CHAPTER 2

FAULT DETECTION IN INDUCTION MACHINES

A new technique for identification of nature of fault in rotating machines is discussed in this chapter, based on the pattern variation in the signals’ spectrum called Peak Variation Response (PVR) noticed in the spectral estimation of the recorded voltage and current signals when motor is operated at power frequency AC input.

This chapter discusses on the fault diagnosis in three phase Squirrel Cage Induction Machine (SCIM) for specific faults like a) stator winding fault b) rotor bar broken fault c) ball bearing fault and d) notched tooth gear fault.

2.1 PVR FOR ROTATING MACHINE FAULT DETECTION

It would appear at the first glance that time domain variations on measurements of voltage, current signal and speed are indicative of faults. However, it is not possible to isolate the nature of fault from the metric of signal variations. For this reason the frequency domain approach is used. The spectrum of the current or voltage x(F) is obtained from the time domain record x(t) by using the standard Fast Fourier Transform (FFT) routine.

This thesis proposes the estimation of the nature of fault using the PVR in the spectrum i(F) or the v(F) of the acquired signals i(t) and v(t) respectively. The PVR varies for (i) various types of faults and (ii) for variations in operating conditions of the machines. The relative variations are
traced through (i) frequency changes (ii) changes in amplitude of the spectral peaks (iii) the relative shift in the sidebands of each of the spectral peaks. These variations are noticed in the fundamental and higher order frequencies identified at $nf_o$ (where $f_o = 50$Hz here, $n = 1, 2...9...$) both in analytical and experimental simulation.

In this thesis experiments are done by deliberately creating faults across the section of machine components at minor level (2% to 5%) and major level (10% to 20%) for modeling specific types of faults that induces vibration and malfunctioning of rotating machine. The causes of fault may be due to

(i) Shorts in stator winding

(ii) Loosened gear fittings

(iii) Broken balls in ball bearings

(iv) Misalignment of gear-shaft housing

Motors considered for experiments are chosen with different winding designs, pole numbers, and power ratings. These were tested by deliberately including fault conditions on the rotating motor while operating under different loading conditions.

2.1.1 Stator Winding Fault Detection in Three Phase Squirrel Cage Induction Machine (SCIM)

Stator faults are usually related to insulation failure, which generally leads to phase-to-phase, phase-to-ground faults etc. These faults may occur due to undetected turn-to-turn faults, which finally grow into major ones. Almost 30%-40% of all reported induction machine failures fall into
this category. The primary causes for failure of stator insulation are i) high stator-core or winding temperatures, ii) slack core lamination, slot wedges and joints, iii) loose bracing for end winding, iv) contamination due to oil, moisture and dirt, v) short circuit or starting stresses, vi) electrical discharges, vii) leakage in cooling systems.

There are a number of standardized techniques like resistance test, temperature test etc, to detect insulation faults for large generators and motors with stator windings rated 4kV and above. However, for low voltage motors, the insulation borne-fault detection procedures are yet to be standardized.

Thomson & Fenger (2001) demonstrate through different industrial case histories that MCSA (Machine Current Signature Analysis) is a powerful technique for monitoring the health of three-phase induction motors. An essential ingredient of the diagnostic strategy is the inclusion of parameters such as motor design, rating of the motor, duty cycle to the drive, mechanical load/drive train characteristics and operational load condition at the time of diagnosis.

Nandi et al (2005) present a brief review of mechanical, electrical related faults and of their diagnosis. It is seen from various publications that the noninvasive MCSA is by far the most common technique to diagnose faults. Other techniques for fault detection based on axial flux-based measurements, vibration analysis, transient current, and voltage monitoring, etc. have been discussed for automated fault detection in many other literature.

Tallam et al (2007) provide a survey of existing techniques for detection of stator-related faults, which include stator winding turn faults, stator core faults, temperature monitoring, and stator winding insulation fault.
The root causes of fault inception, available techniques for detection and recommendations for further research had been presented. Although the primary focus is on the online and sensorless methods that use machine voltages and currents to extract fault signatures, the offline techniques such as partial discharge detection had also been examined.

