chosen for fault detection which evaluates the transient and steady state operations and it has been described in the previous chapters in the form of dynamic models the purpose of the chapter is to validate the simulation results.

As the turn fault occurs in the winding, the machine parameters become unbalanced such as current, which create a rotating magneto motive force (MMF) waves in a stator that have a negative and positive rotating components of current. To achieve the desired outcomes a squirrel cage induction motor is used which is configured as a 4-pole with 2HP. The induction motor has 48 slots and the coil pitch is calculated to be seven slots, and each pole consists of four coils per pole per phase, the voltage of 220V is chosen so that it can be adequate to run the machine even under faulted conditions without stressing the windings, this is the rated voltage of the machine.

Three phase supply voltage from the mains which is rated at 500V/25A is supplied to a 100V variac which works in conjunction with the measuring instruments namely voltmeters, ammeters and power meters this variac is used to vary the input voltage from the range of 0-700V that is the applied to the stator winding coils.

At time t=0, which is the transient measurement the rotor is standstill and as the variac is slowly varied the motor starts to rotate; wattmeter monitors the total active power across the machine which is then used to predict the equivalent circuit parameters; which are necessary for simulation and modelling of the induction motor in the Matlab. As the voltage reaches 220V the speed increases and the machine goes to steady state and the voltmeters are connected to a 300V pin. The machine is configured as a Y-connected four pole; induction motor is the main component to be evaluated.

The behaviour of the machine is observed in the waveforms on the oscilloscope and are compared to the result that were obtained on the simulation conducted on the Matlab software. The short circuit path is created using a 5-ohm resistor with an ammeter in series to measure the short circuit current along the faulted path; the resistor is also used to increase the number of shorted coils.

$$\text{coils per pole} = \frac{N_{slots}}{N_p * \mathrm{P}} \qquad (4-1)$$

$$= \frac{48}{3x4} = 4 \text{ coils per pole per phase}$$

$$\mathrm{Y} = \frac{N_{slots}}{\mathrm{P}} \qquad (4-2)$$

$$= \frac{48}{4} = 12\ slots$$

From the above calculation, it can be concluded that in order to know the location of the poles within a phase, they are separated by 12 slots

For this machine two thirds of the full pitch is used to run the machine as a 4-pole induction motor.

$$\text{pole displacement} = \frac{2}{3} \times \text{ Y} \qquad (4-3)$$

$$= \frac{2}{3} \times 12$$

$$= 8 \text{ slots}$$

Where N_{slots}: number of poles

N_p: number of phases

Y : Full Pitch

So the poles phases that is phase A in relation to phase B and phase C as well are displaced by eight slots away from each other to ensure the 120-degree phase shift between the phases.

Table 5-1 Stator Winding Slot Configuration for 4-pole Machine

Stator Winding coordinates		
Phase A	**Phase B**	**Phase C**
1 (*Input* for phase A)	**17 (Input for phase B)**	**33 *(Input for phase C)***
(2,3)	(18,19)	(34,35)
(4,5)	(20,21)	(36,37)
(6,7)	(22,23)	(38,39)
(8,26)	(24 ,42)	(40,58)
(25,28)	(41,44)	(57,60)
(27,30)	(43 ,46)	(59,62)
(29,32)	(45,48)	(61,64)
(31,49)	(47,65)	(63,81)
(50,51)	(66,67)	(82,83)
(52,53)	(68,69)	(84,85)
(54,55)	(70,71)	(86,87)
(56,74)	(72,90)	(88,10)
(73,76)	(89,92)	(9,12)
(75,78)	(91,94)	(11,14)
(77,80)	(93,96)	(13,16)
79 (Neutral)	**95 (Neutral)**	**15 (Neutral)**

Figure 5-1 Experiment setup

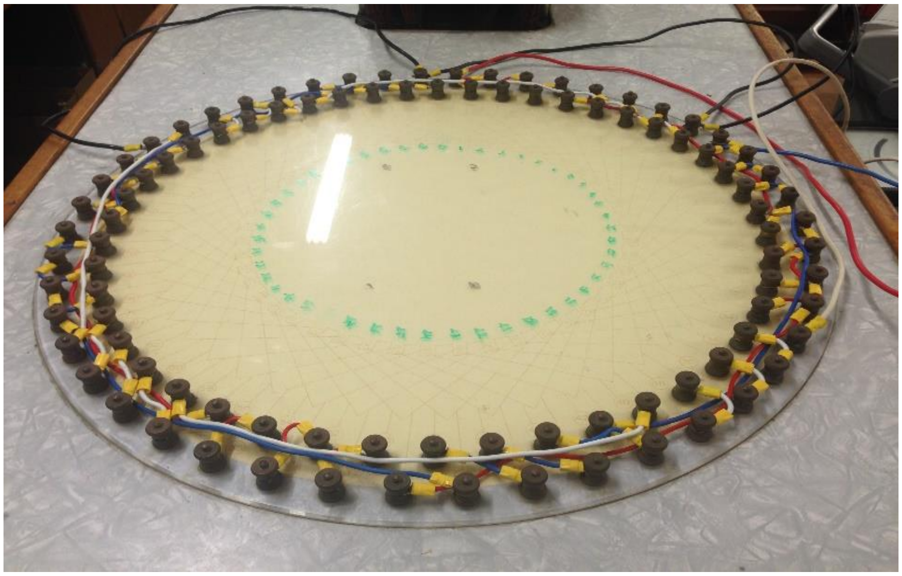

Figure 5-2 Stator winding slot configuration

From table 5-1 it was possible to wire the stator winding as a 4-pole machine, with 2 HP rated power, from the coils it is possible to draw a schematic of the layout in AutoCAD to elaborate the coil per pole per phase. The motor winding is configured such that it operates as a four-pole motor with pole displacement of eight slots displacement per pole per phase.

Motor Specifications

Power: 2/2 HP

Voltage: 220 V- 50 Hz

Current: 4.8 A/ 5.8 A/4.6 A

Pole: 3 phase-4 pole

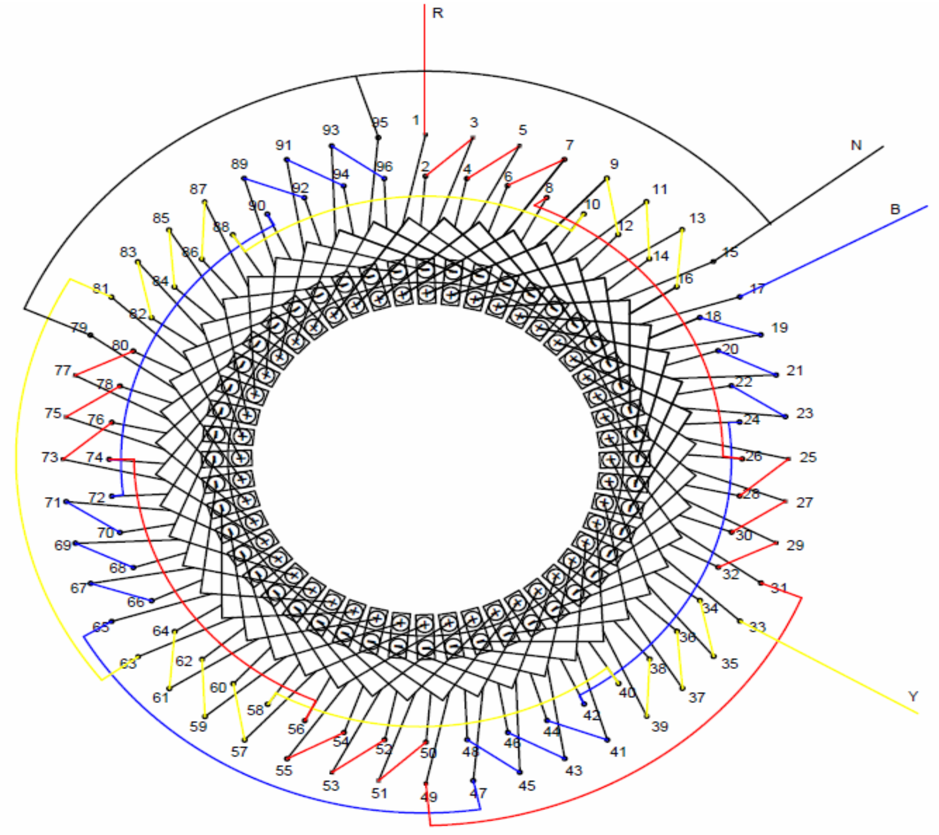

Figure 5-3 Stator winding layout using AutoCAD simulation tool

5.1 Healthy Coils

Table 5-2 Induction motor operational parameters for healthy stator

	Current [A]	Voltage [V]	Active Power [W]
Phase A	2.6	220	-
Phase B	2.7	220	-
Phase C	2.6	220	-
Wattmeter 1	-	-	0
Wattmeter 2	-	-	17

