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Performance Evaluation of Three Phase Induction Motor in Arbitrary Reference Frame

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ABSTRACT

Steady state analysis technique in line with d-q reference frame was adopted to characterize the behaviour of the three phase induction electric motor for purpose of improved performance. Having identified the problem of low power factor and poor efficiency of the machine under study required better consideration of the operational behaviour of the three phase induction motor. This research presents the analysis and performance of a three phase induction motor with and without the presence of stator core-resistance in the d-q reference model. The parameters of the machine was obtained using experimental simulation application tool computer software, matlab (simulink) was used for the development of the electric motor equations and behaviour for analysis and comparism. The starting currents of the induction motor under investigation is initially large as a results of jerking behaviour of the starting current without the addition of core resistance, giving a poor torque behaviour of 6.8N-m. The three phase induction machine was significantly improved by the addition of core resistance which gives better torque characteristics with 14.9N-m. This means that higher torque was achieved by the insertion of stator-core resistance from 6.8N-m to 14.9N-m which seriously reduced the current and increases the torque characteristics thereby minimizing machine losses that could attract more load consumption for payments of tariff (pay for more Energy consumed) especially in the industrial set-up. Essentially, the setback of the machine parameters including the initial high currents, low power factor and poor efficiency has been remarkably improved in the measurement performance of 0.78% efficiency of the machine which will lead to reduction in energy losses to attract more commercial values and required to do more robust (capacity work). As the torque build up characteristics increase gradually as the value of the stator are resistance was added which also increase in a similar manner.

CHAPTER 1

INTRODUCTION

1.1. Background of Study

The use of three phase induction motor in the industries will continue to increase due to the fact that induction machines are simple and rugged in construction, which gives them an inherently high reliability and robustness. This is why they are widely called the workhouse of industries. Again, the three phase induction motors need only one source of power, hence are self-starting and use no capacitor, start winding, centrifugal switch or other starting device; and they are available in power range from a fraction of a kW to several MWs compared to their single-phase counterparts. They are and are suitable for the vast majority of drive applications involving constant speed, e.g. pumps, fans, compressors, conveyors, rolling mills.

Modern trends and development of speed control methods of induction motors have also foster the increased in the demand of induction motors in electrical drives extensively. (Aspalli *et al* 2014; Vabuderan *et al*, 2015).

The stator of a three phase induction motor consists of poles carrying supply current to induce a magnetic field that penetrates the rotor, when supplied with power. To optimize the distribution of the magnetic field, the windings are distributed in slots around the stator, with the magnetic field having the same number of north and south poles.

For squirrel cage induction motor, the electromagnetic principle is used for its operation. So, when connected to a three-phase voltage supply, the stator winding establishes a steady rotating magnetomotive force (mmf) in the air gap. The speed of rotation of the field or flux is constant and is defined by the supply frequency and the number of machine poles:

The rotating field or air gap flux links the rotor and induces an emf in the rotor circuit. Since the rotor consists of bars or windings, which are short-circuited at the ends, there is current flow driven by the rotor induced electromagnetic force (emf).The rotor current produced field interacts with the stator magnetic field to produce force or torque in such a direction by the Lenz's Law to realized the rate of change of flux linkage, that is, in the same direction as the field: This force on the rotor conductors set the rotor in motion. This simply is how the squirrel-cage motor works.

1.2 Statement of the Problem

There exist in literature several models for the study of three phase induction motor and for the calculation of important quantities of the machine either in these frames for the steady state, dynamic state or transient state analysis. Two main models that are commonly used in the literature are: 1) The per-phase equivalent circuit found in (Chapman, 2012) The dynamic three-phase model found (Krause et al, 2013). The first model is simple, but it cannot work in dynamic conditions neither perform q-d-0-frame transform, which is the basis of many advanced vector control algorithms. The second model does not have the same two issues as the first one, in many literature core loss is commonly ignored in the quadratic-direct-zero (qd0) frame machine models. It is based on this that this proposal is made.

1.3 Aim of the Research

The aim of this research is to carryout performance evaluation of a three phase induction motor in arbitrary reference state, for improved performance

1.4 Objectives of the Research

The specific objectives are:

i. To formulate equation for the calculation of machine quantities such as voltage, torque and power in dynamic mode.

ii. To formulate an equivalent circuit diagram for an induction motor in arbitrary reference state with core losses.

iii. To study the effect of changes in the design parameters on the performance of the motor.

1.5 Scope of the Research

The model of induction motor can effectively be carried out using the reference frames techniques. Induction motor can be modeled by taking one of the generalized arbitrary reference frames, that is the stator reference frame, rotor reference frame, synchronous rotating reference frames. This work will consider and compare implanting synchronous rotating reference frame method. Because the steady nature of this stator d-axis current makes this reference frame useful when a computer is used in simulation and one of advantages of this frame is speed and angular position can be taken into consideration at any instant of time. The mathematical equations of the induction motor involve differential equations that vary with respect to time.

1.6 Significance of the Research Work

The induction machines particularly the squirrel cage machine for example it is simple but robust in construction that is why it is used in all kinds of environments and for long durations of time. Similarly, induction motors have high efficiency of energy conversion, and are very reliable especially for industrial performance therefore, owing to this simplicity nature of construction, induction are considered very useful and good property of low maintenance costs it is relatively cheap compared to DC and Synchronous Motors. Suitable model analyses of this motor is required to make the performance of the electric motor to be more interesting especially in academic and industrial setting as well as commercial uses.

CHAPTER 2

LITERATURE REVIEW

2.1 Extent of Past Work Reviewed

Following the consideration of Yiqi *et al.,* (2017), induction machine models have been used for ages in many industrial and academic fields including machine characterization and model extraction as found in control design, fault detection, power electronics design, loss minimization, and many others. Generally, machines are designed for full-load conditions where the copper loss is dominant

Per half the earliest time-honored model for induction motors in a natural frame of reference and using a multiple coupled circuit approach was published in the famous work by Fudeh and Ong (1983). This model focused on the analysis of space harmonics and their influence on motor transients. In this model, symmetrical machine was assumed. All magnetomotive forces (MMFs) in the machine are represented on the harmonic by harmonic basis - as a sum of fundamental and higher space harmonic components.

Another work by Luo *et al.*, (1995) gave way to the development of this field further, where a major step forward was made. Here, the authors presented an induction motor using winding functions, and modelled this on the basis of a multiple coupled circuit. What is now clear is that their model represents the standard for induction motors modeling, and has done so for the last two decades, notably in relation to, a range of fault conditions and their investigation. The key feature of the model is that it can account for different winding distributions, without the nature of that winding (wound or cage winding) affecting the model. Similarly, the model makes no assumptions about symmetry or the lack of it.

Arbitrary q-d-0-frame model with the core loss have been proposed by Levi (1995), in which it is being expressed directly as parallel resistors in magnetizing branches of d-q equivalent circuits. But the model is proposed for steady-state vector controller design and the model accuracy is not provided.

2.1.1 Machines with two Stator Winding

Consider when 1-0 motor has two stator winding like the stator for a split-phase motor consists of two windings held in place in the slots of a laminated steel core. The two windings consist of insulated coils distributed and connected to make up two windings at 90 electrical degrees apart. One winding is the running winding and the second winding is the starting winding using a capacitor. But the normal 3-phase winding machines are popular and have 3-phase sets of windings. The advantages mentioned above apply to machines with two identical or non-identical stator winding sets. Depending on the rotor the machine maybe synchronous, induction or synchronous reluctance.

Ogunjuyigbe *et al* (2018) Modeled and analyzed a dual stator-winding induction machine using complex vector approach. In this work, complex vector modeling technique is utilized to develop and simulate a dual stator-winding induction machine with squirrel-cage rotor.

