Abstract—Induction motors are widely used in industry as prime electro mechanical energy conversion devices. Consequently the condition monitoring and fault diagnosis of induction motors have received significant attention recently and become an integrated part of various maintenance strategies. Induction motors are widely used in transportation, mining, petrochemical, manufacturing and in almost every other field dealing with electrical power. These motors are simple, efficient, highly robust and rugged thus offering a very high degree of reliability. But like any other machine, they are vulnerable to faults, which if left unmonitored, might lead to catastrophic failure of the machine in the long run. On-line condition monitoring of the induction motors has been widely used in the detection of faults. This paper delves into the various faults and study of conventional and innovative techniques for induction motor faults.

Keywords—induction motor faults, fault diagnosis, MATLAB/SIMULINK model, Time Domain Analysis.

1. INTRODUCTION

Induction motors are the mainstay for every industry. However like any other machine, they will eventually fail because of heavy duty cycles, poor working environment, installation and manufacturing factors, etc. With escalating demands for reliability and efficiency, the field of fault diagnosis in induction motors is gaining importance. The induction machines may be used in some important applications in the place of D.C. machines. The most important feature which declares induction motor as a tough competitor to D.C. machines in the drives filed is that its cost per KVA is approximately one fifty of its counter-part and it possesses higher suitability in the hostile environment. Although induction motors are reliable, they are subjected to some mode of failures. These failures may be inherent to the machine itself or due to operating conditions. The origins of inherent failures are due to mechanical or electrical forces acting in the machine enclosure. Unexpected faults and failures in these machines can lead to excessive downtime and generates large revenue losses in terms of maintenance and production. If the faults are not prognosticated beforehand, it may result in large revenue losses as well as pose threat to reliability and safety of operation. However, many methods have been proposed for fault detection and diagnosis, but most of the methods require a good deal of expertise to apply them successfully.

Broadly, an induction motor can develop either internal fault or external fault. With reference to the origin, a fault may be mechanical or electrical. Fault can be classified as stator fault or rotor fault depending on the location of the fault. Faults associated with the moving parts like bearing and cooling faults are categorized as rotor faults [1]. Specifically, induction motor faults can be broadly classified into bearing failures, stator faults, rotor faults, air gap eccentricity, mechanical vibrations, etc.

The induction motor is subjected to primary types of fault and related secondary faults. Fig.1 (a) classifies the sources of induction motor faults. In Fig. 1(b), the internal fault tree is depicted and Fig. 1(c) illustrates the external fault tree for an induction motor.
Fig. 1 (a) Sources of Machine Faults

Fig. 1(b) Block Diagram Presentation of Internal Faults
2. INDUCTION MOTOR FAULTS

Profound efforts have been devoted to Induction motor fault diagnosis. Depending on the region of fault occurrence, induction motor faults are mainly put under the following five categories.

2.1. Bearing Faults

Generally, a rolling-element bearing is an arrangement of two concentric rings. A set of balls or rollers spin in raceways between the inner ring and outer ring. Bearing defects [2] may be categorized as “distributed” or “local”. Distributed defects include misaligned races, waviness, surface roughness and off-size rolling elements. Localized defects include spalls, pits and cracks on the rolling surfaces. These localized defects create a series of impact vibrations at the instant when a running roller passes over the surface of a defect whose period and amplitude are calculated by the anomaly’s position, speed and bearing dimension. Mechanical vibrations are produced by the flawed bearings. These vibrations are at the rotational speed of every component. The bearing dimensions and the rotational speed of the machine are used to determine the characteristic frequencies associated to the raceways and the balls or rollers. The condition of the bearing is ascertained by examining these frequencies. This task is accomplished using mechanical vibration analysis techniques.

The bearing consists of mainly of the outer race and inner race way, the balls and cage which assures equidistance between the balls. The different faults that may occur in bearing can be classified according to the affected element:

- Outer raceway defect
- Inner raceway defect
- Ball defect
2.2. Stator Faults
An induction motor is subjected to various stresses like thermal, electrical, mechanical, and environmental [11]. Most stator faults can be attributed to such stressful operating conditions. Faults in the stator winding such as turn-to-turn, coil-to-coil, open circuit, phase-to-phase and coil-to-ground [11-12], are some of the more prevalent and potentially destructive faults. If left undetected, these may eventually cause cataclysmic failure of the motor. The three main divisions discussed in [11] of stator faults are the following.

a) Frame:
   - Vibration
   - Circulating currents
   - Earth faults
   - Loss of coolants

b) Lamination:
   - Core slackening
   - Core hot spot

c) Stator windings fault:
   - End winding portion (turn-to-turn faults, fretting of insulation, local damage to insulation, damage to connectors, discharge erosion of insulation, displacement of conductors, contamination of insulation by moisture, oil or dirt, cracking of insulation and so forth).
   - Slot portion (insulation fretting, displacement of conductors).