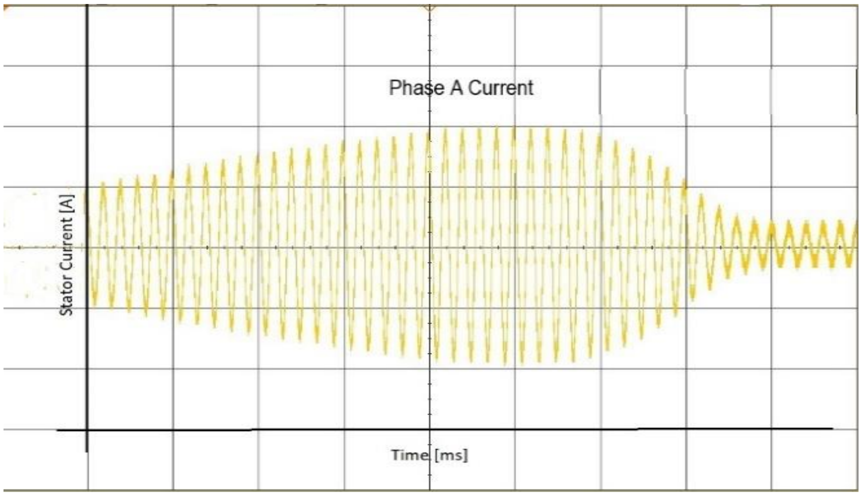

Figure 5-4 Current in phase A

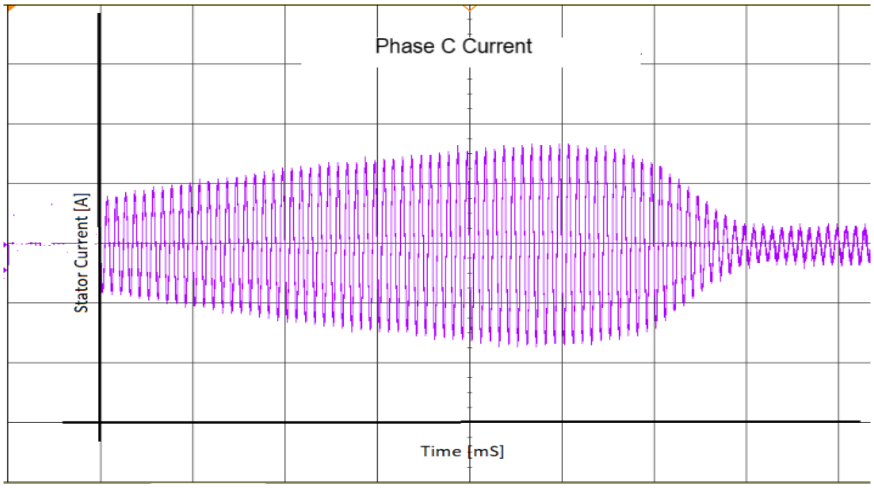

Figure 5-5 Current in phase B

As the motor starts up (transient state) phase current as in figure 5-4 and 5-5 is high for a short period to steady state, the resistance of the stator is very low compared to the reactance, this will result in a high inrush current, and the currents waveform verifies the phenomenon that at starting the current is very high. As the motor ramps up in speed, the inrush current drops to lower values as the torque of the machine decreases at rated speed. Tabulated results in the table 5-2 are a reflection of motor parameters at no load, since the motor is healthy all three-phases are balanced and voltage supplied is balanced the motor is operating at manufacturers range. Transient current unbalance at start-up will cause the motor to trip and hunt in speed due to asymmetric magnetic field set up in the stator by these unbalance currents.

5.2 Motor steady-state operation during over voltage condition

Table 5-3 Induction motor operational parameters for over voltage condition

	Current [A]	Voltage [V]	Active Power [W]
Phase A	3.8	250	-
Phase B	3.7	250	-
Phase C	3.5	250	-
Wattmeter 1	-	-	0
Wattmeter 2	-	-	25

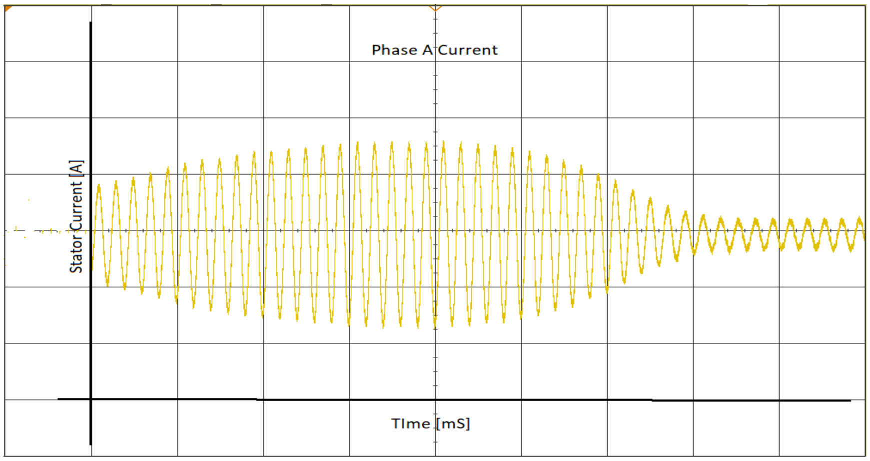

Figure 5-6 Current in phase A

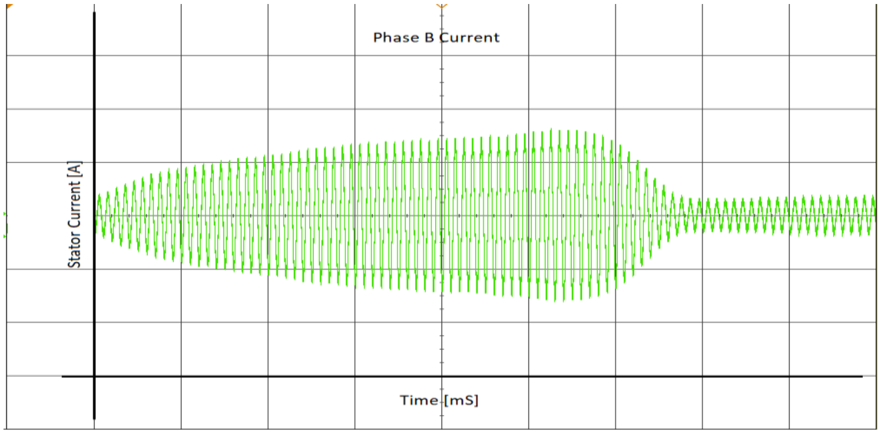

Figure 5-7 Current in phase B

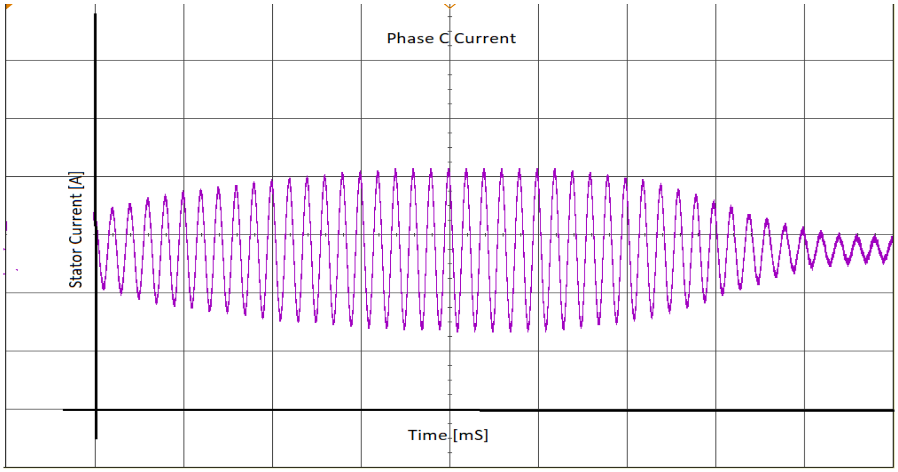

Figure 5-8 Current in phase C

Tabulated results for motor operating at 250 V, which is a 30 V difference higher than the motor rated voltage, the steady state current of the motor increases with an increase in voltage as the motor operates at no load condition. Due to the characteristic behaviour of the motor flux density, which is proportional to the supply voltage, an increase in supply voltage increases the flux density pushing the motor to magnetic saturation and increasing the losses in the motor. To cater for an increase in losses the motor current drawn will increase, the current increase introduces undesired thermal rise in the stator winding.

The stator conductors are selected based on motor current density defined by the motor rated current with additional room for temporary overloading. As the over voltage condition occurs, the motor draws high current and altering the current density on the stator winding, this additional current adds a thermal stress on the motor and when allowed to run for a long time the motor insulation gets destroyed and incipient stator short circuits are prevalent. The rotor speed above the rated voltage starts to vibrate and oscillates which might damage the rolling element bearings when on load. The higher the supplied voltage in over voltage condition increases the transient current curve as in figure 5-7 and 5-8, if this current does not settle to a rated value at full load it causes undesirable trips due to over current protection operating to isolate the motor.