2.2 Doubly-Fed Machines

The dual winding machine (Self-cascaded machine) recently christened the brushless doubly-fed machine (BDFM) was introduced by "HUNT" in 1907. In same year "Broadway" presented a paper on self-cascaded machine with a low-speed motor or high frequency brushless alternator.

2.3 Dual Winding Synchronous Reluctance Motor

A reluctance motor is a type of electric motor that induces non-permanent magnetic poles on the ferromagnetic rotor. The rotor does not have any winding. Torque is generated through the phenomenon of magnetic reluctance. There are various types of reluctance motors. Synchronous reluctance, variable, reluctance, switched reluctance, variable reluctance stepping. Reluctance, motors can deliver high power density at low cost, making them ideal for many applications.

The disadvantages are high torque ripples i.e. the difference between maximum and minimum torque during one revolution. Until the early twenty-first century their use was limit by the complexity of designing and controlling them. These challenges are being overcome by advances in the theory, by the use of sophisticated computer design tools.

2.4 Dual Winding Synchronous Motor

A synchronous motor is an AC motor, at steady state, rotation of the shaft is synchronized with the frequency of the supply current, the rotation period is exactly equal to an integral number of AC cycles. Synchronous motors contain multiple AC electromagnets on the stator of the motor that create a magnetic field which rotates in time with the oscillation of the line current. The rotor with permanent magnets or electromagnets turns in step, with the stator field at the same rate, provide the second synchronized rotating magnetic field of any AC motor.

CHAPTER 3

MATERIALS AND METHOD

3.1 Material Considered

The analysis of this research work considered the basic procedure in different stages such as model development and simulation. Simulation will be conducted using MATLAB/Simulink software for machine study based on the formulate equations. The model equation for the MATLAB program shall be based on analytical approach.

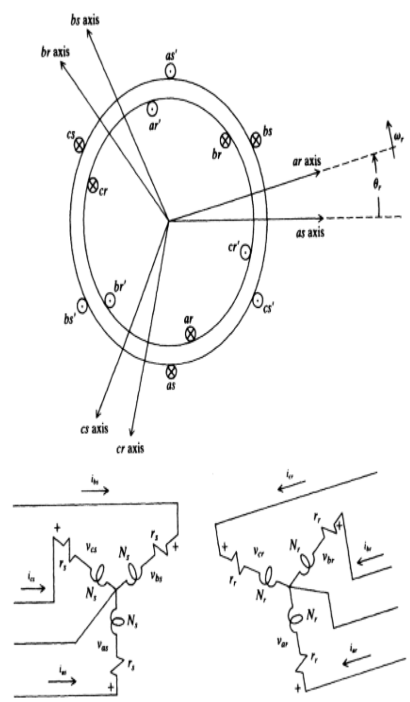

Figure 3.1: Induction motor winding pattern in d-q reference frame

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3.2 Voltage Equation in ABC Frame

The representation of electric machine variable given as:

$$\left.\begin{aligned} V_{as} &= i_{as} r + \frac{d}{dt}\lambda_{as} \\ V_{bs} &= i_{bs} r + \frac{d}{dt}\lambda_{bs} \\ Vcs &= i_{cs} r + \frac{d}{dt}\lambda_{cs} \end{aligned}\right\} \qquad (3.1)$$

The Rotor Voltage equation can be written as (3.2):

$$\left.\begin{aligned} V_{ar} &= i_{ar} r + \frac{d}{dt}\lambda_{ar} \\ V_{br} &= i_{br} r + \frac{d}{dt}\lambda_{br} \\ V_{cr} &= i_{cr} r + \frac{d}{dt}\lambda_{cr} \end{aligned}\right\} \qquad (3.2)$$

The mathematical representations of flux lingages in rotor as stator winding are given as:

$$\begin{bmatrix} \lambda_S^{ABC} \\ \lambda_R^{ABC} \end{bmatrix} = \begin{bmatrix} L_{ss}^{abc} & L_{sr}^{abc} \\ L_{rs}^{abc} & L_{rr}^{abc} \end{bmatrix} \begin{bmatrix} i_s^{abc} \\ i_r^{abc} \end{bmatrix} \qquad (3.3)$$

Where the parameters of the reference frame are given as;

$$\left.\begin{aligned} \lambda_s^{abc} &= (\lambda_{as'}\ \lambda_{bs'}\lambda_{cs})t \\ \lambda_r^{abc} &= (\lambda_{ar'}\ \lambda_{br'}\lambda_{cr})t \\ i_s^{abc} &= \left(i_{as'}i_{bs'}i_{cs}\right)t \\ i_r^{abc} &= \left(i_{ar'}i_{br'}i_{cr}\right)t \end{aligned}\right\} \qquad (3.4)$$

For an idealized machine, six (6), first –order differential equation are used to describe the system machine operation, through self and mutual inductances. The varying inductances are transformed into differential equations with constant coefficient with reference to q-d-0 transformation.

3.3 Proposed Machine (Motor) Technique

The representation of figure 3.2 shows the winding pattern of the proposed machine (induction motor). The analysis is on dynamic three (3) – phase machine performed in d-q frame with the idea of core loss connected in parallel in addition to stator resistance at the same time..

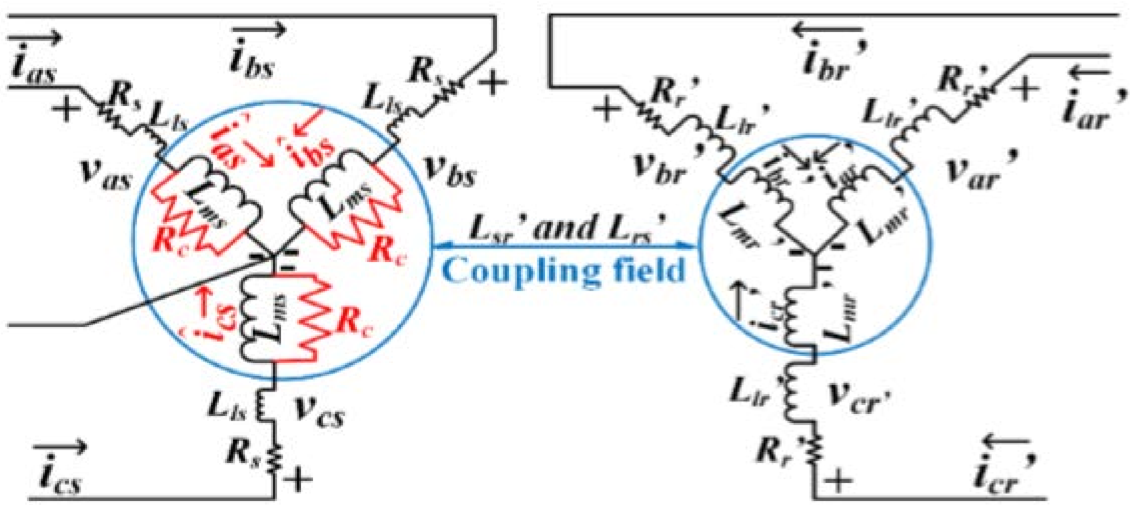

Figure 3.2: Winding arrangement of the Proposed Induction Machine

3.4 Model of the Machine in Arbitrary Q-D-0 Reference Frame

Table 3.1: Induction Machine parameters for Analysis

Parameters	Values
Phase Voltage(V_s)	220V

Stator Resistance(R_s)	74.02Ω
Rotor Resistance(R_r)	62.01Ω
Core Resistance (R_c)	0.6482Ω
Stator Leakage Inductance (L_{ls})	0.2084H
Rotor Leakage Inductance (L_{lr})	0.2084H
Magnetizing Inductance(L_{ms})	3.3477H
Number of poles	4
Frequency	50Hz
Friction coefficient(B_m)	0.0000N-m .s/rad
Moment of Initial(J_m)	0.0025N-m .s^2/rad

Source: Research desk, study case under investigation

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Three-phase Induction Motor Simulated and Analysis

The analysis discusses the results obtained from the three-phase induction motor using MATLAB/Simulink. The results obtained from an induction motor without the core resistance included. Inclusions are presented.

