ABSTRACT
Abstract—A three-phase induction motor is one of the most popular and versatile motor in electrical power system and industries. It can perform the best when operated using a balanced three-phase supply of the correct frequency. However, deviation from this causes a great reduction in torque, power and efficiency. One of them, which is the most severe condition is single-phasing. The single phasing is nominally interpreted as blowing out of fuse in one of the line, but in fact, it is a special case of insertion of impedance in the line. In this paper, the authors have studied the relationship between the torque, current and power in terms of an impedance inserted in series with the line. The authors have also experimentally performed the observations with insertion of different amount of impedance. The simulation model is also presented along side.

Keywords: Induction motor, slip, speed, torque, starting torque, maximum torque, full-load torque, simulation.

1. INTRODUCTION
Three-phase induction motors are widely used in industrial devices, and most of them are connected directly to the electric power distribution system. Therefore, it is very important to clarify the effect of voltage variation in the distribution system voltage on the characteristics of IM. The three phase induction motors are designed to work under three phase balanced voltage condition, but a small amount of voltage unbalance that is caused by the introduction of a negative sequence voltage may increase the current very substantially. In ordinary circumstances also a minor unbalance is also present, but it is tacitly understood to be negligibly small. Its effect on the motor can be severe and the motor may be over-heated and hence burn. The negative effects of voltage unbalance on the performance of three-phase induction motors include: higher losses, higher temperature rise of the machine, reduction in efficiency and a reduction in developed torque. The efficacy of normal operation of a motor from an unbalanced supply depends directly on the degree of unbalance at the terminals of the machine.

In this paper, performance of a three-phase induction motor under unbalanced voltage is studied.

2. EQUIVALENT CIRCUIT & GOVERNING EQUATIONS
For an Induction Motor, the torque is directly proportional to the product of flux per stator pole and rotor current. The electromagnetic torque in synchronous watt can be expressed as

\[ T = \frac{3}{2\pi N_s} \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2} \text{ N-m} \]  \[ \ldots \ldots \ldots \ (1) \]

From the given equation, it is clear that \( T \) is directly proportional to \( E_2 \). However, we know that \( E_2 \) is proportional to supply voltage. Hence, torque is very sensitive to any changes in supply voltage. Changes in supply voltage not only affect the starting torque but also the torque under running conditions. If supply voltage decreases, \( T \) decreases. Hence, for maintaining the same torque, slip increases. i. e. speed falls.

Figure 1. speed-torque characteristics of IM
The above figure shows the torque-speed characteristics of an induction motor. At full-load, the motor runs at speed N, when mechanical load increases motor speed decreases till the motor torque again becomes equal to load torque. Torque developed by a motor remains same if the slip-speed remains same.

![Figure 2. Equivalent circuit of an induction machine](image)

The figure shown above shows the equivalent circuit of an IM wherein the stator and rotor parameters are shown. Under unbalanced operating conditions of an induction motor, the negative sequence currents, however set up a reverse field, so that if the rotor slip is ‘s’ with respect to the positive sequence field, it will be (2-s) relative to the negative sequence field. Herein, the MATLAB software is used to investigate the performance of induction motor. Nevertheless, during simulation of the model a point was noted wherein the induction motor model was not able to accept an impedance in series with the supply terminals. Hence, as a remedy insertion of impedance for single phasing has been adopted making use of distributed parameters. This is a major limitation of the orthodox MATLAB model.

3. MOTOR UNDER EXPERIMENTATION

A simple laboratory setup was adopted in which a three phase induction motor connected to 400 volt, 3-ø ac supply through a star-delta starter and a dc generator coupled to it was used as a load on the machine. The dc generator power was consumed in a lamp load. The motor was supplied unbalanced voltage by changing the impedance connected in one of the lines. The cases represented in Table 1 were investigated to analyze the performance of the motor under unbalance.