2.3. Rotor Faults
Rotor faults [13] can be induced by electrical failures such as a bar defect or bar breakage or mechanical failures such as rotor eccentricity. The first fault occurs from thermal stresses, hot spots, or fatigue stresses during transient operations such as start-up, especially in large motors. A broken bar changes torque significantly and became dangerous to the safety and consistent operation of electric machines [14]. The second type of rotor fault is related to air gap eccentricity. This fault is a common effect related to a range of mechanical problems in induction motors such as load unbalance or shaft misalignment. Long-term load unbalance can damage the bearings and the bearing housing and influence air gap symmetry. Shaft misalignment means horizontal, vertical or radial misalignment between a shaft and its coupled load. With shaft misalignment, the rotor will be displaced from its normal position because of a constant radial force.

2.4. Eccentricity Faults
Unequal air gap between stator and rotor results in eccentricity [15] of induction motor. In general, air-gap eccentricity can be of two types: the static air-gap eccentricity and the dynamic air-gap eccentricity. A mixture of both forms, called mixed eccentricity [16] and the axial non uniformity of air gap, known as inclined eccentricity [17] have also been accounted. The minimal radial air-gap length is fixed in space for static air-gap eccentricity. On the contrary, the center of rotor and the center of rotation do not coincide for dynamic eccentricity. In this case, the position of minimum air gap is not fixed in space but rotates with the rotor. An erroneous positioning of the rotor or stator during the commissioning phase may give rise to static eccentricity. It may also be caused by stator core ovality. A cause of dynamic eccentricity can be a bent shaft, bearing wear and movement, or mechanical resonances at critical speeds.

2.5. Vibration Faults
Vibrations are natural processes in induction motors which are caused by the oscillations of mechanical parts of the motors. These oscillations are reflected in the external system attached with the machine shaft. Consequently, machine related frequency spectrum is generated which is unique for a healthy motor. Each fault in the motor changes the frequency component of the spectrum. This can be compared with the reference spectrum to perform fault detection and diagnosis.
3. DEFINITIONS

In time domain analysis following factors are consider:

3.1 Rms(Root Mean Square) Value

The value of an AC voltage is continually changing from zero up to the positive peak, through zero to the negative peak and back to zero again. The RMS value of the vibration acceleration can be used for primary health investigation of the machine. The RMS of a variant X is the square root of the mean squared value of X. RMS level increases with increase in fault severity level.

\[ \text{RMS} = \sqrt{\frac{1}{N} \sum (X_i - \mu)^2} \]

Where

- N is number of samples.
- \( X_i \) is the amplitude of individual sample.
- \( \mu \) is the mean value of samples

3.2 Peak Level

The Peak Level of the discrete time signal is

\[ \text{PEAK LEVEL} = \text{MAXIMUM}(X_i) \]

Peak level is indicative of occurrences of impacts. For low-level fault, peak level is good indicator.

3.3 Crest Factor

The crest factor, is the ratio of peak value to the RMS value, yields a measure of spikiness of a signal. Crest factor of radial vibration signal is often used to indicate the rolling bearing faults. Crest factor for healthy bearing is more as compared to that of damaged bearing, in many cases. CREST FACTOR = PEAK VALUE / RMS VALUE

The crest factor is initially increases with fault level but it decreases with the increase in fault severity after a particular level.

3.4 Skewness

Skewness is a measure of symmetry, or more precisely, the lack of symmetry about its mean. A distribution, or data set, is symmetric if it looks the same to the left and right of the center point of Gaussian distribution. Negative values of Skewness indicate the data that are skewed left and positive values for right skewness. The skewness is found as the consistent parameter with respect to fault severity.

\[ \text{SKEWNESS} = \left[ \frac{1}{N} \sum (X_i - \mu)^3 \right] / \sigma^3 \]

where \( \sigma \) is the standard deviation of the time record.