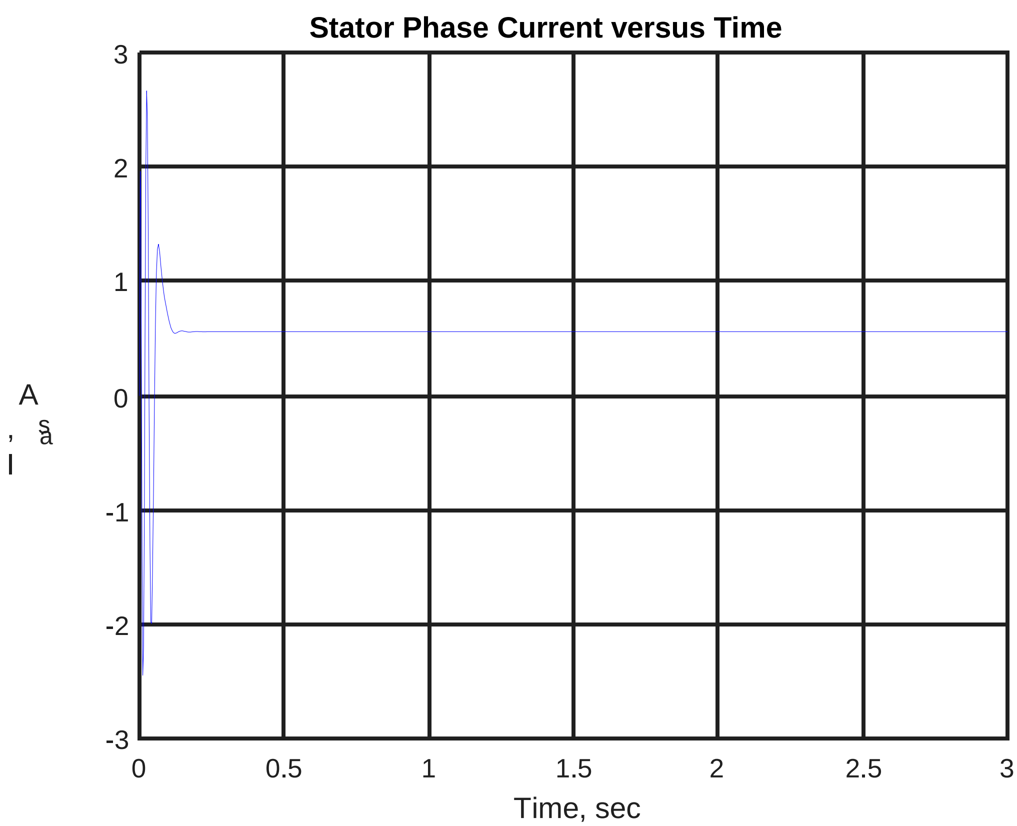

Figure 4.1: Shows the relationship between the stator and Time with the consideration of three-phase motor without stator core resistance.