However, in spite of many research inline it is observed necessary to distinguish the type and intensity of faults in machines based on the relevant frequency components that may be present due to harmonics is discussed in the rest of this thesis report.

2.1.2 Empirical Method to Detect Short Circuit Fault in Stator Winding

Two main classes of stator winding failures can be considered. They are asymmetry in the stator windings such as an open-phase failure and short-circuit of a few turns in a phase winding. The former allows the machine to operate with a reduced torque while the latter leads to a catastrophic failure in short time. A short circuit is recognized as one of the most difficult failures to detect. The usual protection might not work on the motor. The motor might keep on running while the heating in the shorted turns would soon cause critical insulation breakdown. If left undetected, turn faults will propagate, leading to phase-to-ground or phase-to-phase faults. Ground current flow results in irreversible damage to the core and the machine must be removed from service. Incipient detection of turn faults is therefore mandatory. One of the simplest but most effective methods is the continuous monitoring of the negative sequence of the stator core, but the detection of minimum number of shorted turns is difficult through them.
The objective here is to identify current components in the stator winding that are only a function of shorted turns. The following predictor equation (Nandi et al, 2005) gives the components in the air-gap flux waveform that are a function of shorted turns:

\[
    f_{st} = f \left\{ \frac{n}{p} (1-s) \pm k \right\}
\]

(2.1)

where, \( f_{st} \) is frequency components that are a function of shorted turns in Hz

\( f \) is supply frequency that represents the fundamental frequency in Hz

\( n = 1, 2, 3… \) sideband’s number respective to the particular harmonic

\( k = 1, 3, 5… \) harmonic order

\( p \) is pole pairs

\( s = \frac{(N_s-N)}{N_s} \)

where, \( N_s \) is the synchronous speed of the motor in RPM

\( N \) is the rotational speed of the motor in RPM

The diagnosis of shorted turns via machine current is based on estimating the frequency components given by Equation (2.1), in that, these rotating flux waves can induce corresponding current components in the stator winding.

2.1.3 Experimental Test bed for Stator Winding Fault Detection

The specification of the three phase Squirrel Cage Induction Motor (SCIM) with mechanical loading used for experimental study is of 415V, 1.5
kW/2hp, 1430RPM, 3.4A rating. The SCIM has 36 slots with one coil per slot, four coils per phase having 54 turns in each coil. The number of turns per phase is 324, in which the tapping has been taken at 1% (3rd turn), 3% (10th turn), 5% (16th turn) and 10% (32nd turn) turns in all the three phases. The tapping in the stator winding of a coil is the extension of the insulated conductor. The edge of the tapping has been cut; insulation has been removed by scratching and then soldered. The edge of the tapping is disconnected whenever required to simulate an open circuit fault. Photograph of experimental test bed for TPSCIM stator winding fault emulation is shown in Figure A1.1.

Experiments are conducted with the above SCIM while simulating turn-to-turn fault in B-phase, phase-to-phase (B-Phase and Y-phase) and open circuit fault in Y-phase. The currents and voltages were acquired through data acquisition systems discussed in Section 1.6 which subsequently are analyzed through signal processing techniques discussed in Section 1.7.2.

The following sections discuss on detection of fault through PVR with experiments conducted on prototype fault models.

2.1.3.1 Case 1 – Study on PVR for healthy machine

Healthy motors’ stator current is acquired in no-load condition which is subject to DSP analysis discussed in section 1.7.2 as shown in Figure 2.1. The spectrum shows peak at 50Hz the specific supply power frequency. The fundamental frequency 50Hz is dominant compared to harmonic peaks at 100Hz and 150Hz and the amplitudes are higher for loaded condition, as observed while experimenting on the motor with healthy components. Magnitude less than -60dB is considered as noise in this thesis.
Figure 2.1  Stator current with PVR for healthy motor operated at 400V under no-load condition

2.1.3.2  Case 2 - Study on turn-to-turn winding fault

Figure 2.2 shows the stator currents’ PVR for the test motor with two tappings of B-phase being deliberately shorted to simulate turn-to-turn fault at 100V and 400V under no-load condition.

