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Stability Analysis of a Three-Phase Induction Motor under Asymmetrical Fault Conditions Using FEA Simulations

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ABSTRACT: - This paper presents stability analysis of asymmetrical stator faults in electric motors. The study was carried out using Finite Element Analysis solver. The motor was simulated for 2 cases; healthy motor and motor with asymmetrical fault. Asymmetrical fault occurred at 0.4s and lasted for 0.2s after which the motor later regained stability. The graphics of the torque showed that the loaded motor oscillates around 315.2 Nm when the fault occurred and settled at 20 Nm after 0.6s. It was also observed that the speed dropped slightly and oscillates around 1420 rpm after 0.2s when load was connected and went into generating mode immediately asymmetrical fault occurred and regained stability after 0.6s while the speed of the unloaded motor remained unchanged. The phase currents of the loaded motor increased to 14.1690 A at 0.2s and further increased to about 141.2 A as a result of asymmetrical fault at 0.4s and later maintained a steady state stability of 14.1690 A after 0.6s when the fault was removed. The magnetic saturation areas were observed in both cases.

KEYWORDS: Asymmetrical faults, FEA Simulations, Loading conditions, Stability, , Three-phase induction motor.

I. INTRODUCTION

The investigation of stability is one of the major scientific and technological problems in the design of electrical machines. By the stability of a machine we mean the ability of the machine to re-establish a steady-state mode after disturbances of the initial mode, for example; changes of the external load, changes of supply voltage, etc. The process of pull into synchronism of the machine after asynchronous start-up is also a property of stability of the machine.

Induction motors (IM) are widely used in small and large industries, such as electric power stations, oil refiners, and factories. Product lines will be stopped if these motors fail to operate. In addition to the disturbance of their operation, IM faults shorten their life-time. So, analysis of the faults is important from performance improvement and longer life-time points of view. The asymmetrical faults of IM account for more than 70% in proportion of IM failures. In fact, a more precise model of the machine is necessary for an accurate stability analysis of the machine behavior in both healthy and faulty cases [1]. A detailed analysis of short circuit faults requires a precise model. The models of the induction machine, such as the multi winding model, multi-turns and the model of Park [2] are not practical to make changes in the electrical stator and rotor. They represent the electrical behavior of the equivalent induction machine. They do not take into account the electric or magnetic phenomena such as induced currents, magnetic saturation and the effect of complex geometry. Asymmetrical faults cause a large circulating fault current in the motor leading to localized thermal overloading. This one can cause open-circuit failures (melting of conductors), short circuit faults (insulation damage) in the electrical circuit, and electrical fire.

In this paper, the transient analysis was done using 2D finite element electromagnetic field analysis. The designed geometric dimension is modeled using Maxwell2D solver. FEA approach can be successfully used because it takes into account the non-linearity of the magnetic material being suitable for a detailed study of the IM behavior with faults. The use of simulation tools helps the researchers to emphasis the effects caused by faults in an electrical machine and to develop efficient fault detection methods [3], [4].

Using FEA, the changes in electric, magnetic and mechanic behavior of the machine due to any fault can be easily observed without the need of opening the machine, or experimenting in laboratories. The main idea is to understand the electric, magnetic and mechanical behavior of the machine in its healthy state and under asymmetrical fault conditions [5].

The magnetic fields distribution, the torque and the winding characteristics of the IM are presented. The simulation results of the IM using the FEM analysis will be presented, both in the case of healthy and faulty condition.

1.1 Stator Asymmetry

According to the surveys [6], the majority of failure related to a motor stator is breakdown of the turn-to-turn insulation. Although the induction motor can still run when some of the turns are shorted, they can consequently lead to damages on adjacent coils and a stator core, so that a ground fault can occur. To reduce repairing costs and outage time due to the stator winding fault, the early detection of inter-turn short circuit is useful [7].