5.3 Motor steady-state operation during under voltage condition

Table 5-4 Induction motor operational parameters for under voltage condition

	Current [A]	Voltage [V]	Active Power [W]
Phase A	1.5	45	-
Phase B	1.3	45	-
Phase C	1.2	45	-
Wattmeter 1	-		13
Wattmeter 2	-		5

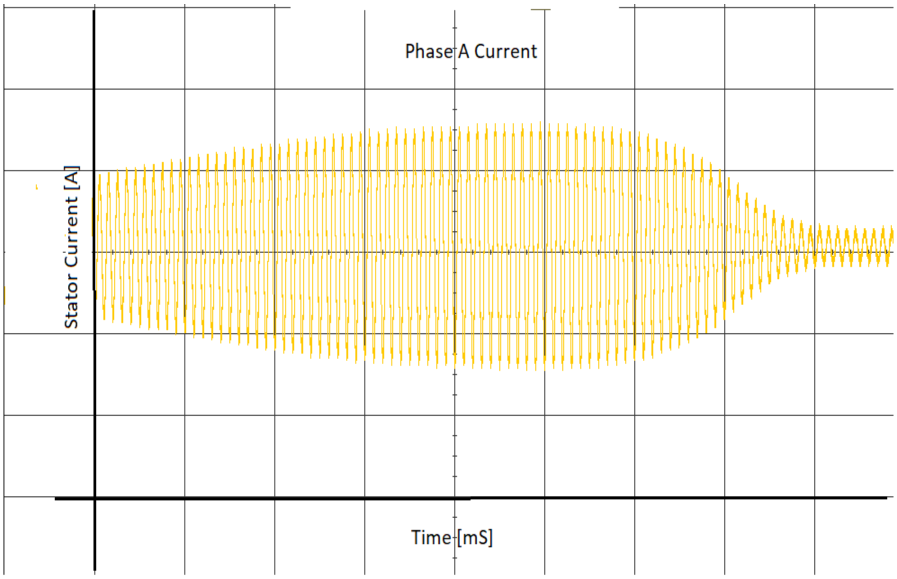

Figure 5-9 Current in phase A

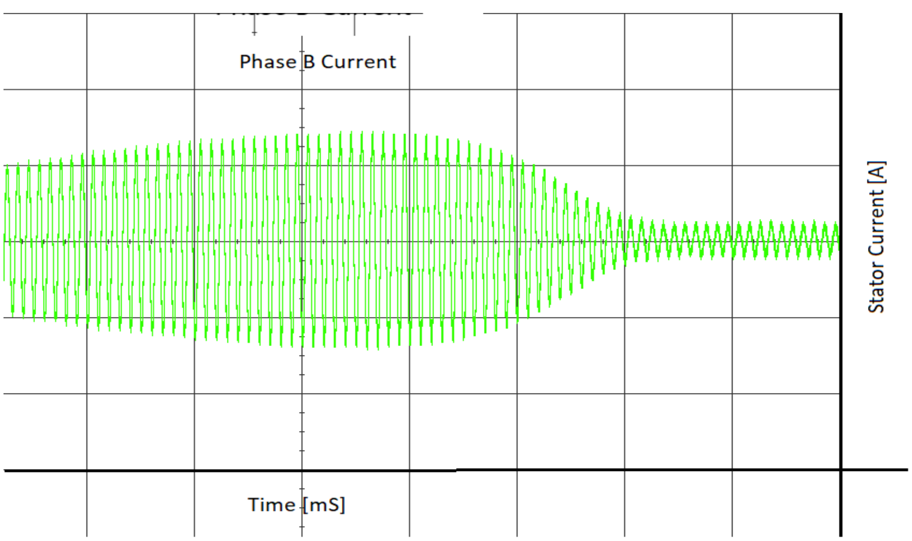

Figure 5-10 Current in phase B

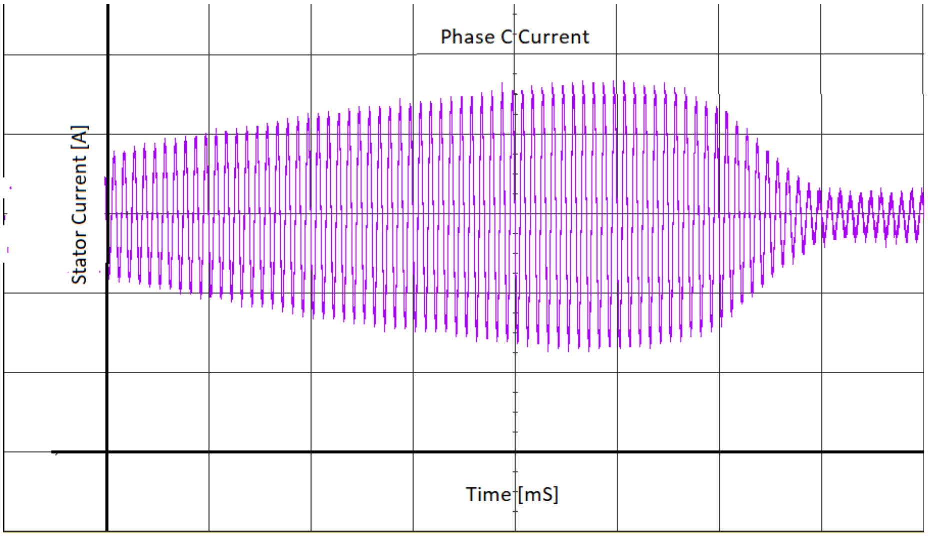

Figure 5-11 Current in phase C

Tabulated in table 5-4 are the result for steady-state operation of an induction motor with an under voltage condition. The motor at startup draws higher current to over come the stator resistance and stator inductances as shown is figures 5-10 and figure 5-11, as the motor picks up speed from transient to staedy-state the current decreases but does not reach the rated current value due to the applied voltage being lower than the required voltage to produce the rated current, the no load condition also influences the amount of current drawn by the motor. The output power delivered by the motor shaft to drive the coupled load is proportional to the supply voltage and the current required by the load. A drop in voltage while the motor is delivering a constant torque to the load, will increase the motor current to compensate for a change in voltage to maintain the torque and output power required by the load, this sudden rise in current increases the thermal stress across the motor stator winding.

A further reduction of supply voltage to the stator of an induction motor reduces the rotating flux across the stator, the flux is directly proportional to the rotor speed, the reduction in flux reduces the motor speed below the rated speed as governed by the number of poles as well as the supply frequency. The rotor speed oscillates, this oscillation creates vibration on the motor rolling element bearings which may lead to premature bearing failures. The thermal stress caused by excessive current may give rise to capacitive currents which act on bearings to cause a ruggged surface and may create heat on the lubrication of the bearing leading to failure.

5.4 Motor steady-state operation during single phasing condition

Table 5-5 Induction motor operational parameters for single phasing condition

	Current [A]	Voltage [V]	Active Power [W]
Phase A	0	0	-
Phase B	3.7	10	-
Phase C	3.5	10	-
Wattmeter 1	-	-	0
Wattmeter 2	-	-	0

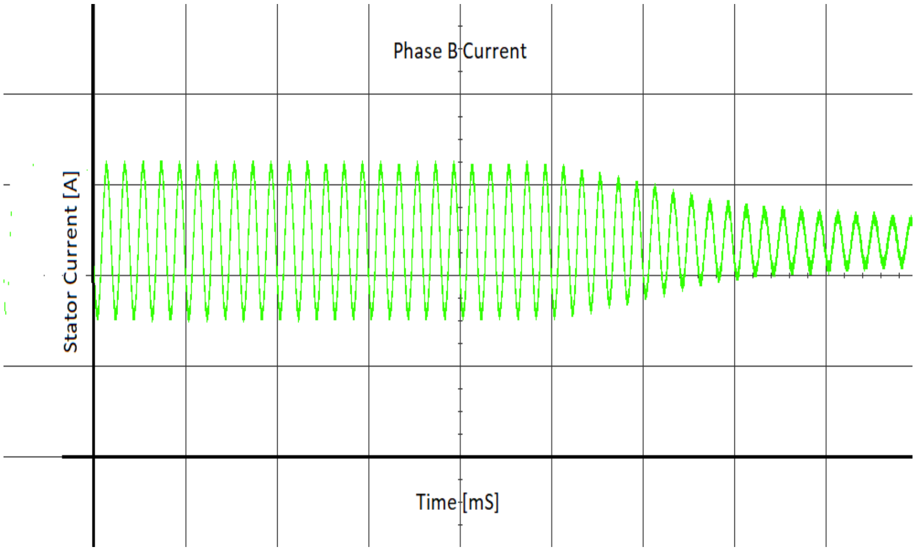

Figure 5-12 single phasing current flowing in phase B

For the induction motor in principle for it to turn, is such that the spatial distribution of the stator winding and the phase distribution of the three-phase input supply ensures the generation of the three-phase synchronous rotational electromagnetic field. The absence of one phase due to single phasing condition Phase A, the rotational electromagnetic field cannot be set up to start the motor. Tabulated results in table 5-5 verify the theoretical analysis that the induction motor cannot start under the single phasing condition.