4.2 Stator D-Q Axis Current Results without Core Resistance

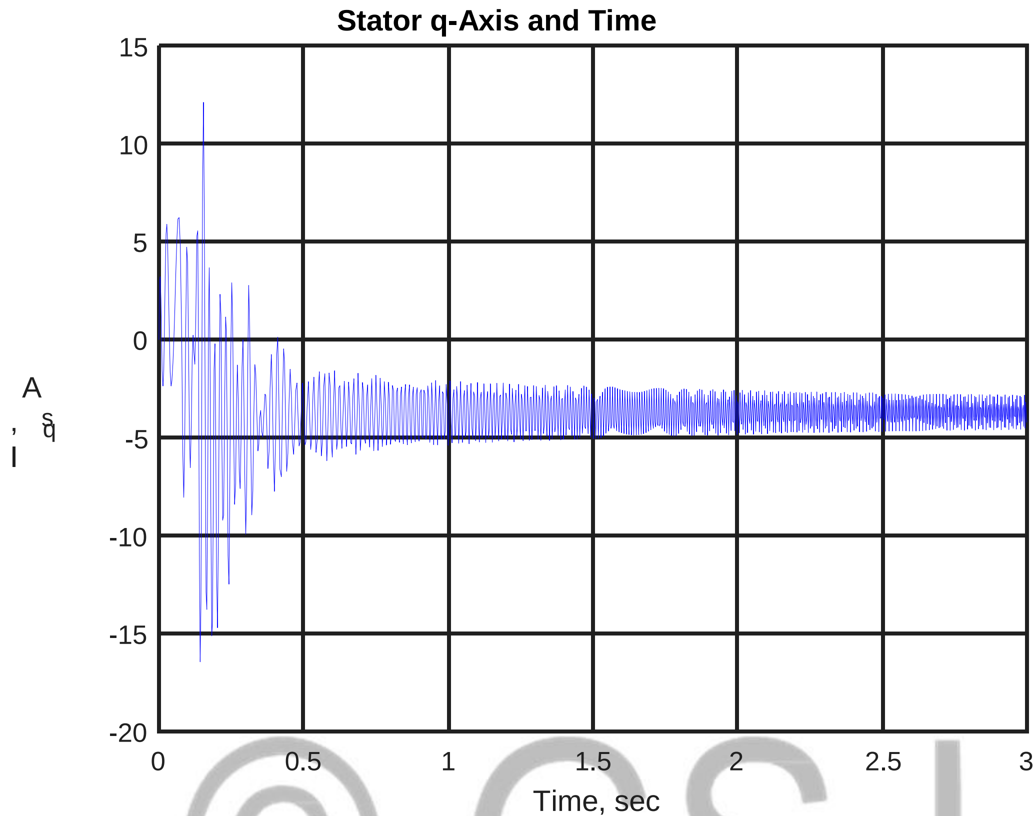

Figure 4.2: The Stator Current Arrangement in Time without Core Resistance

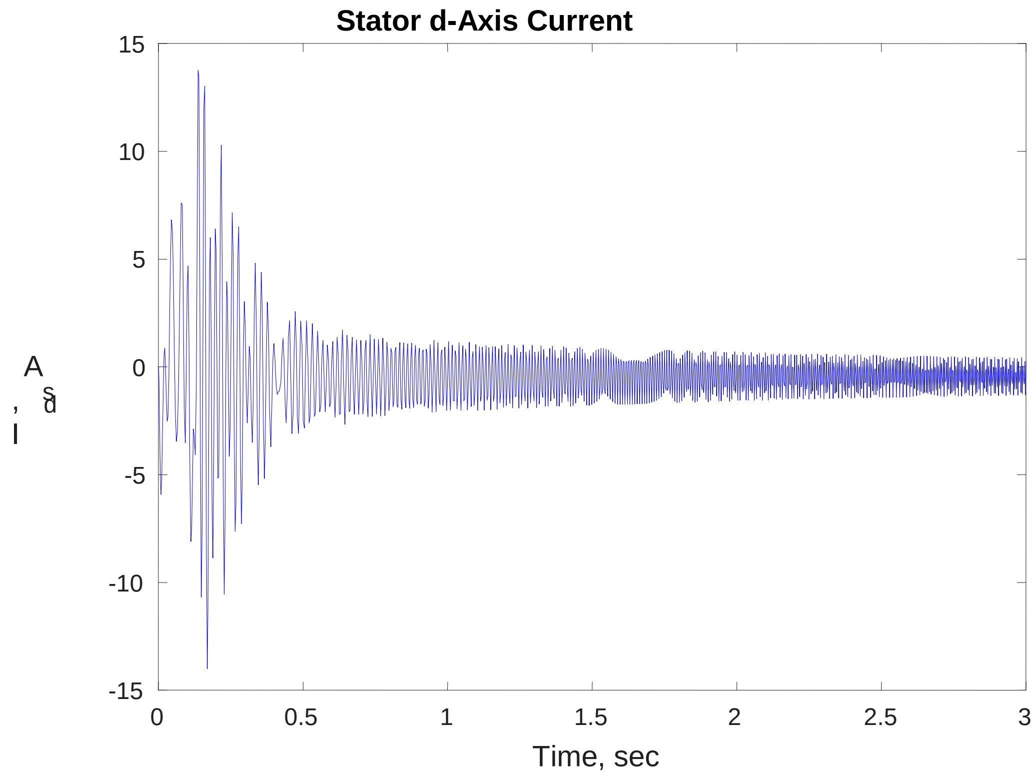

Figure 4.3: The Stator d-q Axis Current without Core Resistance

4.2.1. Rotor D-Q Current Results without Core Resistance

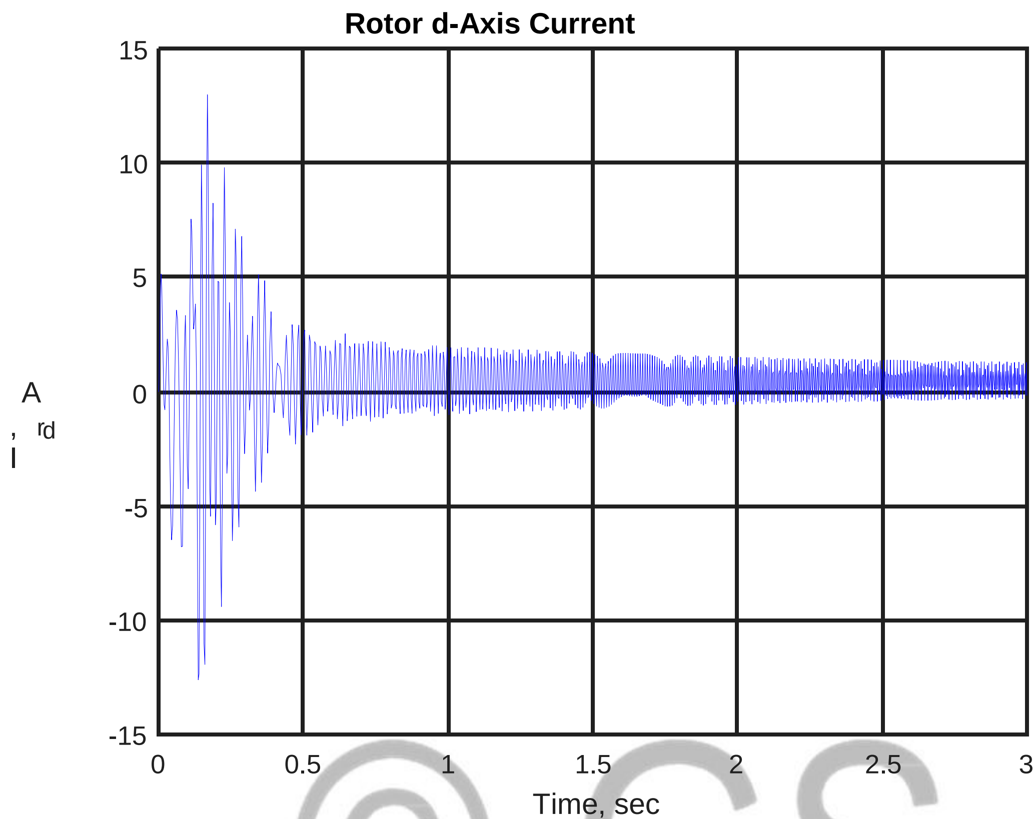

Figure 4.4: The Stator d-q-axis Current without Core Resistance

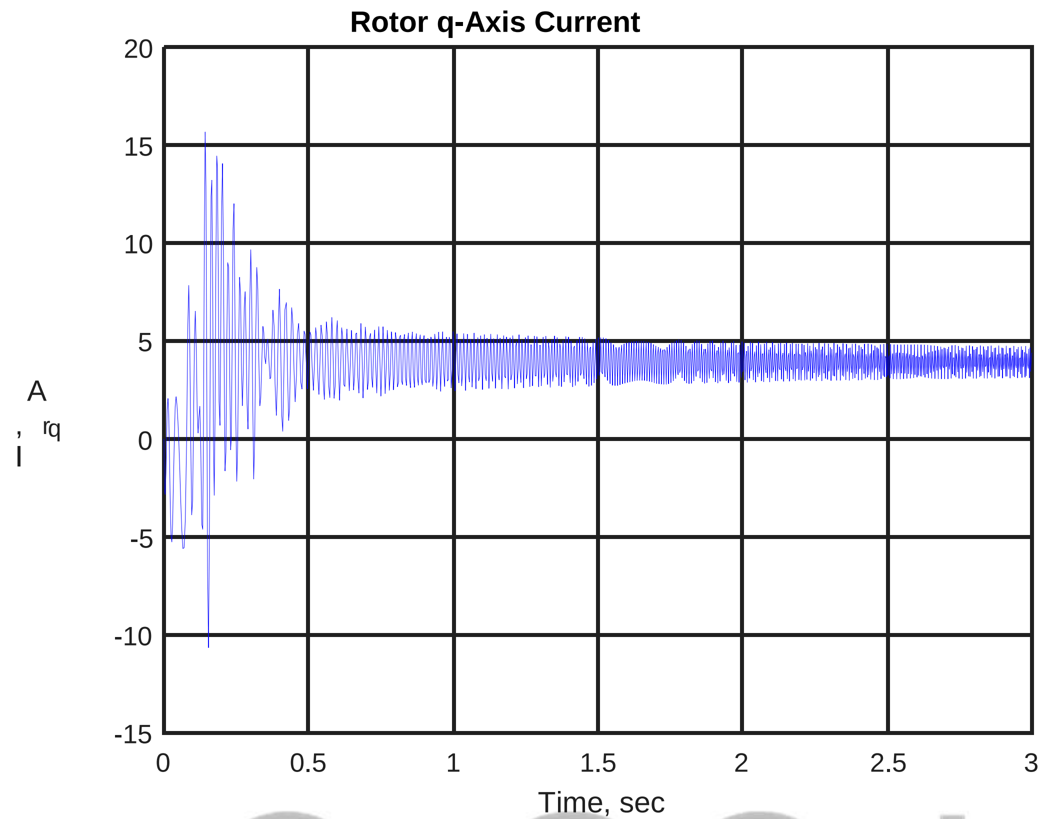

Figure 4.5: Three-Phase Rotor d-q Current of Induction Motor with Stator-Core Resistance Addition