3.5 Kurtosis Value

It is a measure of whether the data are peaked or flat relative to a normal distribution. A uniform distribution would be the extreme case. High kurtosis indicates a "peaked" distribution and low kurtosis indicates a "flat" distribution near the mean value.

\[ \text{KURTOSIS} = \left[ \frac{1}{N} \sum (X_i - \mu)^4 \right] / \sigma^4 \]

The kurtosis value increases significantly up to low level ball defect however it decreases back to value corresponding to healthy case.

4. SQUIRREL CAGE INDUCTION MOTOR FED PWM INVERTER MODEL

Due to the advancement in the power electronics semiconductor devices such as IGBTs, MOSFETs and GTOs etc are being used these days with induction motor to achieve variable speed for many power electronics and drives applications. In the industries, PWM inverter fed induction motors are widely replacing DC motors and thyristor bridges day by day for variable speed applications with very competitive pricing. This kind of force commutated power electronics semiconductor devices based inverters provided variable frequency and variable voltage efficiently. Many power electronics devices has already been used by the researchers but it
has been widely observed that the IGBT inverter gives more efficient results as compare to other semiconductor devices for various applications. Therefore, in the present work, a squirrel cage SPWM inverter fed induction motor with IGBT inverter and direct torque control technique jointly simulation model has been developed and proposed in the recent MATLAB/Simulink environment.

A three-phase squirrel cage induction motor having rating of 3 HP, 220 V, 1430 RPM is fed by a SPWM inverter with direct torque control technique jointly has been considered and shown in Fig. 2. The base frequency of the sinusoidal reference wave is 50 Hz whereas the triangular carrier wave's frequency is set to 1650 Hz. It corresponds to a frequency modulation factor mf of 33(50Hz×33=1650 Hz). The maximum time step has been limited to 10 μs. It is needed due to the relatively high switching frequency (1650 Hz) of the inverter. It is recommended that mf should be an odd multiple of three and that the value ought to be as high as possible [17]. The PWM inverter is built entirely with standard Simulink block sets. The induction motor’s rotor is kept short circuited for simulating the effect of squirrel cage induction motor. The stator leakage inductance is set to twice to its actual value for simulating the effect of smoothing reactor which is placed between the inverter and motor. The SCIM is started from standstill condition and the speed set point is set to 1430 RPM for full load condition.

With the help of this simulink model bearing fault can be easily detected with the help of speed and torque measurement. The stator current, rotor current, rotor speed and developed electromagnetic torque motor signatures have been used for analysis purpose. Since, we are focusing on transient analysis of the induction motor. By using the model, the successful detection of bearing fault of the SCIM is carried out in the transient condition. If we increase friction then the flat spots will be created inside the bearing. Consequently, overheating will occur. Therefore, the bearing will get damaged. Due to this reason, the motor will reach in the idle condition for long periods. The developed simulation model has been simulated only for 1s time for clear revelation of the transient characteristics of the motor[5].
5. RESULT
With the help of matlab/simulink model collect the data of the induction motor by using various definitions formula calculate various time domain parameters of induction motor. Fig3(a) shows the vibration signal of induction motor in healthy bearing Fig3(b) shows the vibration signal of induction motor in faulty bearing. When inner race bearing fault occurs in the induction motor PEAK value, RMS value, shape factor, upper bound, lower bound these time domain parameters increases and crest factor, kurtosis value, Skewness, clearance factor, Impulse factor these time domain parameters decreases. Table 1&2 shows these time domain parameters value.

Fig:3(a) vibration signal of induction motor in healthy condition

Fig:3(b) vibration signal of induction motor in faulty condition
Table 1 shown the data which is extracted from the time domain signal of the Induction motor in healthy condition. When motor is on no load condition. All the time domain parameters are shown below.