1.2 Causes of Asymmetrical Fault

There are many reasons that can cause the degradation on the stator insulation. The causes can be summarized as [8], [9];

1. Thermal stresses due to thermal ageing and thermal overloading: For the thermal ageing, it is a result from the operating temperature. As known, the insulation life gets half for every 10o k increase in temperature. To cope with the thermal ageing due to the temperature in the windings, reducing the operating temperature or increasing the class of insulation materials can be applied. Thermal overloading can be caused by the applied voltage variations, unbalanced phase voltage, cycling overloading, obstructed ventilation, higher ambient temperature, etc. All of these can increase the temperature and can initiate the thermal stress in the machine.
2. Electrical stresses due to voltage stresses in the windings: The voltage stress in the windings can be caused by having a void in the insulation, which can cause the partial discharge. In addition, the surge on electrical supply system can initiate the voltage stresses in the windings as well.
3. Mechanical Stresses: These stresses might be due to coil movement, which is a result from the force inside the machine, and rotor striking the stator, which is caused from many reasons, such as bearing failures, shaft deflection, rotor-tostator misalignment, etc.
4. Environmental stresses/Contamination: the winding insulation can be deteriorated by chemicals, such as oil, moisture or dirt, etc.
5. Ageing: the winding insulation can be degraded by time.

II. MATERIALS AND METHODS

2.1 Finite Element Method (FEM)

FEM is a computer based numerical technique for calculating the parameters of electromagnetic devices. It can be used to calculate the flux density, flux linkages, inductance, torque; induced emf etc., in the FEM, the large electromagnetic device is broken down into many small elements [10]. The behavior of an individual element can be described with a relatively simple set of equations. The computer can solve this large set of simultaneous equations. From the solution, the computer extracts the behavior of the individual elements. The FEM provides detailed information about the machine nonlinear effects (based on its geometry and material properties). This modeling approach is capable of obtaining an accurate and complete description of an electrical machine [11]. The magnetic circuit is modeled by a mesh of small elements. The field values are then assumed to be a simple function of position within these elements, enabling interpolation of results. The time required to calculate the field distribution may be very long, depending on the number of elements considered. A compromise must be reached between using finer meshes to achieve higher accuracy and the processing resources needed to achieve reasonable simulation times. The FEM is very flexible, especially for new designs incorporating new shapes. However, long time simulation requirements reduce its attractiveness for a case when a control algorithm needs to be incorporated [12]. Other researchers have done various works using finite element solver as can be found in [13] and [14].

The main formulas used in finite element analysis are the Ampere law and conservation of flux density law [14];

$$\nabla \times H = J + \frac{\delta D}{\delta t} \qquad (1)$$

$$\nabla \times E = -\frac{\delta B}{\delta t} + \nabla \times (v \times B) \qquad (2)$$

$$\nabla \cdot D = \rho \qquad (3)$$

$$\nabla \cdot B = 0 \qquad (4)$$

Where

E, D - are electric field intensity and electric flux density respectively

H, B - are the magnetic field intensity and magnetic flux density, respectively,

J - is the current density, and

v - is the velocity of the conductor with respect to B, and

ρ - is the electric charge density

2.1.1 Finite Element Model of Induction Motor

A model of the IM was constructed using Maxwell 2D software. There are four steps involved in finite element analysis [5]:

- Definition of geometrical parameters and construction of 2-D model.
- Definition of physical parameters such as regions, materials etc.
- Construction of electric circuit model.
- Meshing of the study domain and solving of problem.

Fig. 1 shows the complete geometrical 2D model of the IM while table 1 shows the simulation parameters

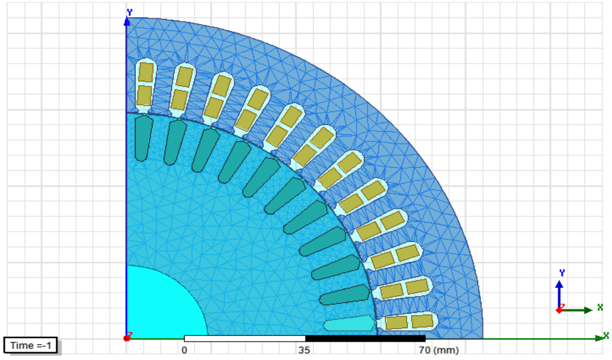

Figure 1: Finite Element Model of the induction motor

One can build electric machines using Maxwell in different ways. However, the process is simplified by letting the RMxprt do the most of the job. RMxprt is a machine model whereby a software user can insert machine design parameters and related information. In the process of imputing the design data in the RMxprt, a user has to specify the dimensions of the stator and rotor of the machine and related parameters such as machine type, number of poles of the machine and control type [15].

Furthermore, a user has to specify the rated parameters such as speed and voltage. A user has also to specify other parameters such as winding, slot, wire, conductors, insulation and some other related parameters [16].