A very low voltage applied to the stator of an induction motor, the motor interprets the supply as a two-phased supply as the third phase, which is phase A, is open. The open phase introduces a high resistance, which restrict the flow of current, so that all the current that going to the open phase is split between the two remaining phases. A sudden increase in current across the two remaining phases as the voltage is slowly increased, the rotor stalls drawing more current. The test was aborted as the current was going high this was done to protect the stator winding against winding breakdown due to heat that is generated by high current. Based on ohms law principle, as in figure 5-12 a path of low resistance allows for a flow of high current, this high current introduces heat in the current path.

5.5 Motor steady-state operation during voltage unbalance condition

Table 5-6 Induction motor operational parameters for voltage unbalance condition

	Current [A]	Voltage [V]	Active Power [W]
Phase A	1.6	150	-
Phase B	1.8	160	-
Phase C	3.7	130	-
Wattmeter 1	-	-	
Wattmeter 2	-	-	

A small change in the motor supply voltage per phase, if the change is not uniform across all three-phases of the supply then that voltage deviation is interpreted as unbalance by the induction motor. The changing voltage presents a sudden increase in the motor stator current depending on the degree of change; the current will increase to counteract the effect of change. During the voltage, unbalance scenario the excessive rise in current produced heat and the absence adequate cooling system the stator winding is compromised and prone to burn out due to heat.

The motor is supplied with lower voltage in order to control and minimize the current rise to protect the stator winding against over current, at 160V across the white phase (phase B) yielding a current of 1.8 A. The lower the voltage applied to the phase of an induction motor the higher the current rise, if the current rise exceeds the motor rated current, over current protection scheme of the motor operates to protect the motor from overheating.

5.6 Motor steady-state operation with incipient winding short-circuit

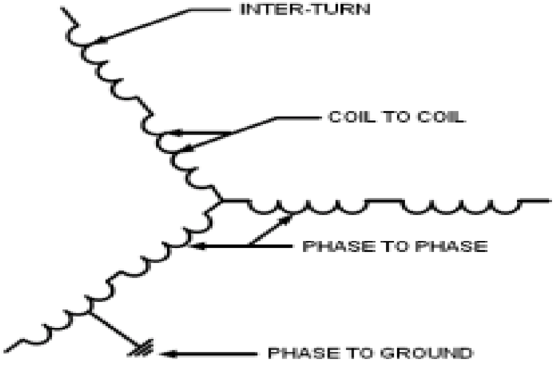

Figure 5-13 Possible stator-winding faults in induction motors

The figure 4-13 shows a combination of possible stator winding related faults that may occur on the winding. Inter-turn short circuit occurs when two or more turns of each phase lose the insulation and a short against each other creating lesser number of turns on the affected phase. The lesser the number of effective turns per phase the lower phase resistance and the more current flow. Phase-phase short circuit occurs when two or more phase short, creating a short circuit path. The fault loop will allow the flow of excessive current due to low resistance and the motor current becomes unbalance as the phases are shorting thus the machine interprets the motor as a two phase machine and during this condition the motor does not start as the three-phase rotating magnetic field cannot be created. Phase-ground phase occurs between one or more phases of the motor with ground; essentially the phase current is seen as a leakage current to ground and trips the motor on earth fault due to the flow of current to ground.

Insulation resistance test on each phase of the machine

Phase-Phase insulation resistance at 500 V

- Phase A – Phase B = 20 MΩ
- Phase A – Phase C = 21 MΩ
- Phase B – Phase C = 20.8 MΩ

Phase-Earth insulation resistance at 500 V

- Phase A – Earth = 23 MΩ
- Phase A – Earth = 20 MΩ
- Phase B – Earth = 26 MΩ

Phase-Phase resistance (using a fluke meter-DMM)

- Phase A – Phase B = Open line (O/L)
- Phase A – Phase C = Open line (O/L)
- Phase B – Phase C = Open line (O/L)

Phase to phase resistance in Mega ohms when injected with 500 V is high; this is an indication that there is no short circuit path between the two adjacent phases in the stator winding, the existence of a short circuit path will allow for a flow of leakage current. Higher values of insulation resistance for old winding is desirable to prove the integrity of the winding that is free of contamination and shorted path. Dielectric absorption ratio and polarization index ratio for phase-phase test is greater than a minimum of one, the winding polarizes in one minute.

Any short circuit that exists between a phases to earth would create a short circuit path of very low resistance, as the direct current (DC) voltage is applied, the existence of a short creates a path for leakage current to flow to ground thus dropping the resistance. Higher values of phase to earth insulation resistance prove the absence of short circuit in the phase-earth path.

5.6.1 Two shorted turns

Table 5-7 Induction motor operational parameters with two shorted stator turns

	Current [A]	Voltage [V]	Active Power [W]
Phase A	3	220	-
Phase B	2.1	220	-
Phase C	2.2	220	-
Short Circuit loop	1	-	-
Wattmeter 1	-	-	0
Wattmeter 2	-	-	11

Table 5-7 shows the phase currents for a motor having two shorted turns in the stator winding across phase A, these current values are obtained at the motor rated voltage of 220 V. Due to a short circuit, the short circuit path is created through a 5-ohm resistance allowing a current flow of 1A to pass through the resistor as fault current.