<table>
<thead>
<tr>
<th>LENGTH (N)</th>
<th>PEAK VALUE</th>
<th>RMS</th>
<th>CR</th>
<th>KUR</th>
<th>SKEW</th>
<th>CLF</th>
<th>IMF</th>
<th>SHF</th>
<th>UB</th>
<th>LB</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1:1000)</td>
<td>0.1805</td>
<td>0.0655</td>
<td>2.7542</td>
<td>2.7609</td>
<td>0.0223</td>
<td>3.9904</td>
<td>3.4124</td>
<td>0.3081</td>
<td>0.1807</td>
<td>-0.2127</td>
</tr>
<tr>
<td>(1001:2000)</td>
<td>0.2318</td>
<td>0.0650</td>
<td>3.5622</td>
<td>3.1417</td>
<td>0.0650</td>
<td>5.3598</td>
<td>4.4959</td>
<td>0.3129</td>
<td>0.2320</td>
<td>-0.2469</td>
</tr>
<tr>
<td>(2001:3000)</td>
<td>0.2171</td>
<td>0.0638</td>
<td>3.3995</td>
<td>2.8715</td>
<td>0.1269</td>
<td>4.9468</td>
<td>4.2218</td>
<td>0.3129</td>
<td>0.2173</td>
<td>-0.2103</td>
</tr>
<tr>
<td>(3001:4000)</td>
<td>0.1805</td>
<td>0.0632</td>
<td>2.8543</td>
<td>2.7705</td>
<td>0.0325</td>
<td>4.1768</td>
<td>3.5517</td>
<td>0.3042</td>
<td>0.1807</td>
<td>-0.1614</td>
</tr>
<tr>
<td>(4001:5000)</td>
<td>0.2073</td>
<td>0.0681</td>
<td>3.0418</td>
<td>2.7922</td>
<td>0.0798</td>
<td>4.4695</td>
<td>3.7821</td>
<td>0.3165</td>
<td>0.2075</td>
<td>-0.1834</td>
</tr>
</tbody>
</table>

Table 2 shown the data which is extracted from the time domain signal of the bearing. This data is very useful at the time of deep study of bearing faults. As the faults occurred time domain parameter value is changes from normal condition to faulty condition. All the time domain parameters changes when inner race bearing fault occur in the induction motor.

<table>
<thead>
<tr>
<th>LENGTH (N)</th>
<th>PEAK VALUE</th>
<th>RMS</th>
<th>CR</th>
<th>KUR</th>
<th>SKEW</th>
<th>CLF</th>
<th>IMF</th>
<th>SHF</th>
<th>UB</th>
<th>LB</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1:1000)</td>
<td>2.0169</td>
<td>1.1343</td>
<td>1.7780</td>
<td>2.5033</td>
<td>-0.4414</td>
<td>2.4677</td>
<td>2.1383</td>
<td>1.2547</td>
<td>2.0197</td>
<td>-3.5058</td>
</tr>
<tr>
<td>(1001:2000)</td>
<td>2.0414</td>
<td>1.1219</td>
<td>1.8195</td>
<td>2.4744</td>
<td>-0.3729</td>
<td>2.5170</td>
<td>2.1870</td>
<td>1.2457</td>
<td>2.0440</td>
<td>-3.3323</td>
</tr>
<tr>
<td>(2001:3000)</td>
<td>1.9974</td>
<td>1.1150</td>
<td>1.7913</td>
<td>2.5275</td>
<td>-0.3549</td>
<td>2.4965</td>
<td>2.1617</td>
<td>1.2465</td>
<td>2.0003</td>
<td>-3.7182</td>
</tr>
<tr>
<td>(3001:4000)</td>
<td>1.9364</td>
<td>1.0727</td>
<td>1.8050</td>
<td>2.6488</td>
<td>-0.4121</td>
<td>2.5527</td>
<td>2.1973</td>
<td>1.2317</td>
<td>1.9392</td>
<td>-3.6571</td>
</tr>
<tr>
<td>(4001:5000)</td>
<td>2.0243</td>
<td>1.1241</td>
<td>1.8007</td>
<td>2.5421</td>
<td>-0.2976</td>
<td>2.4876</td>
<td>2.1688</td>
<td>1.2462</td>
<td>2.0270</td>
<td>-3.4056</td>
</tr>
</tbody>
</table>

RMS-root mean square value, CR-crest factor, KUR-kurtosis vale, SKEW-skewness, CLF-clearance factor, IMF-impulse factor, SHF-shape factor, UB-upper bound, LB-lower bound

5. CONCLUSION

This paper attempts to summarize recent developments in induction motor fault diagnostics and prognostics. Various induction motor faults have been discussed. through the condition monitoring of the motor bearing we can easily avoid the critical emergency shutdown as well as reduce the maintenance cost of the motor other faults. Here we also see that through the time domain analysis, we can easily distinguish the signals from normal to faulty condition.

REFERENCES