Table 1: Simulation Parameters

SYMBOLS	DESCRIPTION	VALUE
Rs	Stator resistance	0.669482 Ω
Rr	Rotor resistance	0.524191 Ω
Lls	Stator leakage inductances	0.00195968 H
Llr	Rotor leakage inductances	0.00262285 H
Lm	Magnetizing inductance	0.114572 H
J	Moment of inertia	0.0018 Kgm^2
V	Rated Voltage	380V
P	Power	7.5kW
f	frequency	50Hz

III. RESULTS AND DISCUSSION

The machine was simulated for 2 cases under no load and load conditions;

- Case A: Healthy Machine
- Case B: Motor with Asymmetrical fault

3.1. Case A: Simulation of the Healthy Machine

The dynamic simulation of the machine was done in the Maxwell 2D environment. The analysis is carried out when all the phases are connected. These are for two scenarios: firstly, at no load and secondly at load condition.

3.1.1 Healthy Machine on No-Load Condition

The obtained magnetic fields, torque, speed and phase currents on no-load condition are as shown in Figs. 2-5 respectively.

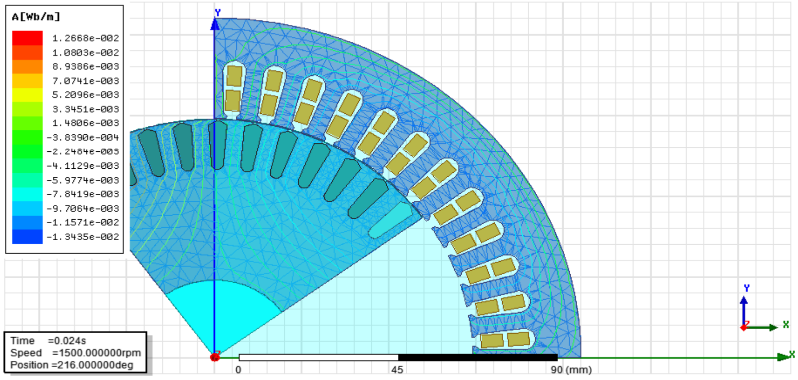

Figure 2: Flux lines on no load

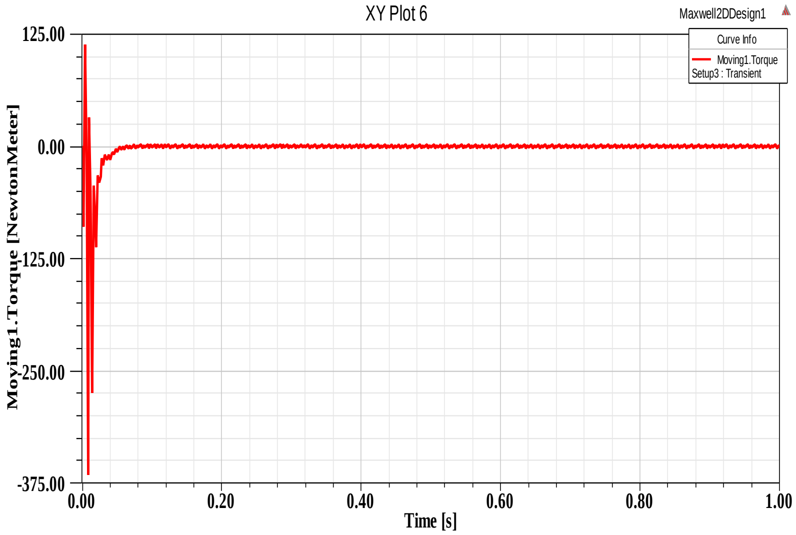

Figure 3: Torque with Time

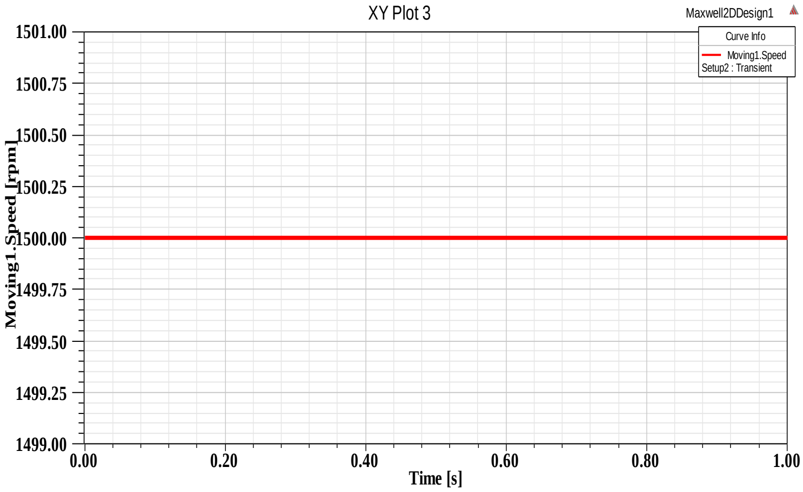

Figure 4: Speed with Time

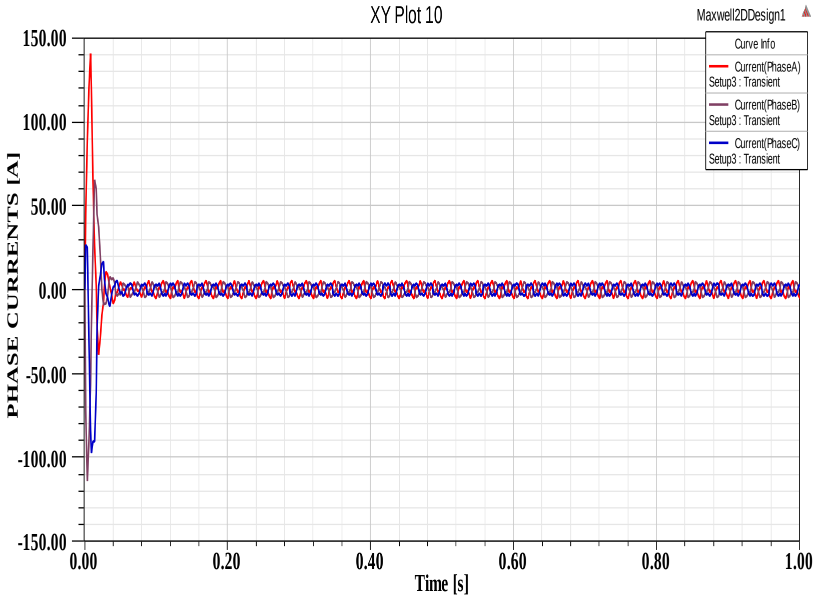

Figure 5: Phase Currents with Time

3.1.2 Healthy Machine on Load Condition

A load of 20 Nm was applied at 0.2s and the obtained magnetic flux density, torque, speed and phase currents on load condition are as shown in Figs. 6-9 respectively.