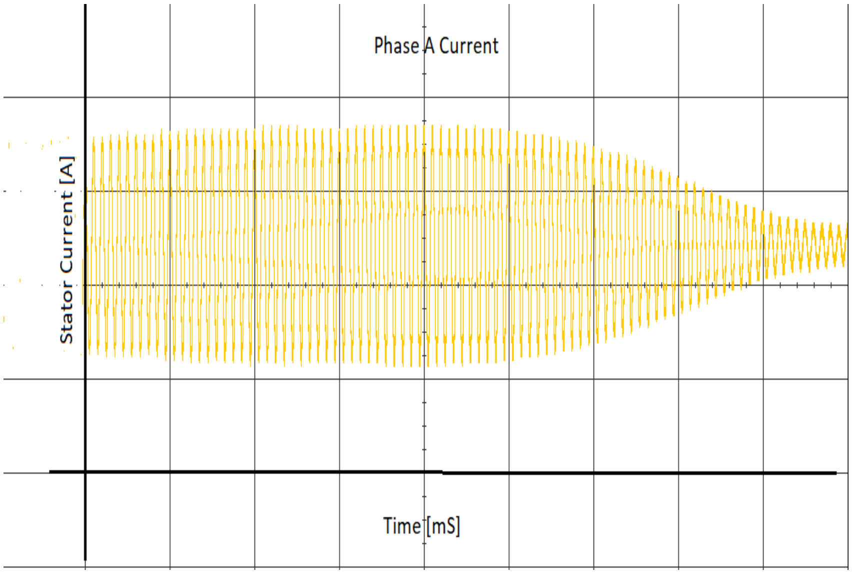

Figure 5-14 Current in phase A

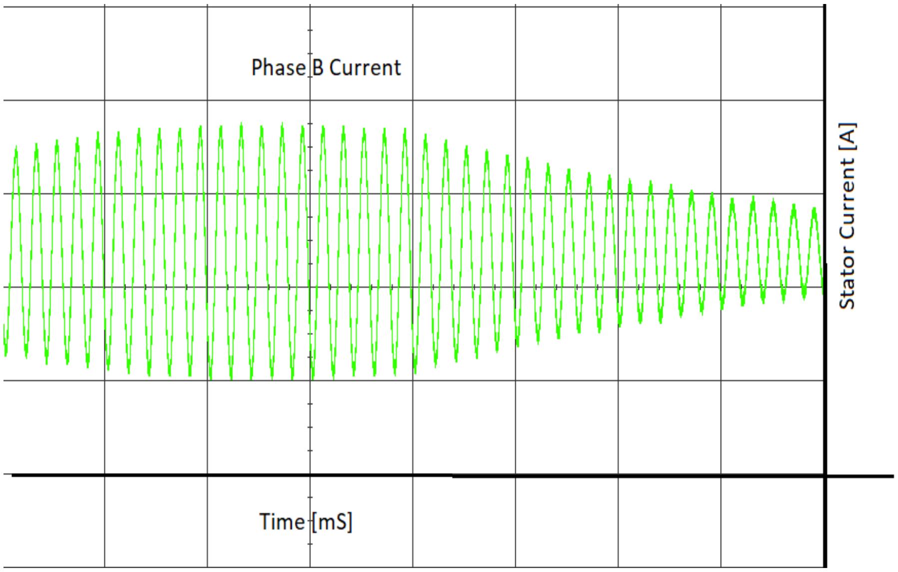

Figure 5-15 Current in phase B

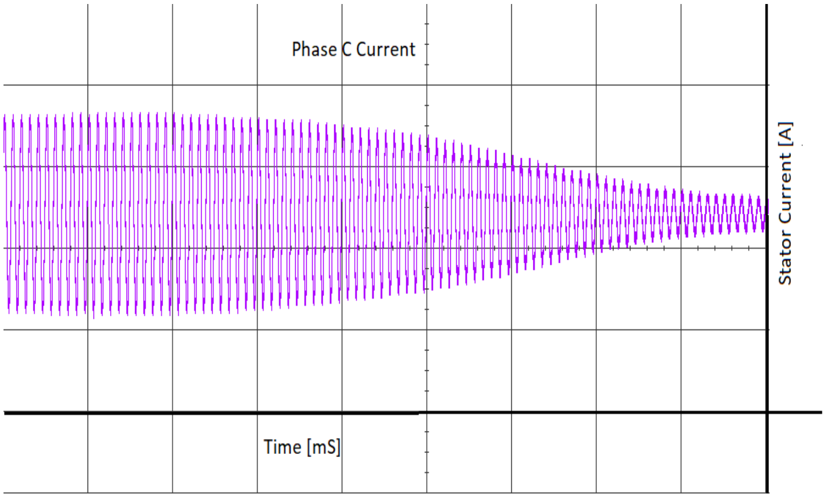

Figure 5-16 Current in phase C

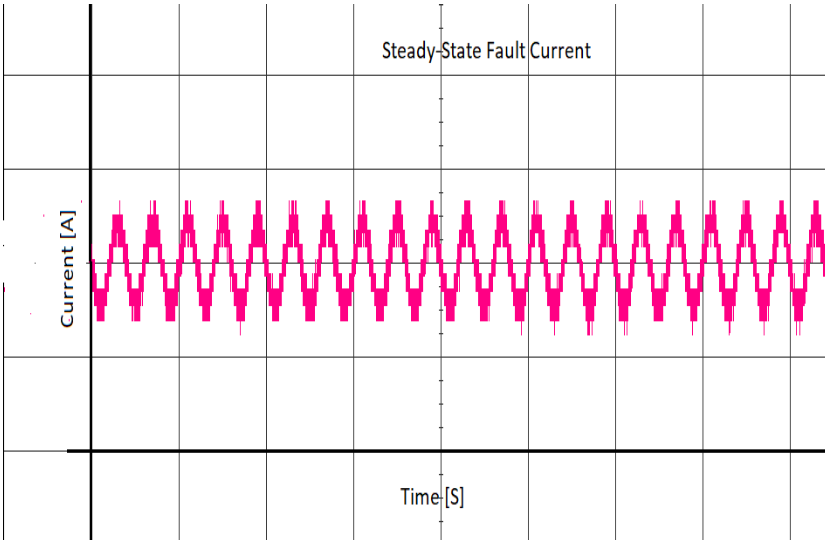

Figure 5-17 Steady-State fault current

The induction motor inrush current is plotted on the figures 5-14 to figure 5-16, regardless of the short circuit incipient the inrush current does not change across all the three-phases of the motor. The incipient of stator winding short circuit on phase A, which is shorted through a 5 ohms resistor for protecting the winding against high current, which might damage the insulation. At steady-state, the motor stator resistance per phase changes, such that the shorted phase exhibit the lower phase resistance, current by ohms law flows in the loop of lower resistance. As observed, the 1 A of fault current flows in the shorted loop due to low current, the remaining healthy phases draw lesser current as more current will flow through phase A. the current draw is unbalance, the unbalance loading of each phase is an indication of fault in the stator due undesired short circuit. For healthy winding, balanced three phase current is expected, any deviation from zero in figure 5-17 is an indication of fault current flowing in the path of low resistance.

5.6.2. Three shorted turns

Table 5-8 Induction motor operational parameters with three shorted stator turns

	Current [A]	Voltage [V]	Active Power [W]
Phase A	3.6	220	-
Phase B	2.2	220	-
Phase C	2.3	220	-
Short Circuit loop	3	-	-
Wattmeter 1	-	-	0
Wattmeter 2	-	-	17