4.2.2. Electromagnetic Torque Results without Core Resistance

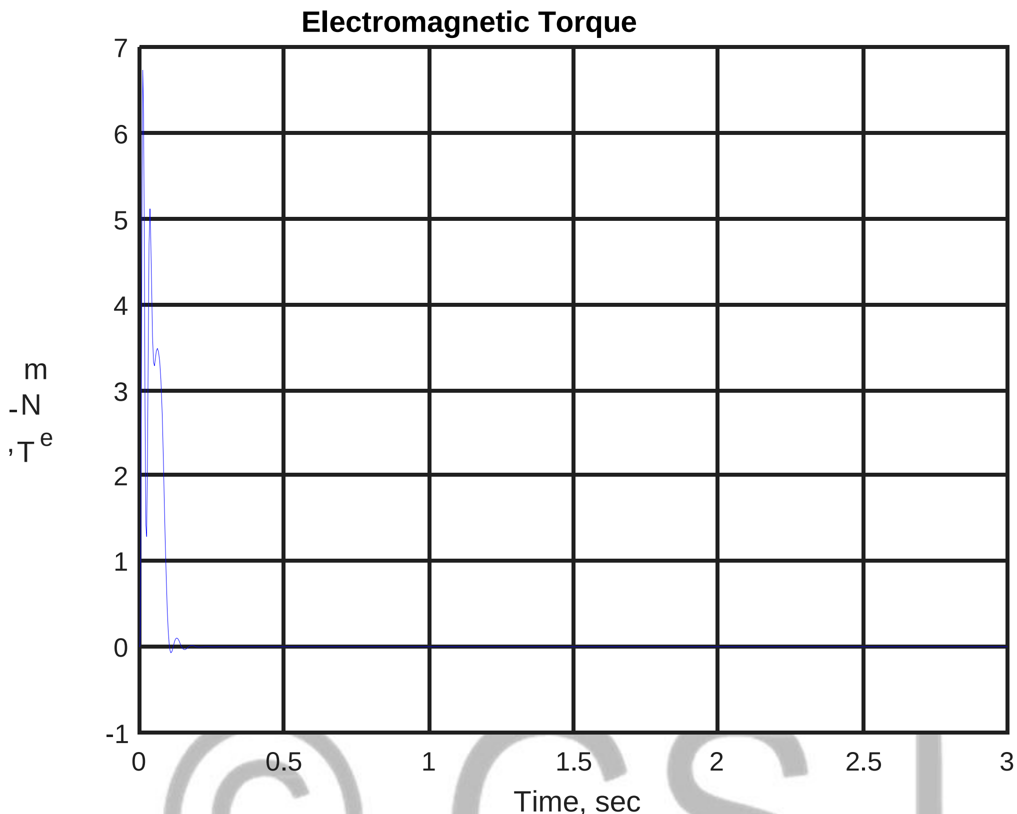

Figure 4.6: The behaviour of electromagnetic torque under no load condition.

4.2.3. Motor Speed Results without Core Resistance

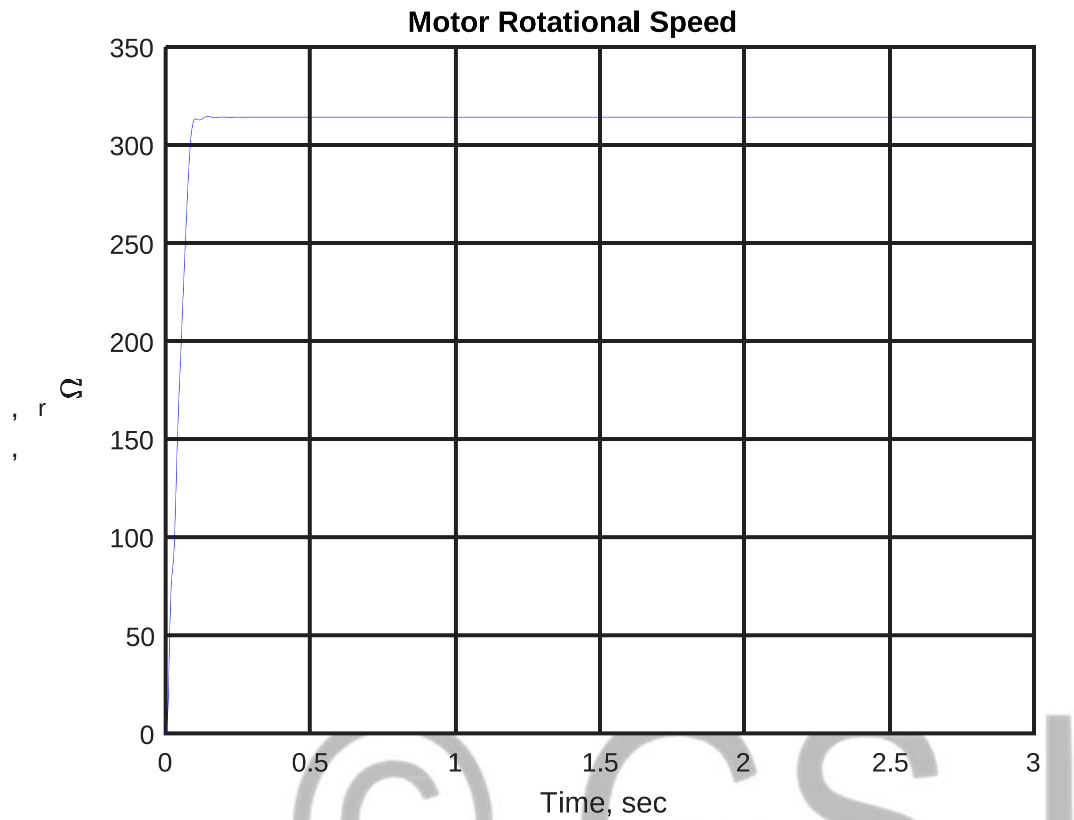

Figure 4.7: Motor Rotational Speed, with time, sec

4.3 Results and Discussion of the Induction Motor with Core Resistance

In section 4.2, we made analysis of the performance of a three phase induction motor without core resistance. In this arrangement, it is assumed that there is no core loss; hence the motor is in ideal state. However, in reality there is no ideal or perfect machine. Hence, in this section, we will attempt to evaluate the performance of the motor when core resistance is added or included in the circuit.

4.3.1. Stator Phase Current Results with Core Resistance

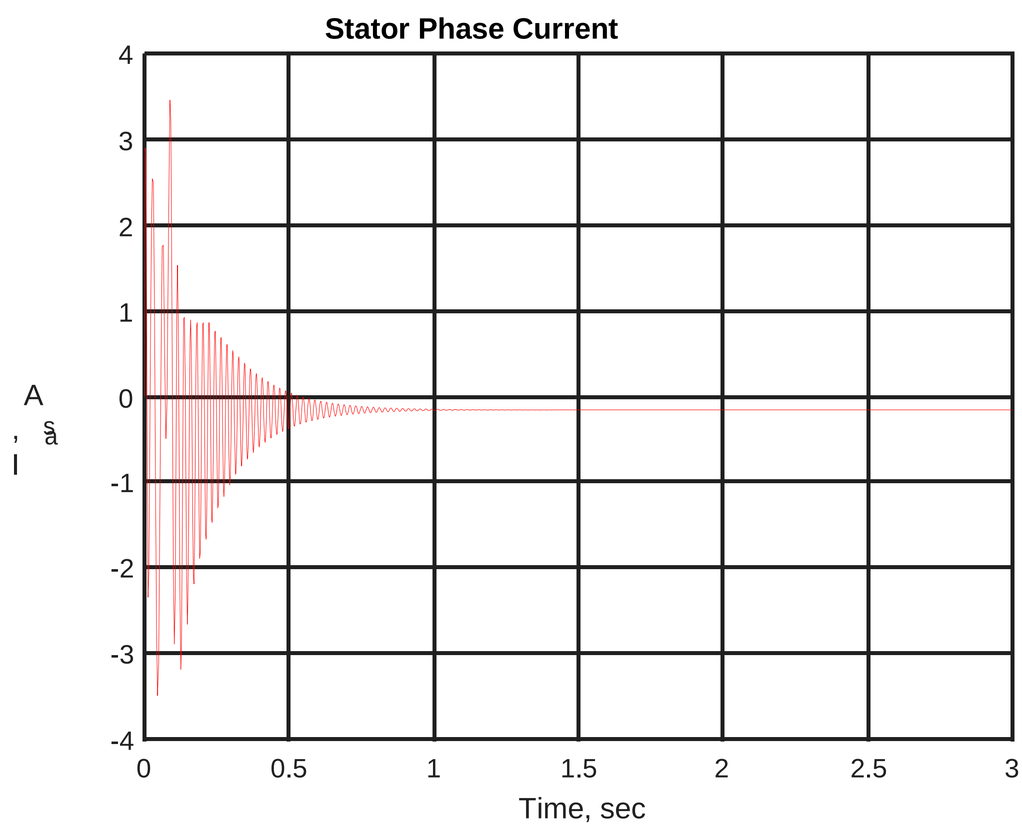

Figure 4.8: The Stator phase current with core resistance.