The spectrum has sidebands with -33dB for 25Hz, -32dB for 75Hz, -42dB for 125Hz, -43dB for 175Hz as PVR while testing with supply of 400V. Uniquely even harmonic peak occurs at 100 Hz with side band peaks at 75Hz and 125Hz. The sideband frequencies have been estimated for n=1, 2, 3, k=1. The Left Side Band (LSB) is 25Hz and Right Side Band (RSB) is 75Hz, 100Hz and 125Hz that are observed as fault frequencies for turn-to-turn fault both empherically and experimentally. The fault frequencies calculated through predictor Equation (2.1) matches with the experimental values, thereby confirming the presence of turn-to-turn winding fault in the machine. The dB values of amplitude response for the applied input voltage of 400V are greater than for 100V, though with the same pattern of fault frequencies in
the PVR as shown in the Table 2.1 (based on the rating of three phase SCIM motor used) for experiment.

PVR observed during turn-to-turn fault (or interturn fault within the same phase) exhibited the current with spectrum distribution with PVR shifts at steps of 25Hz each along Right/Upper Side Band (RSB) and Left/Lower Side Band (LSB) for the \( n^{th} \) harmonic frequency components at 50Hz, 150Hz as seen in Figure 2.2. As the pattern of PVR of spectrum distribution for 400V is same as that of 100V, in this thesis the experiments are carried out at lower voltage for three phase SCIM.

Table 2.1 Turn-to-turn fault evaluated using Equation (2.1)

<table>
<thead>
<tr>
<th>( \text{Left side} )</th>
<th>( n^{th} ) Harmonic peak ( F_{\text{peak}} ) (Hz) ( (n=1, 2, 3...) )</th>
<th>( \text{Right side} )</th>
<th>( F_{\text{peak}} ) (Hz) + 25Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_{\text{peak}} - 25Hz )</td>
<td>( F_{\text{peak}} + 25Hz )</td>
<td>( F_{\text{peak}} - 25Hz )</td>
<td>( F_{\text{peak}} + 25Hz )</td>
</tr>
<tr>
<td>25</td>
<td>50</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>75</td>
<td>100</td>
<td>125</td>
<td>125</td>
</tr>
<tr>
<td>125</td>
<td>150</td>
<td>175</td>
<td>175</td>
</tr>
</tbody>
</table>

Figure 2.2 Stator current with PVR for turn-to-turn fault at 100V and 400V under no-load condition
2.1.3.3  Case 3 - Study on phase-to-phase fault due to winding short circuit

Phase-to-phase fault is done experimentally by shorting one tapping of B-phase with another tapping of Y-phase to simulate phase-to-phase winding fault on the three phase SCIM operated at 300V under no-load condition.

The spectrum has PVR with multiple fringes termed here as spectral sidelobe disbursion. The multiple sidelobes of -9dB for 50Hz, -31dB for 100Hz, -26dB for 150Hz is seen in Figure 2.3. The presence of multiple sidelobes confirms the presence of phase-to-phase winding short. Amplitude for the odd harmonic peaks is higher than for even harmonic peaks.

![Figure 2.3](image)

Figure 2.3  Stator currents’ PVR with sidelobe disbursion for phase-to-phase (B-Y) fault at 300V under no-load condition

2.1.3.4  Case 4 – one-turn open in one phase of the three phase SCIM

Experiment under voltage input on the three phase SCIM with stator winding induced with one-turn open in the R-phase only, has been analyzed under no-load and load condition. Supply voltage of \( V_r = 136V, V_y \)
$V_a = 142\text{V}, \ V_b = 138\text{V}$ is applied to the three phase SCIM with one-turn deliberately open circuited. The SCIM was energized with reduced voltage supply so as to not damage, but to continue to run the motor. Figure 2.4 and Figure 2.5 exhibit the voltage, current and their respective PVR are observed with operating the motor under no-load and mechanically loaded conditions respectively. The PVR of voltage and current spectra for loaded and unloaded condition shows PVR with fringed sidelobe disbursion for both $v(F)$, $i(F)$ as odd harmonics at (50Hz, 150Hz, and 250Hz) and even harmonics at 100Hz, 200Hz and 300Hz that are observed only for $v(F)$.