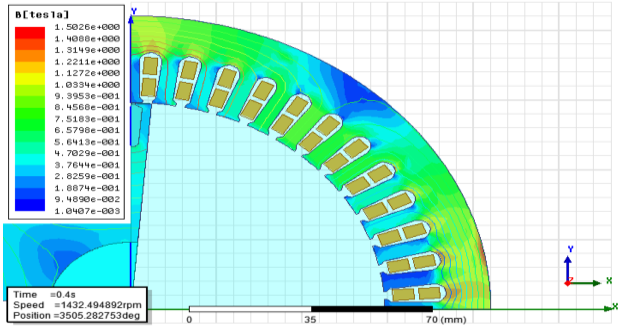

Figure 6: Magnetic Flux Density on load condition

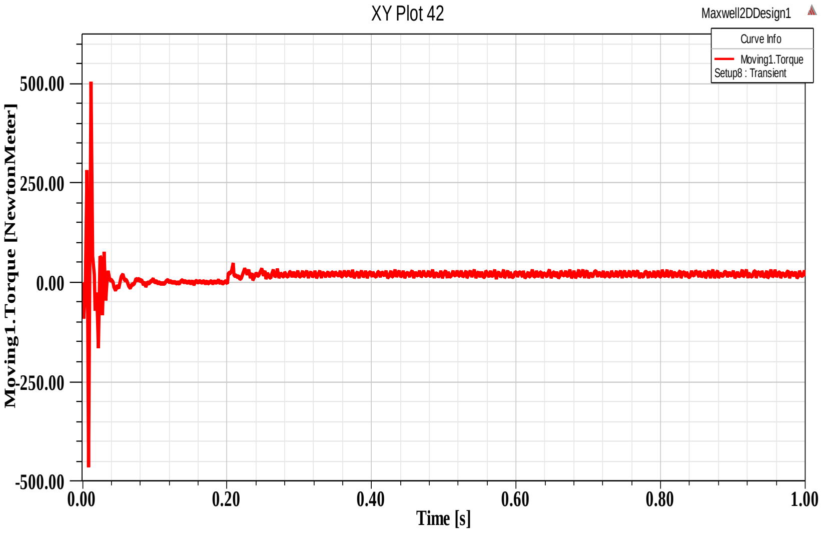

Figure 7: Torques with Time

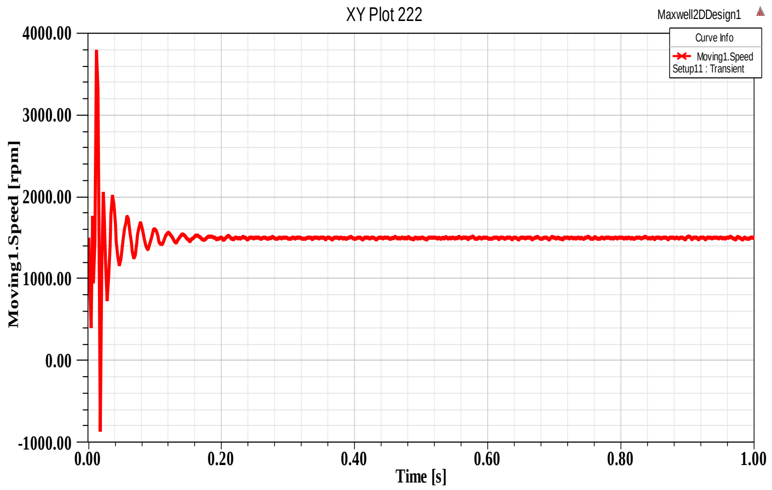

Figure 8: Speed with Time

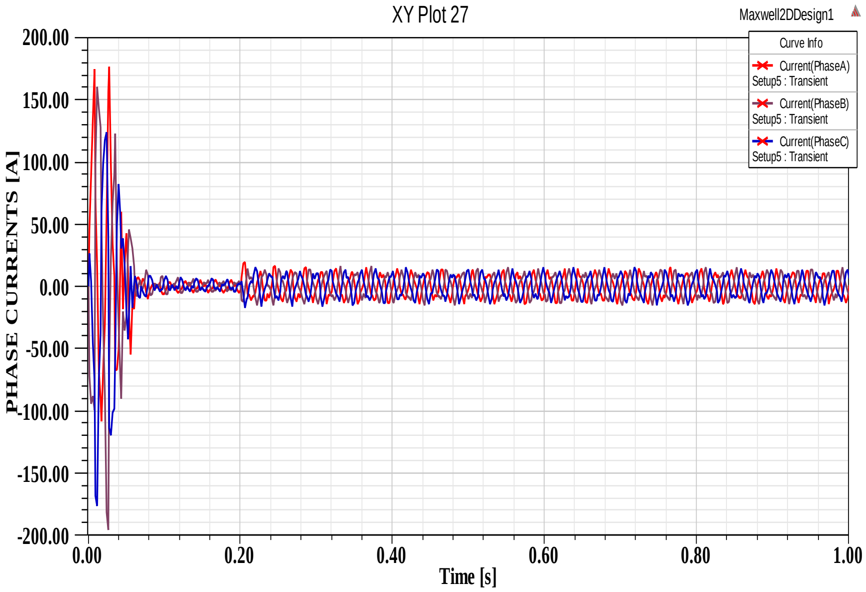

Figure 9: Phase currents with Time

It can be observed that the response of the machine to changes under no load condition remains the same with respect to the magnitudes of the parameters. However, the loaded machine takes longer to settle in steady state compared to the unloaded one (ratio of approximately 1:2 times). A torque of 20 Nm with little transients was produced by the loaded machine in steady state against no torque in unloaded condition as expected. Also, the speed dropped to 1420 rpm and regained stability when the load was applied. Similarly, the steady state current was 5.7123A and there was an increase at about 14.1690A when the load was introduced at 0.2s.