The three-phase stator current of the three phase electric motor with core resistance of stator was added which is illustrated in Figure 4.8 in-phase variable. As illustrated for phase A, the motor stator current rose from 0amps to the peak of 3.6amp when the motor started. Again, the stator current for phase B and C can also be shown by displacing the angle by 2π/3. Here, unlike the motor without core resistance, the transient was seen from 0 to 1 seconds before the motor moved to a steady state mode. Again, the initial rise in stator shows the behaviour which has draws high starting current. The graph result also shows current saturation as a result of inclusion of core resistance.

4.3.2. Stator D-Q Current Results with Core Resistance

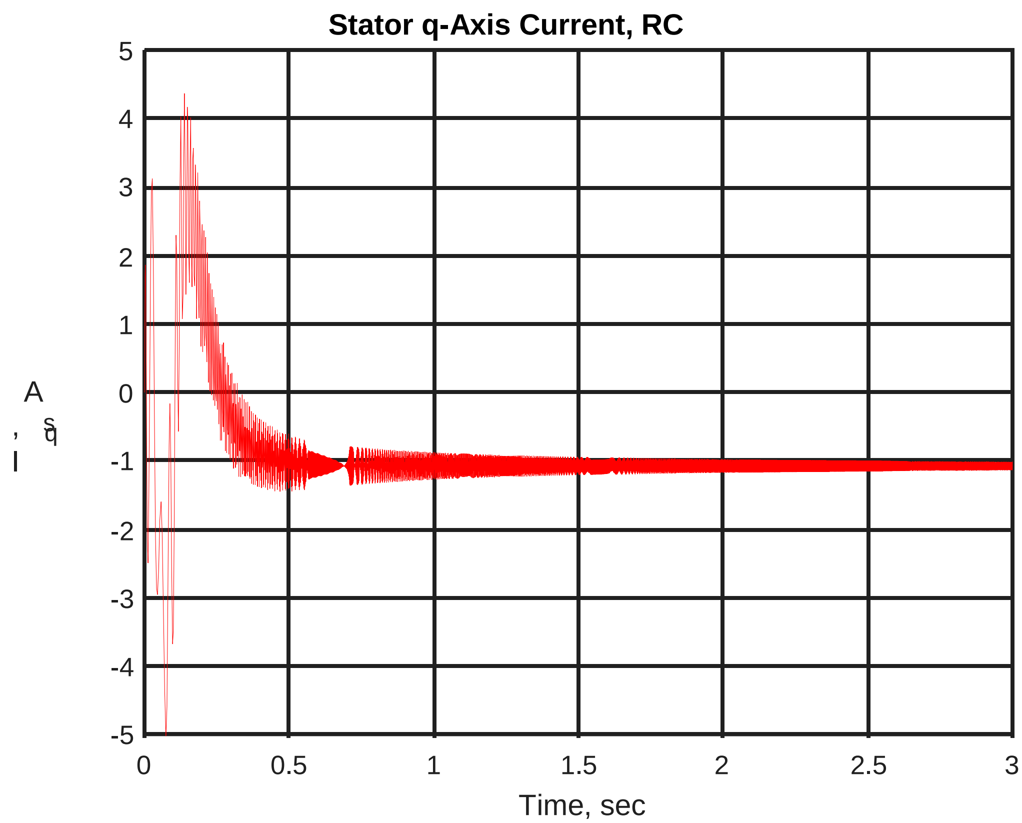

Figure 4.9: The characteristics of stator q-axis current and time, sec

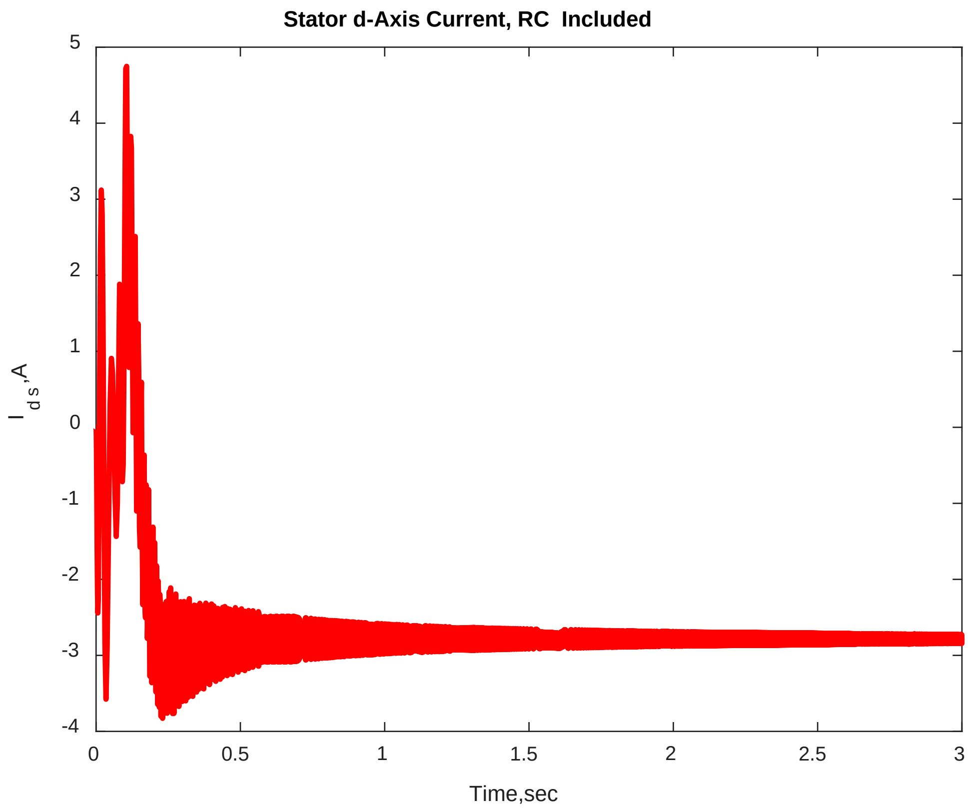

Figure 4.10: the repreentation of three-phase stator induction with addition of stator core resistance

The d-q axis of stator variable of three phase induction motor with the stator core resistance neglected is illustrated in the analysis of the graphs illustrates the behaviour of the motor current in stator q-axis. The motor stator q-axis current rose from 0amps to the peak value of 4.8amp when the motor started. Unlike the motor without the presence of core resistance, the transient lasted beyond 0.5 seconds. However, due to the presence of core resistance, the peak current value reduced from 12amps to 4.8amps. In Figure 4.10, the stator d-axis current was illustrated as well. The current rose from 0amps to a peak value of 4.9amps on start. Again, transient was also seen to be beyond 0.5 seconds.