![Graphs of Voltage, Current, and Spectra](image)

**Figure 2.4** One-turn open in a phase at no-load for three phase SCIM
(a) Voltage and current signal (b) its PVR with spectral sidelobe disbursion
Figure 2.5  Open turn fault in a phase winding at half-load condition for three phase SCIM (a) Voltage and stator current signal (b) PVR in voltage and current spectrum

The PVR show spectral sidelobe disbursement in stator current with sidelobes variation response for odd harmonics. The multiple sidelobes are absent in voltage signal for half-load condition, when compared to no-load condition as shown in Figure 2.6. The current spectra has PVR differed from case 3, since case 4 did not exhibit even harmonics.

Table 2.2 describes the frequency peaks at nf₀ (f₀ is fundamental frequency, n = 1,2,3,...), their magnitudes in dB, and the sideband frequencies estimated with the DSP analysis on the voltage and current signals obtained from the windings of the test machine with healthy, turn-to-turn, phase-to-phase and open circuit faults respectively.
Figure 2.6 PVR for an open circuit in stator winding (Y-phase) under no-load and half-load condition of three phase SCIM

Table 2.2 Comparison of PVR observed on various fault types in windings of a three phase SCIM under no-load and load condition

<table>
<thead>
<tr>
<th>Machine condition</th>
<th>Input voltage (V)</th>
<th>@ 25 Hz</th>
<th>@ 50 Hz</th>
<th>@ 75 Hz</th>
<th>@ 100 Hz</th>
<th>@ 125 Hz</th>
<th>@ 150 Hz</th>
<th>PVR in i(F), v(F)</th>
<th>Slip</th>
<th>Fig. No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy i(F)</td>
<td>400</td>
<td>-4.7</td>
<td>-52</td>
<td>-56</td>
<td></td>
<td></td>
<td></td>
<td>Peaks at nf, (here 50,100,150,..Hz)</td>
<td>0.01</td>
<td>2.1</td>
</tr>
<tr>
<td>Turn-to-turn fault i(F)</td>
<td>400</td>
<td>-33</td>
<td>1.2</td>
<td>-32</td>
<td>-38</td>
<td>-42</td>
<td>-29</td>
<td>Peaks at multiples of f/2 (here 25 Hz)</td>
<td>0.03</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>-41</td>
<td>-8</td>
<td>-40</td>
<td>-50</td>
<td>-54</td>
<td>-50</td>
<td>-59</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>Phase-to-phase fault i(F)</td>
<td>300</td>
<td>-9.5</td>
<td>-31</td>
<td>-26</td>
<td></td>
<td></td>
<td></td>
<td>Multiple sidelobes for peaks at nf, (here 50,100,150,..Hz)</td>
<td>0.34</td>
<td>2.3</td>
</tr>
<tr>
<td>open turn fault in Y-phase no-load condition v(F)</td>
<td></td>
<td>36</td>
<td>3.6</td>
<td>24.6</td>
<td></td>
<td></td>
<td></td>
<td>Multiple sidelobes for peaks at nf, (here 50,100,150,..Hz); peaks for odd harmonics dominate the even harmonic peaks for voltage; but only odd harmonic peaks appear for current</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>Open turn fault in Y-phase load fault v(F)</td>
<td></td>
<td>36</td>
<td>0.13</td>
<td>29</td>
<td></td>
<td></td>
<td></td>
<td>Multiple sidelobes for peaks at nf, The magnitude 5th harmonic &lt; 7th</td>
<td>2.5</td>
<td></td>
</tr>
</tbody>
</table>
2.1.3.5 Case 5 - Machine performance under balanced and unbalanced supply voltage input

Supply voltage imbalance: When voltages of a three-phase system are not identical in magnitude and/or the phase differences between them are not exactly 120 degrees, voltage imbalance occurs (Fuchs & Masoum (2009)). The main causes of voltage imbalance in power systems can be due to unbalanced single-phase loading in a three-phase system, overhead transmission lines that are not transposed, blown fuses in one phase of a three-phase capacitor bank and severe voltage imbalance (e.g., > 5%) which can result from single phasing conditions.