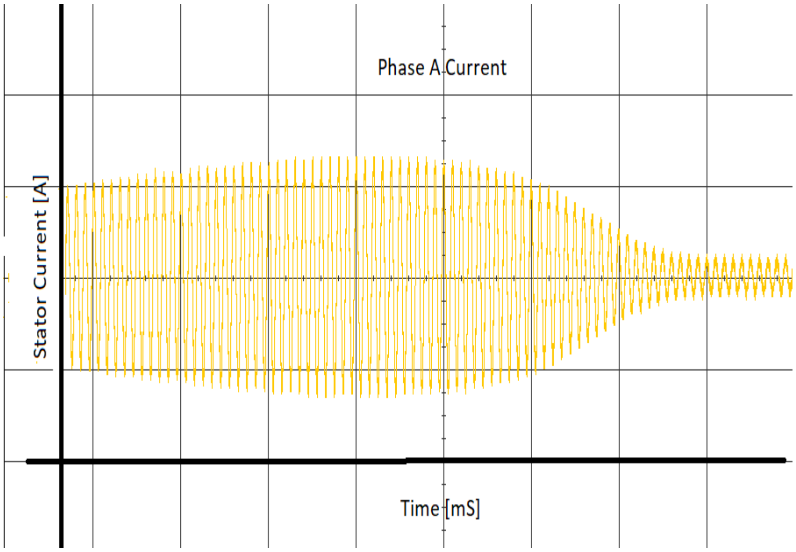

Figure 5-18 Current in phase A

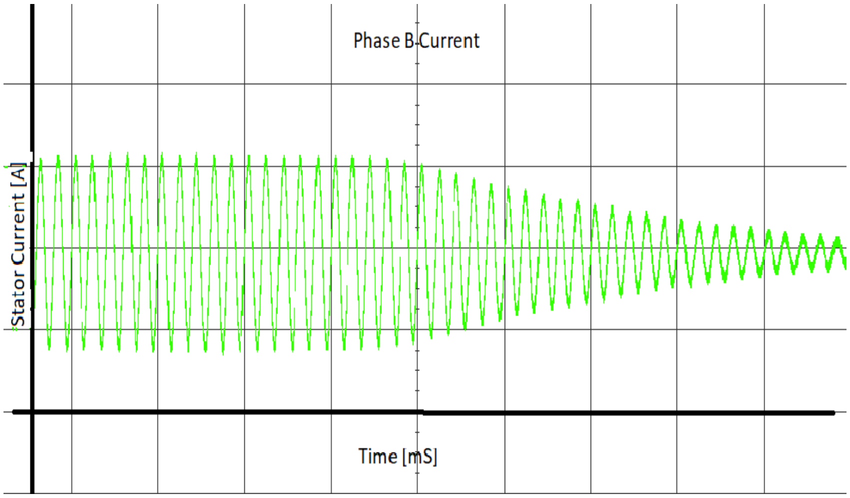

Figure 5-19 Current in phase B

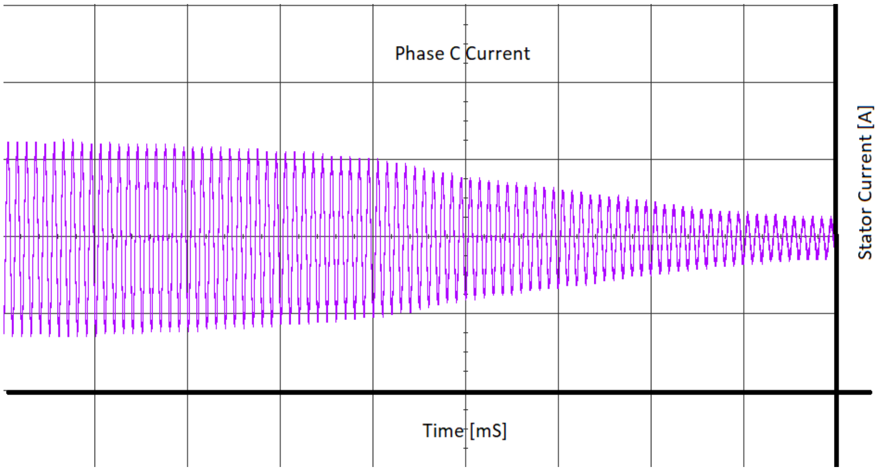

Figure 5-20 Current in phase C

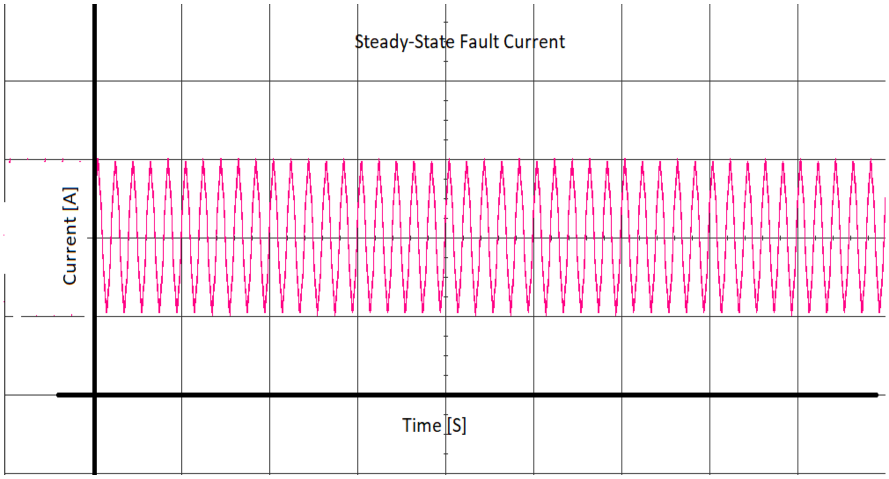

Figure 5-21 Steady-State fault current

With an increase in the number of shorted turns in phase A, the phase resistance on the shorted phase reduces by a fraction as the number of effective turns on the phase decreases. The linear relationship between number of shorted turns and short circuit current is prevalent as in figure 5-21; higher short circuit current reflects higher number of shorted turns. The stator resistance across the three phases is unbalance as an indication of the fault on the phase with lower phase resistance. The phase resistance drop allows vast current to flow in the loop of lower resistance thus increasing the fault current as tabulated in table 8 above. The current unbalance gives rise to a negative sequence component of current, as the per phase current deviates from the rated value, an increase in negative sequence current from zero introduces a counter clockwise rotating field which opposes the direction of rotation of the rotor. A pulsation in motor speed curve is observed and if not corrected can result in undesired bearing vibration.

5.6.3. Four shorted turns

Table 5-9 Induction motor operational parameters with four shorted stator turns

	Current[A]	Voltage[V]	Active Power[W]
Phase A	2.8	220	-
Phase B	2.4	220	-
Phase C	2.4	220	-
Short Circuit loop	3.3	-	-
Wattmeter 1	-	-	0
Wattmeter 2	-	-	19

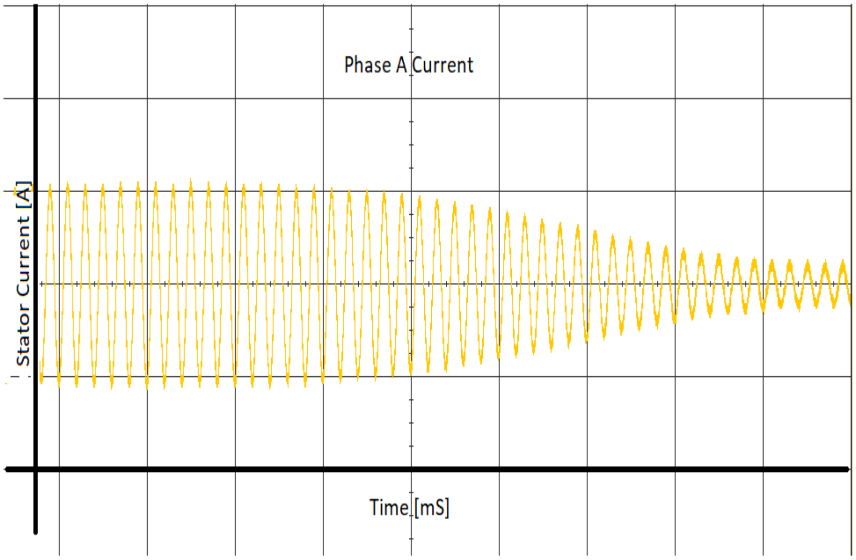

Figure 5-22 Current in phase A

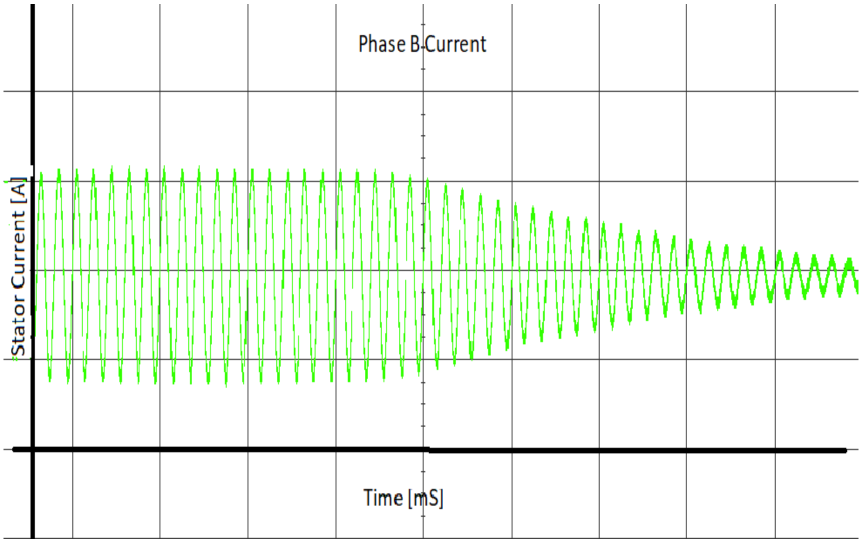

Figure 5-23 Current in phase B

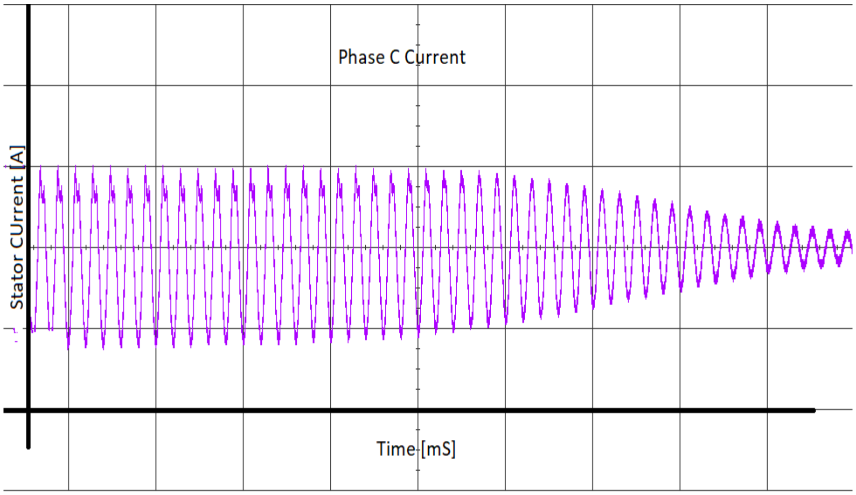

Figure 5-24 Current in phase C

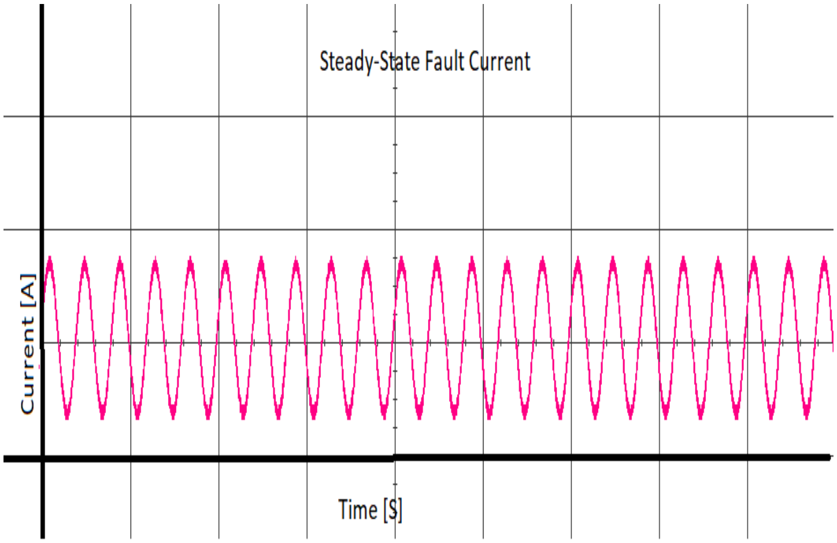

Figure 5-25 Steady-State fault current

Tabulate in table 5-9 is are steady state currents for the motor with four shorted stator turns on phase A, it is evident that the lesser the number of effective turns due to short circuited turns reduces the phase resistance. A further increase in negative sequence current will cause torque and speed pulsation, this pulsation is caused by the magnetic field that is rotating counter clockwise to the direction of the motor at any given time. At rated stator voltage of 220 V per phase, an output power of 19 W is obtained. A further increase in voltage increases the stator current as the motor runs at no load. With a reduced number of effective stator winding turns per phase, creates a path for short circuit due to reduced effective phase resistance evidence in figure 5-25 and reduction in current per phase as reflected in figure 5-22 to figure 5-24. Thermal stress caused by excessive fault current deteriorate the stator winding which creates hot spots that are localized and if not detected these areas of weaker insulation eventually expand to a complete loss of phase.