<table>
<thead>
<tr>
<th>PART I: NO LOAD CONDITION</th>
<th>V₁₂</th>
<th>V₂₃</th>
<th>V₃₁</th>
<th>I₁</th>
<th>I₂</th>
<th>I₃</th>
<th>Speed (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rheostat condition</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 %</td>
<td>422</td>
<td>424</td>
<td>426</td>
<td>4.3</td>
<td>4.3</td>
<td>4.1</td>
<td>1485</td>
</tr>
<tr>
<td>25 %</td>
<td>424</td>
<td>418</td>
<td>430</td>
<td>4.6</td>
<td>3.9</td>
<td>3.7</td>
<td>1490</td>
</tr>
<tr>
<td>50 %</td>
<td>424</td>
<td>410</td>
<td>427</td>
<td>4.8</td>
<td>3.7</td>
<td>3.6</td>
<td>1495</td>
</tr>
</tbody>
</table>

3.1 RESULT ANALYSIS FROM EXPERIMENT

The cases represented in Table 1 were investigated to analyze the performance of the motor under unbalance. The motor was tested in two different load conditions: 1) At no load and 2) At about 25% of full load. The voltage triangles were found to have totally different shape.

From the above experimental results, it is clear that during no load conditions an unbalance in the supply voltage causes the speed to reduce gradually. During loaded conditions, it is observed that an unbalance in the stator voltage causes a drastic reduction in the speed of the motor.

From this positive and negative sequence of the voltages were extracted and fed to the motor circuits to yield the net torque and the speed. This was not in agreement with the approaches available thus for available in standard literatures. This implies possible an impedance present in one of the lines. It can be deduce that worst condition is that if further approaching will yield a condition analogous to single phasing.

4. SIMULATION AND ANALYSIS OF UNBALANCED OPERATION OF AN INDUCTION MACHINE

Simulink is an extremely powerful tool of MATLAB. Simulink is an environment for multidomain simulation and Model-Based Design for dynamic and embedded systems. It provides an interactive graphical environment and a customizable set of block libraries that let you design, simulate, implement, and test a variety of time-varying systems, including communications, controls, signal processing, video processing, and image processing. Using Simulink toolbar and its respective library, a sequence of models can be created to meet the requirements.
SIMULINK MODEL MACHINE SPECIFICATIONS:
Type and Rating: Squirrel cage Induction machine, 5 HP, 460V, 50Hz, 1750 rpm
Stator resistance and inductance: 1.115 Ohm and 5.974 mHenry
Rotor resistance and inductance: 1.08 Ohm and 5.974 mHenry
Mutual inductance: 0.2037 Henry

Initially the machine is supplied 3-phase balanced supply and the results are observed in the form of balanced rotor voltage and currents as shown in Figure 4. Stator currents, rotor current, torque and speed of the machine is also observed to be normal as shown in figure 6.

Now when the unbalance is introduced in the stator circuit in the form of unbalance voltage of phase and magnitude in one of the three phase as shown in Figure 7, the result of it can be observed in the form of unbalance parameter of rotor current, speed and torque of the machine as shown in figure 7 and 8.
So, the result obtained from the unbalanced conditions justifies the abnormality of operation of machine performance in the form of speed and torque. Some MATLAB commands can be used with a great versatility to obtain symmetrical components of applied unbalanced three phase voltages which would have been otherwise required by an interesting but elaborate graphical construction.

5. CONCLUSION

An attempt is made to explain the basic abnormality concerned with the three phase induction machine by conducting experimental analysis and simulation as well in this paper.

Using sufficient number of readings and extrapolations, the single phasing condition can truely be considered as an insertion of an extremely high resistance in one of the line. As the unbalancing in the voltage source can cause excessive losses, heating, noise, vibration, torsional pulsations, slip, and motor accelerating torque, detecting of unbalancing in the voltage applied is important. In the case of unbalanced voltages the efficiency and average output torque of the motor would decrease and the ripple would increase significantly destructing the motor application. Hence, it is extremely essential to analyze the unbalance conditions of an Induction motor.

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