4.3.3. Rotor D-Q Current Results with Core Resistance

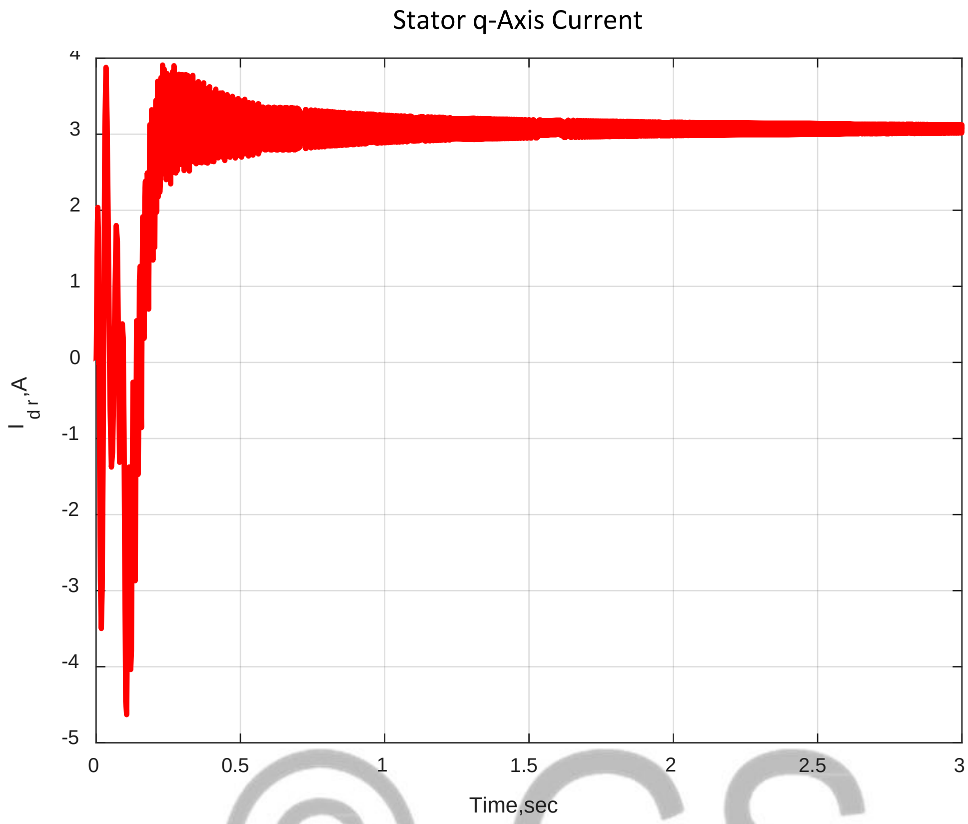

Figure 4.11: Rotor d-q current with core resistance

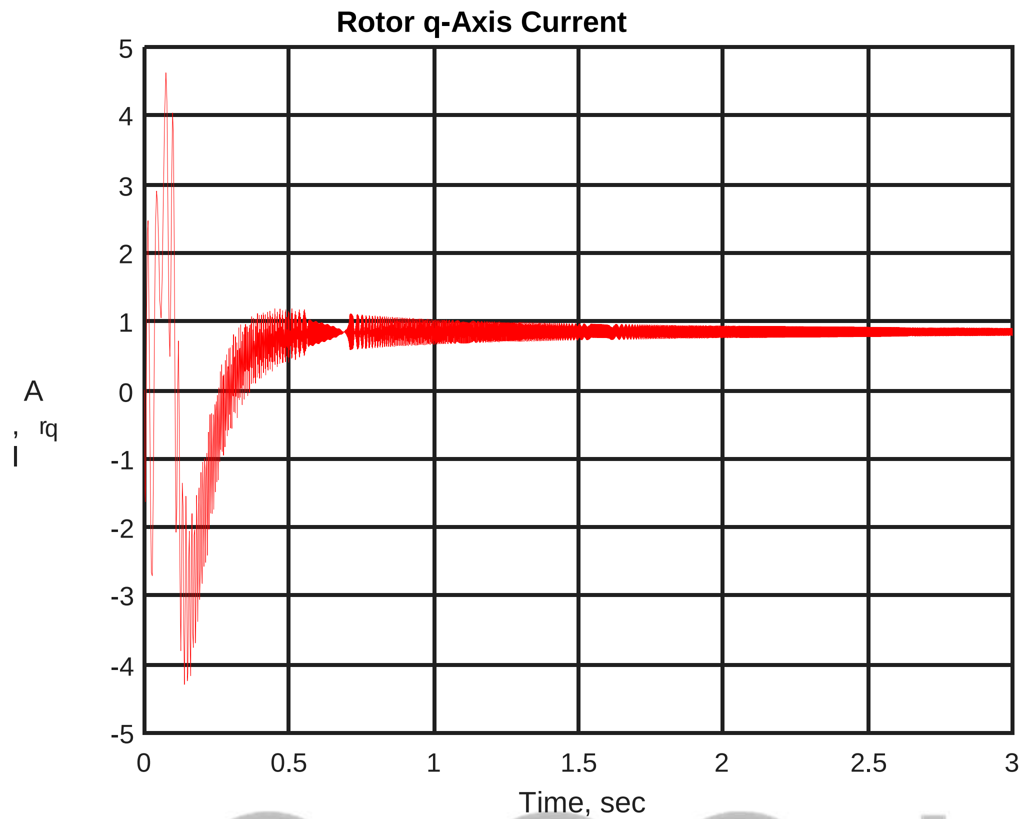

Figure 4.12: The relationship between rotor d-q with core resistance current of core resistance.

The d-q rotor current three phase motor presence the core resistance illustrated in Figure 4.11. As illustrated for the stator d-q current, the motor rotor q-axis current rose from 0amps to 3.9amps when the motor started. The reduction in the peak value of the current as a result of the presence of core resistance. A little transient was seen from 0 to 0.5 seconds before the motor moved to a steady state mode was also seen. Again, the initial rise in the current shows the behaviour of an induction motor, which has draws high starting current. The same characteristic is displayed for the q-axis rotor current in Figure 3.12. Here, the peak current value increased to 4.9amps and the motor gained steady state after 0.5 seconds.