3.2 CASE B: SIMULATION OF THE MACHINE UNDER ASYMMETRICAL FAULT

In this section, the faulty situation is examined in which asymmetrical fault which is a common accident, able to tear windings apart, occurs. The fault lasted for 0.2s after which the motor maintained stability. The simulated results will help to better understand the operational behavior of the machine. The machine was simulated both for load and no-load conditions.

3.2.1 Faulty Machine on No-Load Condition

The electric motor is an important element in industrial process in terms of safety and efficiency, the early detection of its malfunctioning is required. The earlier the incipient fault is detected the easier it will be mitigated. The obtained magnetic fields, torque, speed and phase currents on no-load condition are as shown in Figs. 10-13 respectively.

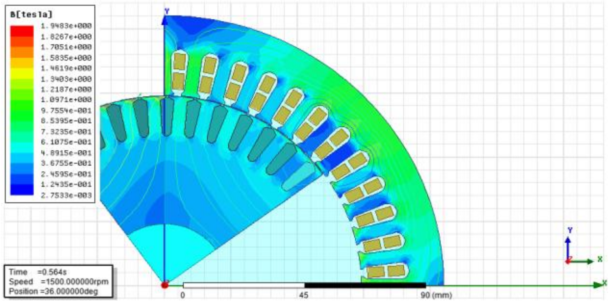

Figure 10: Flux Density on no load

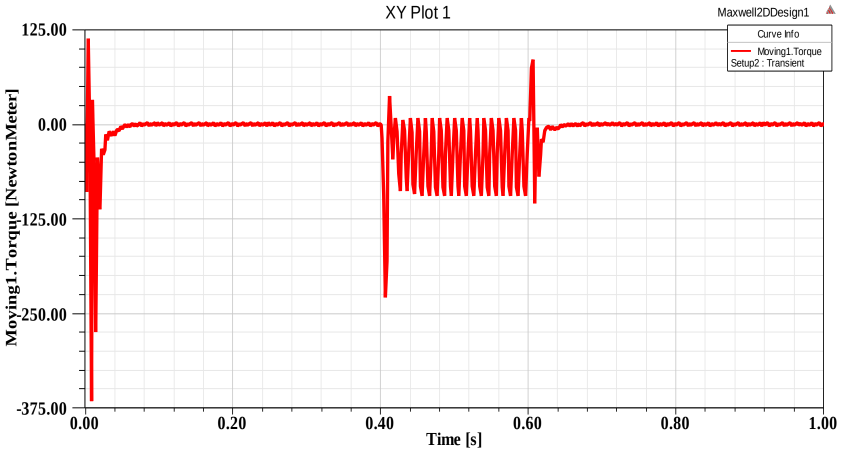

Figure 11: Torque with Time

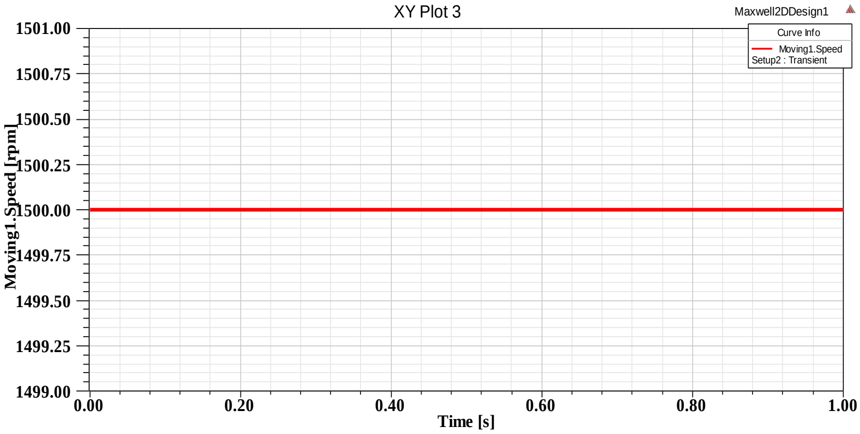

Figure 12: Speed with Time

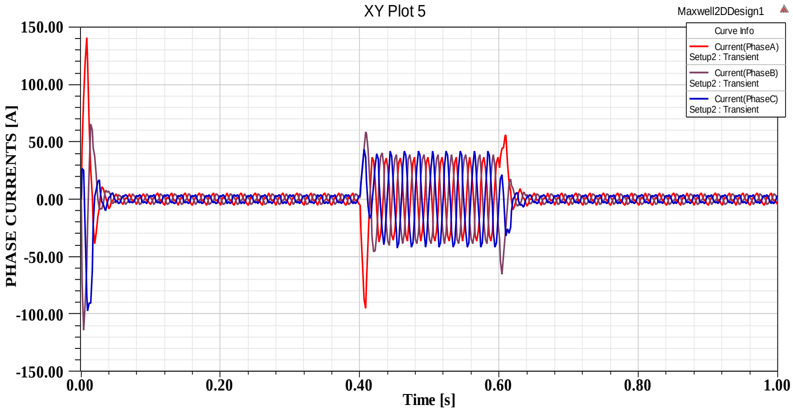

Figure 13: Phase Currents with Time

3.2.2 Faulty Machine on Load Condition

The load was introduced at 0.2s after the motor attained steady state and asymmetrical fault occurred at 0.4s and lasted for 0.2s after which the machine regains stability again. The faulty motor with asymmetrical fault at phase-A was analyzed with Maxwell-2D. As a result of the analysis, the magnetic flux density during the maximum current, torque with time, speed and the current with time graphics for the defined motor were obtained and presented at Figs. 14-17 respectively.