5.6.4. Six shorted turns

Table 5-10 Induction motor operational parameters with six shorted stator turns

	Current [A]	Voltage [V]	Active Power [W]
Phase A	3.2	220	-
Phase B	2.4	220	-
Phase C	2.6	220	-
Short Circuit loop	6	-	-
Wattmeter 1	-	-	0
Wattmeter 2	-	-	20

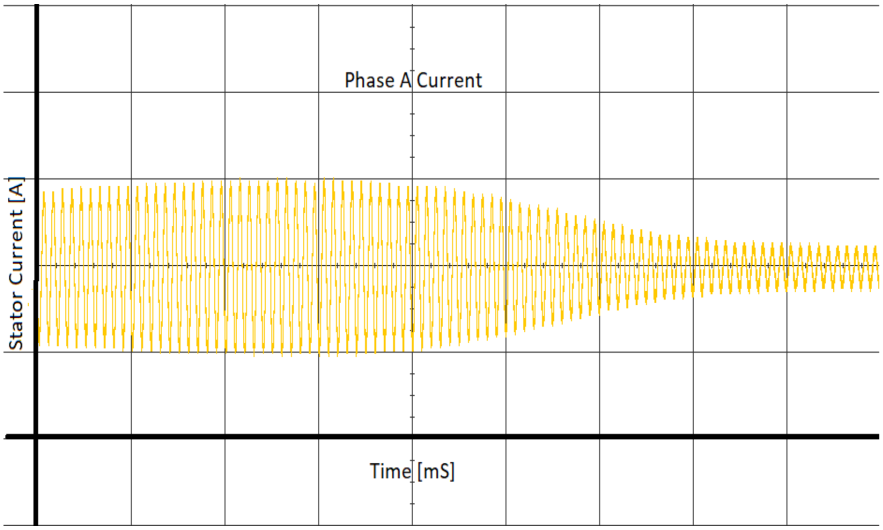

Figure 5-26 Current in phase A

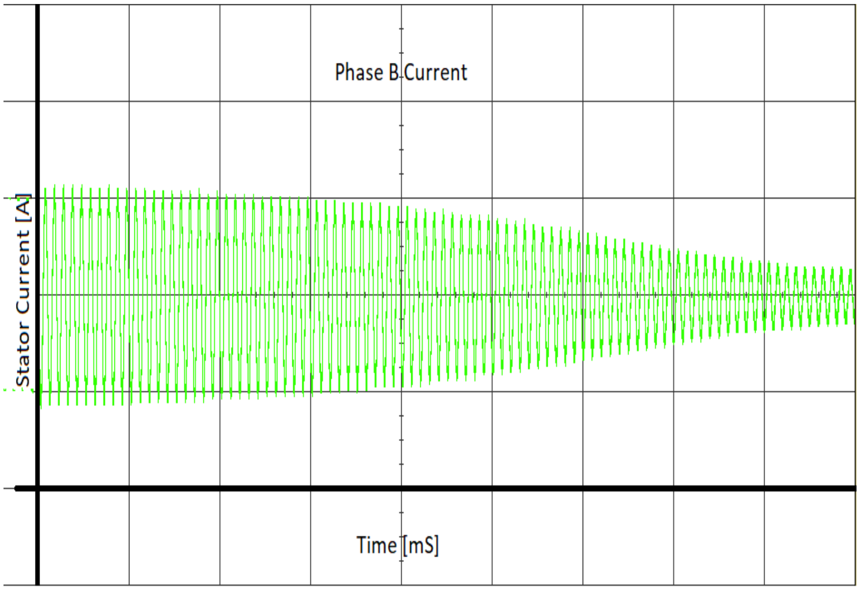

Figure 5-27 Current in phase C

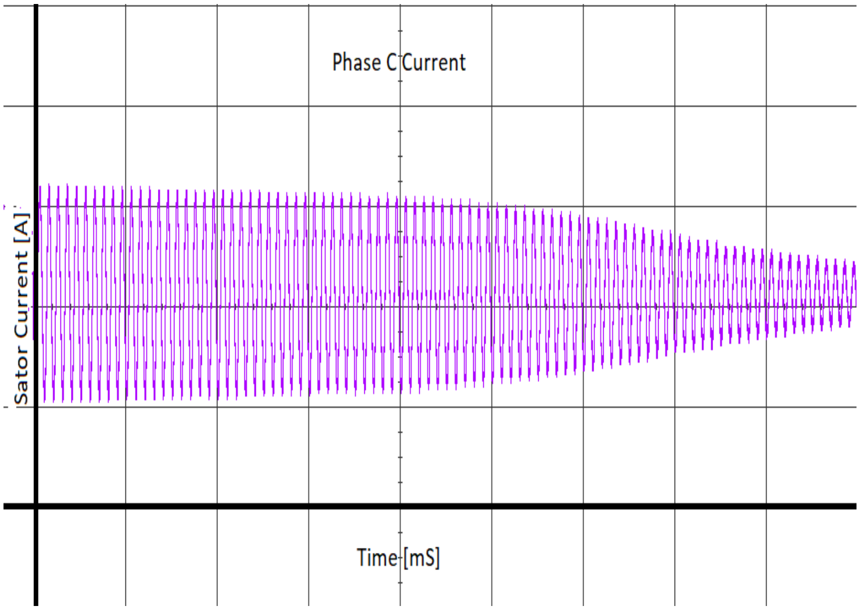

Figure 5-28 Current in phase C

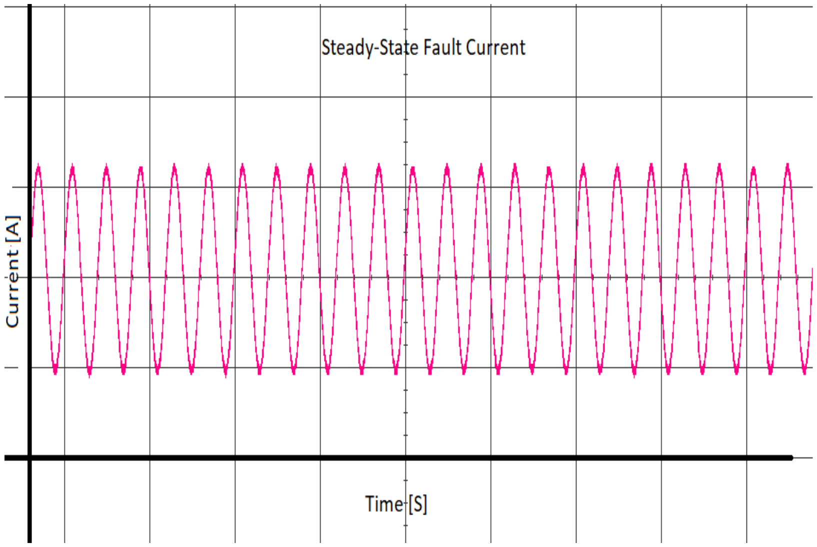

Figure 5-29 Steady-State fault current

The output power delivered by the motor shaft to drive the coupled load is proportional to the supply voltage and the current required by the load. Due to a reduction in resistance, the machine tends to load unbalanced even though it delivers the power but the motor is subjected to puslating torque due to unequal per phase flux created by unbalanced phase currents. , this sudden rise in current increases the thermal stress across the motor stator winding. The impact of the negative sequence current component is evident on the motor rotational speed as it decreases and the vbration spectrum amplitude increases as a direct result of vibration increase. The more the number of shorted turns, the transient current take longer to reach steady state due to unbalance in phase currents, in protection theory the longer the time to settle is intepreted as a fault which triggers a trip and down time. As evident in figure 5-27 to figure 5-28 there is a longer time delay to settle. Figure 5-29 is a sinusodial relationship between number of shorted turns and short circuit current.

5.7. Negative sequence current analysis

The effect of negative sequence current is evident on the machine when the stator fault is prevalent. Under healthy conditions; that is the winding is balanced three-phase with no fault incipient, the negative sequence component of current becomes zero this is because the current in the beta axis is zero. As defined in section three above by equation 3-28 and 3-29, positive sequence current remains maximum being 100% for healthy stator winding while the negative sequence current stays at zero, ignoring the effect of nonidealities in the motor design and manufacturing stage.

Chapter 4 has demonstrated the transformation of mathematical model into a practical model based on a 4-pole induction motor. The method of negative sequence current is sensitive to voltage fluctuations, which is a false signal of stator winding short circuit. Induction motor steady state performance is reliant on the quality of supply; the immunity levels of the supply voltage must be kept close to ideal even through this cannot be achieved due to other loads connected on the point of common coupling in the network.