The experimentation is executed here on the test bed with the power supply of three phase four wire been connected with three phase autotransformer (B₁, B₂, B₃, N as input and A₁, E₁, A₂, E₂, A₃, E₃ as output terminals. A voltmeter is connected across E₁ and E₂ to observe the line voltage). Three single phase transformers of 2kVA rating with (0-230V with two input terminals and other 0V, 110V, 166V, 230V as output terminal) are used. Input side common terminals of three single phase transformers are shorted and the same has been done for output terminals which are connected to neutral. Photograph of experimental set-up for balanced and unbalanced supply emulation has been shown in Figure A1.2. The stator current of the three phases of the induction motor with their fewer winding shorted in gradual steps (one phase at a time) has been acquired. To create an unbalance 110V is connected instead of 230V in a phase. The following section discusses the effect on PVR for machine operated on balanced and unbalanced supply voltage input.

(i) Study on healthy machine supplied with balanced input voltage and operating in no-load

The PVR is observed for the healthy rotating machine applied with balanced three phase voltage input as \( V_r = V_y = V_b = 150V \) under no-load
condition as seen in Figure 2.7. PVR of the voltage signal has peaks occurring for both even and odd harmonic though the odd harmonic occurs with higher amplitude than the immediate following even harmonics. The PVR of current signal exhibited peaks only for odd harmonics. The experiment is repeated for loaded condition as shown in Figure 2.8 using mechanical loading. Similar response is obtained though however the higher order odd harmonics are of lower amplitude than seen for no-load condition with also 7th harmonic peak seen vanished. Table 2.3 shows the study on PVR for three phase SCIM supplied with balanced input.

![Diagram](image)

**Figure 2.7** Three phase SCIM with balanced supply under no-load, its (a) Voltage and stator current signal for R-phase (b) PVR in v(F), i(F)
Figure 2.8 Three phases SCIM with balanced supply under half-load
(a) Input voltage and stator current signal for R-phase
(b) PVR in v(F) and i(F)
Table 2.3 Study on PVR for three phase SCIM supplied with balanced input

<table>
<thead>
<tr>
<th>No-load</th>
<th>Harmonic frequencies (Hz) Amplitude of frequencies have peaks varying in response as</th>
<th>Abnormality in spectral PVR</th>
<th>Figure No. for signal</th>
<th>Figure No. for PVR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input (or) Stator Voltage (V)</td>
<td>50Hz &gt; 150Hz &gt; 250Hz &gt; 350Hz &gt; 450Hz</td>
<td>-</td>
<td>2.7(a)</td>
<td>2.7(b)</td>
</tr>
<tr>
<td></td>
<td>100Hz &gt; 200Hz &gt; 300Hz &gt; 400Hz</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input (or) Stator Current (A)</td>
<td>50Hz &gt; 150Hz &gt; 250Hz &gt; 350Hz &gt; 450Hz, even harmonic for i(F) are almost vanished</td>
<td>-</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Load</th>
<th>Harmonic frequencies (Hz) Amplitude of frequencies have peaks varying in response as</th>
<th>Abnormality in spectral PVR</th>
<th>Figure No. for signal</th>
<th>Figure No. for PVR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input (or) Stator Voltage (V)</td>
<td>50Hz &gt; 150Hz &gt; 250Hz &lt; 350Hz &gt; 450Hz</td>
<td>7\textsuperscript{th} &gt; 5\textsuperscript{th} peak</td>
<td>2.8(a)</td>
<td>2.8(b)</td>
</tr>
<tr>
<td></td>
<td>100Hz &gt; 200Hz &gt; 300Hz &lt; 400Hz</td>
<td>Peak 8\textsuperscript{th} &gt; 6\textsuperscript{th}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input (or) Stator Current (A)</td>
<td>50Hz &gt; 150Hz &gt; 250Hz &gt; 350Hz &lt; 450Hz, even harmonic for i(F) is almost vanished</td>
<td>Peak 9\textsuperscript{th} &gt; 5\textsuperscript{th}</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The PVR for balanced input voltage to machine under no-load has the spectra with harmonic peaks of the three phases showing peaks overlapping each other under balanced condition as seen in Figure 2.10 as estimated from their respective voltage and current signals as shown in Figure 2.9.