4.3.4. Electromagnetic Torque Results with Core Resistance

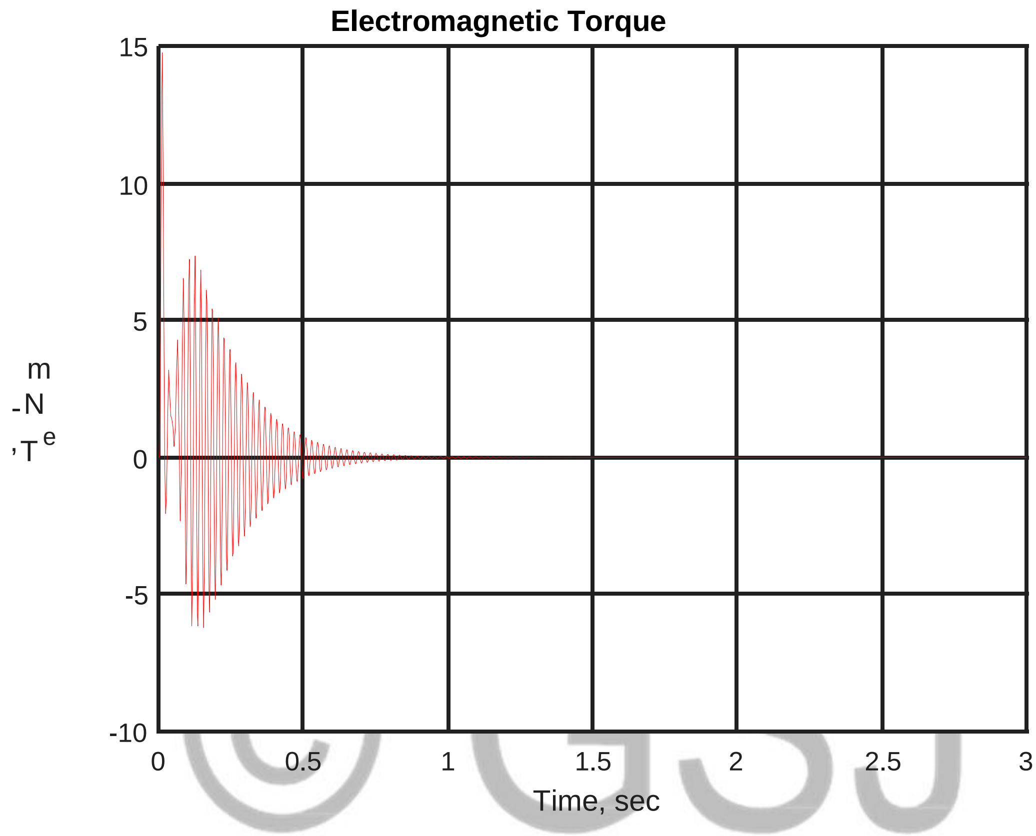

Figure 4.13: The electromagnetic Torque with core resistance

Figure 4.13 describe the behaviour of torque due electromagnetic produced in the case of torque senario and inclusion of core resistance, the motor starting torque to be about 14.9N-m. This value was unstable and reducing until 1 second before the motor reached its steady state condition. With the insertion core resistance stator, the current is seen to have reduced, hence, increased in the starting torque.

4.3.5. Motor Speed Results with Core Resistance

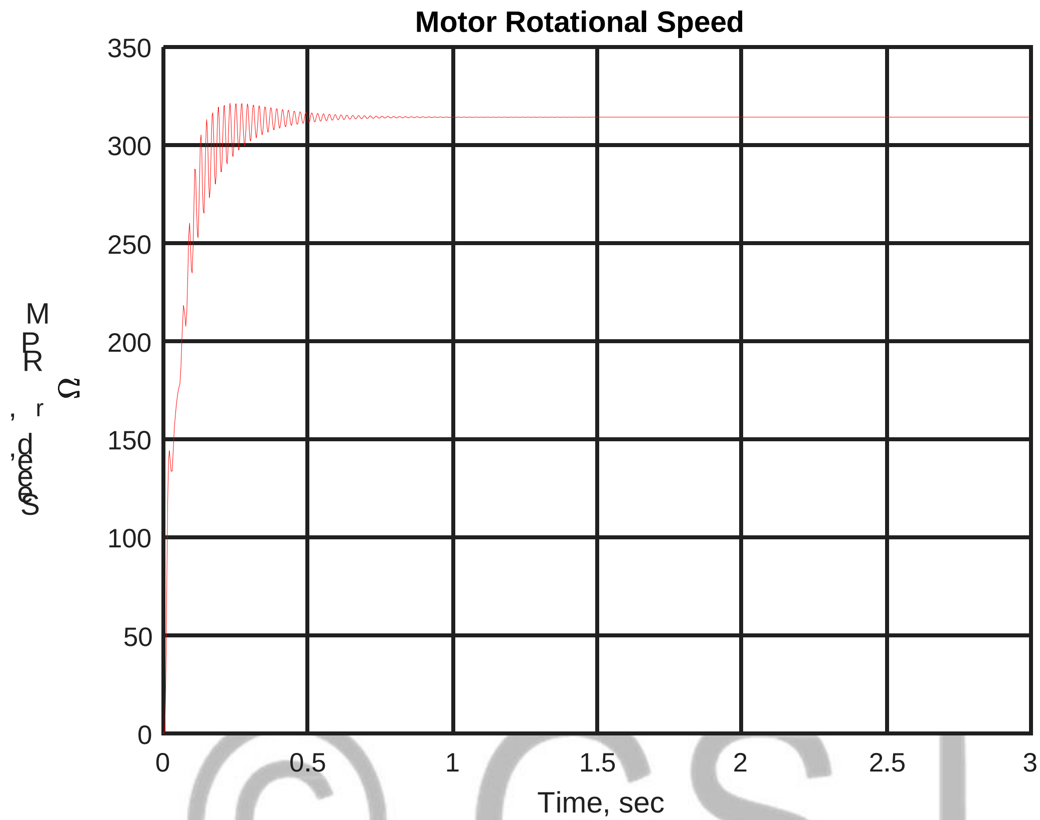

Figure 4.14: Motor rotational speed with time, sec

The run-up speed under this condition is illustrated in Figure 4.14.The speed did rise or takes the normal induction motor speed by attaining to the full synchronous speed at 330 rpm, from 0.3seconds. However, a lot of jerking was seen at the start of the motor. The motor speed developed did take the shape of the starting procedure of a normal induction motor started on-line. The effect in the steady condition was minimal and there was no significant impact the fluctuations in the transient period were much. But then, with this setting, the maximum torque can also occur at a higher speed.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The analysis behaviour of the machine at steady state condition was based on mechanical property. Machine at steady state was based on mechanical property. The characteristic of the machine gives relation between steady state values of the electro-magnetic torque and the rotor speed. The characteristic is dependent on the frequency and of the stator voltage. Therefore any changes in stator voltage will effects the mechanical characteristics. The analysis and performance of three phase motor particularly induction machine with and without the addition of core resistance in the stator was considered in this study case under investigation without stator core resistance. A d-q equivalent circuit of the machine understudy was formulated and simulated using a matrix-laboratory (MATLAB) this was achieved using the machine d-q reference frame technique. The machine input data were used and implemented into formulated machine variable for the study under investigation. The machine operates smoothly when the core resistance was neglected (when operated on ideal case). Similarly when the core resistance is inserted on the stator unit of the motor, there was transient that is jerking behaviour which took longer time to attain system stability. The technique used characterised the voltage, current equation and torque expression which were used for the MATLAB simulations.

Essentially the reactive power, (capacitor) injected in the system shows improvement in the performance characteristics of the 3-phae induction machine

5.2 Contribution to Knowledge

The major contribution to knowledge is the modification carried out by the addition of core resistance (R-c) on the view to improve the peak current value of the induction motor which reduces current behaviour in the start-up condition, although the transient behaviour lasted for about 0.6 seconds. Similarly, the starting torque of the motor with addition core resistance gained improved from 6.8 N-m to 14.9 N-m.

Essentially, high torque characteristics of the motor which was achieved by the insertion of core resistance which evidently reduces the current and increases the torque characteristics, while the steady state time and initial jerking behaviour with addition of stator core resistance remain unchanged. Therefore the machine performance characteristics of power factor and efficiency were utilized.

5.3 Recommendation

This includes the following;

(i) Consideration of multi-phase induction machine should be the centre of focus because of its high flexibility and purpose in the industry.

(ii) Modified induction motor with high efficiency, high power factor are recommended to optimize for power saving.

(iii) Additions of auxiliary winding connected with a balanced capacitor are considered to improve low efficiency in the induction motor.

(iv) The incidence of high starting current experience by conventional three-phase induction motor can be reduced by reactive power compensation or injection.

(v) Machine steady and transient behaviour most always be model characterized before simulation to predicts machine behaviour in order to avoid sudden system collapse.

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