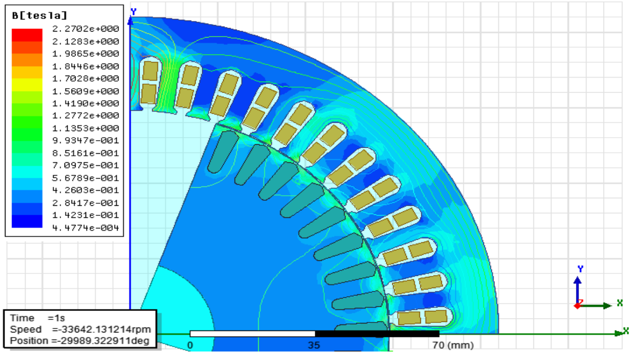

Figure 14: Magnetic Flux Density at stop time

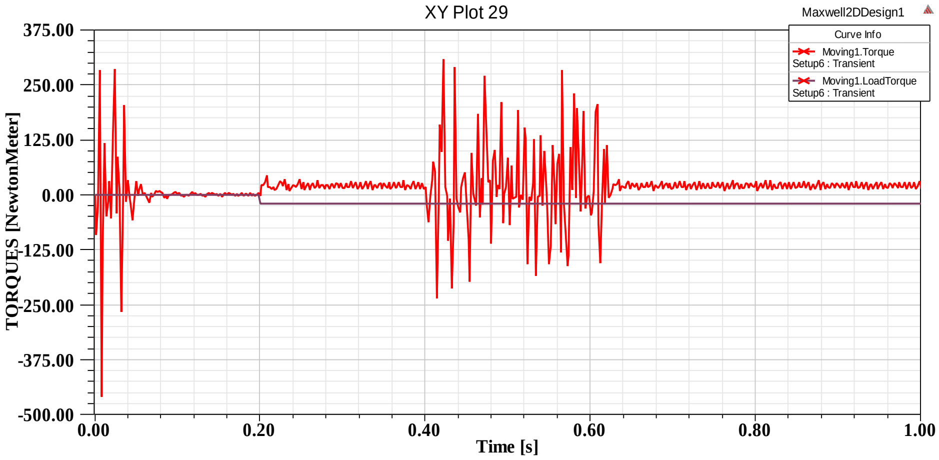

Figure 15: Torque with Time

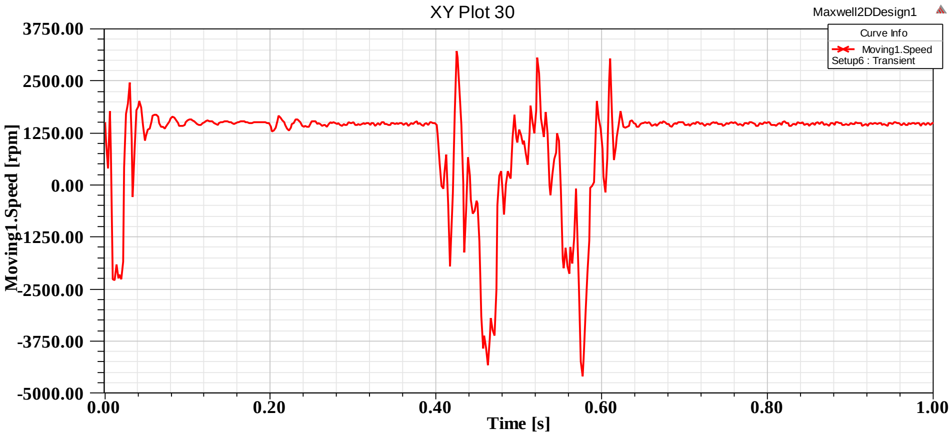

Figure 16: Speed with Time

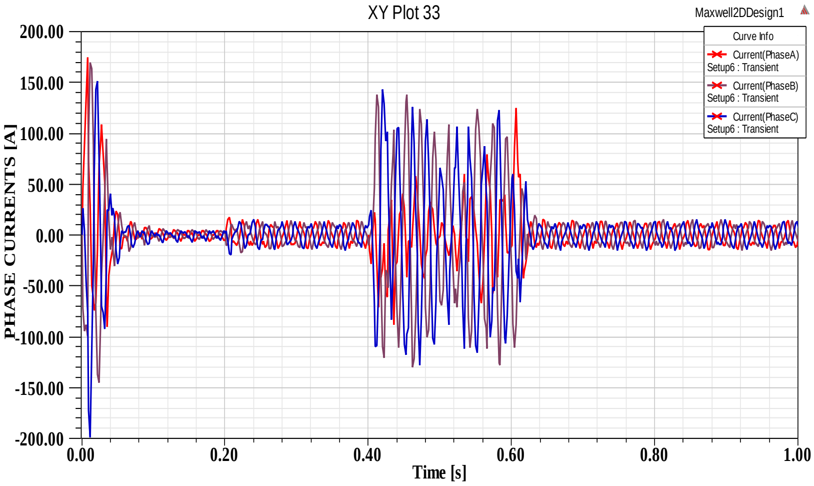

Figure 17: Phase Currents with Time

As it can be seen from the torque graphics, the loaded motor in fig. 15 was able to rotate around 20 Nm (which is the applied load) at 0.2s. Between 0.4s and 0.6s which is the interval during which the fault occurred, the motor oscillates around 315.2 Nm and later settled at 20 Nm after 0.6s. The unloaded motor was observed in figure 11 to be oscillating at a very high rate around 0 Nm between 0.4s and 0.6s and later reached stability immediately the fault was disconnected at 0.6s.

It was observed that the speed dropped slightly and oscillates around 1420 rpm after 0.2s. The loaded motor went into generating mode immediately asymmetrical fault occurred and regained stability after 0.6s while the speed of the unloaded motor remained unchanged.

The phase currents increased to about 14.1690 A when the load was introduced at 0.2s and further increased to about 141.2 A as a result of asymmetrical fault at 0.4s and later maintained a steady state stability of 14.1690 A after 0.6s when the fault was removed. The magnetic saturation areas are observed in figs. 10 and 14.

From the effects of the asymmetrical fault simulated above on the torque and speed it is apparent that we are in presence of the most severe fault. However the machine performance regained stability after the fault was removed at 0.6s.

IV. CONCLUSION AND RECOMMENDATION

In this paper, the stability analysis of a 3-phase induction motor under asymmetrical fault conditions using FEA simulations was performed. The model was built by using the RMxprt and Maxwell 2D software. The healthy machine was first simulated under unloaded and loaded conditions and then was simulated when asymmetrical fault occurred at one of the stator phases which lasted for 0.2s. The magnetic saturation areas were observed in both cases. The result obtained showed that in both cases it was observed that the torque produced by the healthy motor produces fewer oscillations than the machine with asymmetrical fault at the stator phase. It was also observed that the speed dropped slightly and oscillates around 1420 rpm after 0.2s when load was connected and went into generating mode immediately asymmetrical fault occurred and regained stability after 0.6s while the speed of the unloaded motor remained unchanged. There was a high increase in the phase currents (141.2A) in the faulty machine than in the healthy machine. From the effects of the asymmetrical fault simulated on the torque, speed and phase currents, it is apparent that we are in presence of the most severe fault. However, the machine performance regained stability after the fault was removed at 0.6s.

It is recommended that the electrical machines should not be operated under faulty conditions as it can be observed that high increase of currents under faulty condition can cause overheat which can damage the windings while the fluctuations on the torque and speed may result to mechanical vibrations.

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