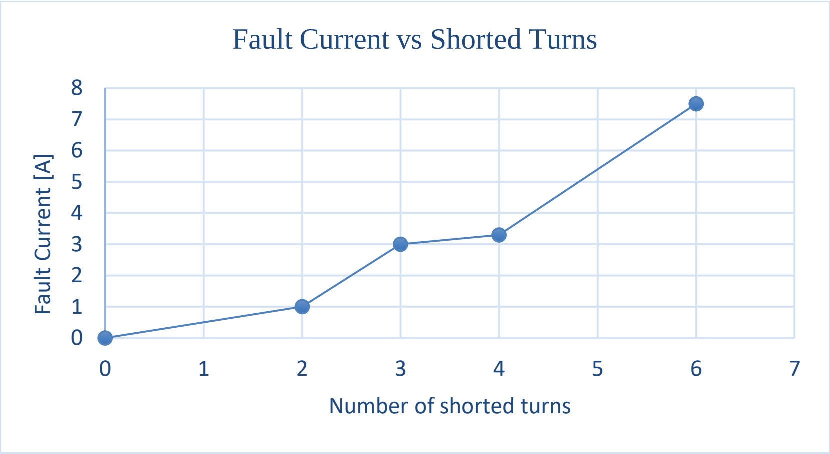

Figure 4-29 Fault current against stator shorted turns plot

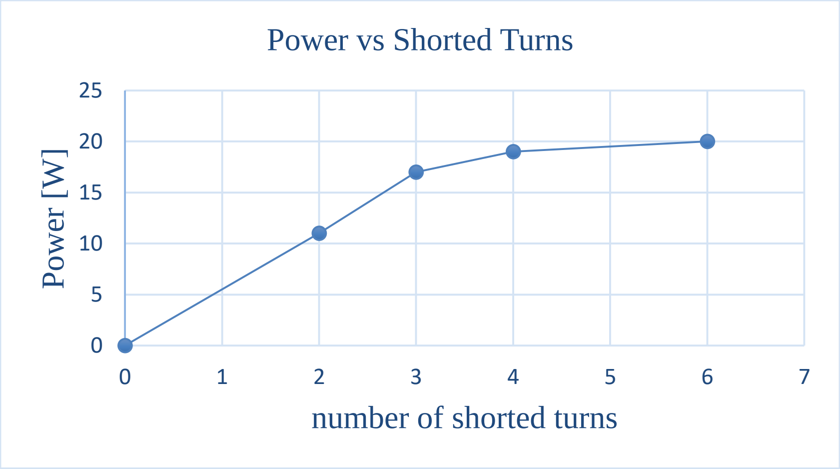

Figure 4-30 Power against shorted turns plot

In a power system, under balanced condition the network is balanced with three-phase voltage supplied to the motor. In the balanced condition, the positive sequence current and positive sequence voltage rotates in the same direction as the network. The negative sequence during balanced condition is zero as there is no component of voltage and current opposing the direction of rotation of the network. As the current drawn by the motor due to the existing stator-winding short circuit becomes unbalance, the overall unbalance factor in current will increase with an increase in the number of shorted turns. This unbalance in current gives rise to a negative sequence current, which produces a flux that cuts the rotor of the motor at twice the rotational velocity of the network, due to high speed of rotation double frequency currents are induced on the rotor surface. Fault current increases with an increase in the number of shorted turns prevalent in the stator winding, as the number of effective turns decreases vast current flows in the shorted loop as in figure 4-30 above.

5.8. Results analysis and discussion

When an induction motor is fed from an unbalance voltage supply as tabulated in table 4-5, negative sequence voltage is induced across the motor stator winding. This induced voltage creates a counter clockwise rotating magnetic flux, which opposes the direction of the main flux, resulting in pulsation in torque and power delivered by the motor shaft to the coupled load. By design, the induction motor can tolerate a certain level of voltage unbalance and if required to operate above the design limit, the motor must be derated to prolong the motor lifespan. Higher voltage unbalance factor caused by a higher degree in voltage unbalance on the supply voltage creates harmonics that are undesirable in the system; the harmonics reduce the motor efficiency due to the harmonic current loss.

As the voltage supplied to the motor deviates from the motor rated voltage, the motor is rated at 220 V maximum allowable voltage for a short duration and suddenly the voltage dip clears back to health condition. The shortly voltage dip creates a back electromotive force in the opposite direction of the supplied voltage; it is out of phase with the three-phase supply voltage. In order for the motor to counteract and cancel the effect of the changing supply voltage the motor will deaccelerate to alter the rotor current which will result in negative torque induction and the rotor speed pulsates because of a negative torque that opposes the driving torque.

During a voltage dip period as seen in table 4-5, while the motor is delivering power to the load and torque that drives the load deviation of voltage gives rise to current spikes to counteract the changing voltage. These current spikes are interpreted and current transients of shorter duration capable of destroying the winding insulation resistance resulting in stator related faults. This motor behaviour is evident when the machine is loaded.

Considering a healthy winding motor, with balanced stator winding exhibiting balanced and consistent winding resistance across all three-phases. With the number of effective stator turns per phase being consistent and equal, the motor will draw a balanced three-phase current as reflected in table 2-2. The negative sequence current component remains at zero due to the balance in current drawn; the negative sequence arises in the event of unbalance in loading of the motor.

Three-phase rotating voltage produces a magnetic field that occupies the air gap between the stator and the rotor. This induced magnetic field rotates at a synchronous speed in the direction at which the rotor rotates. Due to the induced field and the rotor rotating in the same direction at the same rotational velocity, there is no current induced in the rotor by the rotating field as the field maintains a fixed position with respect to the rotor.

An occurrence of a short-circuit condition on the stator winding introduces a phase unbalance in current drawn by the motor per phase. Phase current unbalance produces a change in the negative sequence current, an increase in unbalance factor increases the negative sequence current depending on the number of shorted stator turns or the severity factor of the fault present in the stator. This component, which is negative sequence current, produces a field in the air gap opposite to the rotation of the main magnetic field produced by the supply and that of the rotor.

The induced resulting current path produced by the backwards rotating field offers resistance to the forward rotating current, this results in rapid overheating present in the stator winding causing insulation breakdown. Torque pulsation is evident, as the current becomes unbalance; torque is proportional to the negative sequence current governed by the number of shorted turns as in figure 4-30 that are present causing reduction in effective winding turns, these torque pulsations are transmitted to the stator of the motor.

6. Conclusion

Induction motors are widely used in industrial, commercial and domestic applications due to their smaller frame sizes, robustness and versatility. The advantage of wider speed control over a full range of speeds makes these motors convenient for industrial applications especially in rolling application where variable speed drives work in conjunction with motors. By design, motors are to operate under balanced supply conditions and intact stator winding, without any phase imbalance. Due to the nature of demand and nonlinear loads connected to the commercial network as well as domestic demand, the utility network is always under a strain and this strain produces voltage unbalance.

In this paper an attempt has been made to analyze the induction motor performance and steady state parameter change when the quality of supply changes. The power quality parameters under analysis were

- Under voltage condition
- Over voltage condition
- Voltage unbalance and or single phasing
- Harmonic distortion
- Stator winding short circuit (inter-turn short circuit)

Matlab Simulink model is developed from induction motor mathematical model; for the purpose of simplicity, transformation to a two-axis model was necessary to predict the motor performance. For stator winding short circuit a method of monitoring the magnitude change in negative sequence current is used as a fault indicator.

The dynamic model and steady-state performance of an induction motor is sensitive to supply parameter change, any deviation in voltage, frequency and harmonic content supplied to the motor affects the dynamic model as evident of the above chapters of this paper. Even though the motor can operate and maintain the load under varying supply condition, but these parameters must not drop below the immunity level. If the deviation occurs for extended period, the motor operate in the region of inefficiency and are prone to overheating due to the losses in the stator winding increases, mechanical damages such as premature bearing failures can occur due to excessive vibration caused by rotor speed variation, which is proportional to the supply frequency.

The simulated results and practical results reflected on the above chapters four (4) and chapter five (5) are in agreement with each which outlines that the supply phase shift and unstable quality of supply parameters such as voltage and harmonic distortion causes a reduction in the motor efficiency. As the line voltage supplied to the motor phasors, in mathematical expression form a closed triangle as a function of phase angle. These voltages are displaced by a 120 degrees phase shift out of phase with one another, a deviation in phase angle affects the output power delivered by the shaft, as the power is a product of current drawn and voltage supplied to the motor. Pulsation in torque is caused by a sudden change in power delivered by the motor.

The method of extracting and monitoring a negative sequence current from the unbalance factor arising from the three phase stator currents is an effective method for fault diagnostic and location in the stator winding. For fewer number of shorted turns, lower severity factor the chosen methods becomes inconclusive as the change in negative sequence current is negligible. As the severity factor increases with an increase in the number of stator-shorted turns typically above five shorted turns the chosen method is effective. An increase in shorted turns reduces the number of effective turns per phase, only in the faulty phase and the degree of current unbalance increases, which is evident in an increase in negative sequence current.

6.1. Future work

The chosen method of stator winding short circuit diagnostic is efficient in locating a shorted turn; the negative sequence current is sensitive to a changing voltage. Any deviation in the incoming voltage changes the present value of the negative sequence current and it is interpreted as a short circuit. To improve the proposed method the following needs to be done for future work:

- The model must sense the asymmetry in supply voltage arising from a voltage event and block the false signal that deviates the negative sequence current.
- Consider the effects of unbalance loads that draws unbalance current and the influence of this load pattern on negative sequence current
- Extract real-time values of three phase currents and send a signal to the relay to isolate the motor immediately.

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