**Figure 2.9** Voltages of three phases, all the three phase voltages combined and its current signal (B-phase) under no-load
Figure 2.10  PVR showing overlap of voltage peaks of three phases and the phase current peaks for the signals shown in Figure 2.9

(ii) Study on unbalance voltage input on healthy machine

The study on effect of unbalanced voltage input on the healthy rotating machine has been signaturred. The effect of unbalanced voltage on the performance of a faulted rotating machine like the three phase SCIM exhibited the PVR for current signal with even and odd harmonic peaks respectively as seen in Figure 2.12 estimated from their respective current signals shown in Figure 2.11. The PVR in Figure 2.12 has only the RSB for each of the odd harmonic peak at 50Hz, 150Hz, 250Hz and 350Hz. Uniquely even peak at 100Hz has LSB at 75Hz and RSB at 125Hz in both v(F) and i(F).

Figure 2.11 Three phase voltages (V_r, V_y, V_b and combined) and B-phase current signal under no-load
2.1.3.6 Case 6 – Study on machine with stator winding fault subjected to balanced and unbalanced supply

Performance of machine without stator winding fault is compared for machine housing stator winding fault when operated with balanced and unbalanced supply. The experiment test bed is as discussed in section 2.1.3.

The PVR of current spectra exhibited sidebands of 25Hz, 75Hz for harmonic peak at 50Hz, sideband of 125Hz, 175Hz for harmonic peak at 150Hz and so on, in the range of ±25Hz for higher order peaks. The PVR exhibited LSB peaks to be of higher amplitude than the corresponding RSB peaks for each of nf₀ as seen in Figure 2.13. Additional peak at 38Hz and lowered amplitude of peaks due to vibration of the machine observed in the response for unbalanced supply input to the rotating machine as shown in Figure 2.14.
Figure 2.13 PVR for B-phase current under balanced supply voltage input as $175V_{LL}$ in all the three phases.

Figure 2.14 PVR for R-phase current under unbalanced supply voltage input as $128V-150V-128V$ to SCIM
2.1.3.7 Case 7- Single phasing

Experiment on the healthy motor operated under intact R-phase, Y-phase but with B-phase unconnected (single phasing) show voltage and current signals as in Figure 2.15. The machine is operated at rated speed with equal three phase input supply voltages. The PVR are shown from Figure 2.16 to Figure 2.18, wherein it is observed that B-phase shows zeroing voltage. The current spectrum exhibited odd and even harmonic peaks though the odd harmonic peak is of higher amplitude than the immediately following even harmonic peak. Also, the unconnected B-phase had the v(F) with higher order harmonics (n = 5, 7, 9) vanished from 150Hz onwards in the voltage spectrum, although the machine continued to run like a single phase machine.

Figure 2.15 Three phase voltages ($V_r$, $V_y$, $V_b$ and combined) and B-phase current signal
Figure 2.16 PVR in v(F) for R-phase

Figure 2.17 PVR in i(F) for unconnected B-phase
Machine voltage and current signaturing through spectral analysis for stator winding fault shows that the PVR in the spectrum has the harmonics with sidebands absent for healthy machine; Odd and even harmonics are present for turn-to-turn fault and multiple sidelobes distribution appear for phase-borne faults.

2.2 ROTOR FAULT DETECTION IN THREE PHASE SQUIRREL CAGE INDUCTION MOTOR

Two different types of squirrel cage rotors are common for induction motors namely, cast and fabricated. Cast cage rotors that are used in motors upto 3000kW rating. Fabricated cages are used for higher ratings and special application machines, wherein possible failure occurs on bars and end ring segments. Cast rotors are impossible to repair after bar breakages or cracks although they are more durable and rugged than fabricated cages. Broken bar and cracked end ring fault share nearly 5-10% of induction motor faults as discussed by Bellini et al (2008).
In the case of stator faults, the operation of the machine is limited to a few seconds only whereas in the case of rotor faults, the operation is not restricted in anyway. Nandi et al (2005), Culbert & Rhodes (2007) demonstrate that MCSA can be extensively used to detect broken rotor bar and end-ring faults in induction machines. The causes for rotor bar and end-ring breakage as discussed in Nandi et al (2005) are:

(i) Thermal stresses due to thermal overload and unbalance, hot spots, or excessive losses, sparking (mainly in fabricated rotors)

(ii) Magnetic stresses caused by electromagnetic forces, unbalanced magnetic pull, electromagnetic noise and vibration

(iii) Residual stresses due to manufacturing problems

(iv) Dynamic stresses arising from shaft torques, centrifugal forces and cyclic stresses

(v) Environmental stresses caused by the contamination and abrasion of rotor material due to chemicals or moisture

(vi) Mechanical stresses due to loose laminations, fatigued parts, bearing failure, etc.

Guasp et al (2008) applied DWT (db44, decomposition level=6, Fs=5kHz) to commercial cage motors with 4 pole, 28 rotor bars, 1.1kW, 400V, 50Hz for the detection of rotor asymmetries (one rotor bar broken and mixed eccentricity) in two alternative ways, i.e., by using the startup current and by using the current during plugging stopping.

The following section discusses on rotor fault analysis through empirical and experimental study.
2.2.1 Experimental Test set up for Rotor Fault Detection

Three phase SCIM of two different ratings have been used for experimental study on the rotor bar broken fault. The rating of the first motor with mechanical loading is 415V, 1.5 kW/2hp, 1430RPM, 3.4A with one rotor bar broken (a hole has been drilled through the bar) as shown in Figure 2.19. Experiment (i) and (ii) has been conducted with the first motor. Photograph of experimental test bed for TPSCIM rotor bar broken fault emulation is shown in Figure A1.3.

The rating of the second motor coupled with DC generator is 415V, 3 phases, 2 poles, 50Hz, 0.7A, 2850RPM, 600turns/phase, 24 slots. Tapping has been taken at 3rd, 5th, 10th, 20th, 150th and 300th turns for stator winding shorting. Some portion of equidistant dimension has been cut as shown in Figure 2.20 and removed at four places on the cage rotor to emulate a poor flux linking pattern. An iron strip of that size has been introduced by inserting in those cut portions as shown in Figure 2.21, so that the cage rotor has totally four iron strips to emulate healthy rotor state and only two iron strips to emulate fault rotor state. Experiment (iii)-(vi) has been conducted with second motor. Figure 2.22 shows axial view of rotor with one iron strip removed in the second motor. Photograph of experimental test bed for TPSCIM rotor crack fault emulation is shown in Figure A1.4.

Various experiments were conducted under no-load and full-load operation under the following conditions:

(i) Healthy rotor

(ii) One rotor bar broken

(iii) Rotor with four iron strips
(iv) Rotor with two iron strips removed out of four iron strips

(v) Continuation of experiment (iii) with stator winding short circuit fault (300th tapping of R-phase and neutral shorted)

(vi) Continuation of experiment (iv) with stator winding short circuit fault (10% of winding short in R-phase)

For the different experiments mentioned above the three phase currents of these motors have been acquired through a data acquisition unit as described in Section 1.6 and analyzed through signal processing technique as discussed in Section 1.7.2.

Figure 2.19 Rotor with one rotor bar broken

Figure 2.20 Cage rotor with its portion removed
2.2.2 Results and Discussions

2.2.2.1 Case 1 – Experiment (i)-(iv) conducted under no-load condition

(i) Machine with healthy rotor under no-load condition

The PVR of current spectrum exhibits peaks at both even and odd harmonics for the healthy machine used in the experiment. The energy of the peak at the odd harmonics is higher, and the subsequent even harmonic peak almost vanishes.
In Figure 2.23 the peaks are observed for odd harmonics at 50Hz, 150Hz, 250Hz, 350Hz, 450Hz and for even harmonics at 100Hz, 300Hz, though 200Hz and 400Hz are vanished here. Also the amplitude of odd harmonic peaks are with

\[ 1^{st} > 3^{rd} \]
\[ 3^{rd} > 5^{th} \]
\[ 5^{th} > 7^{th} \]

But \( 7^{th} < 9^{th} \)

That is, the \( 9^{th} \) harmonic has higher amplitude than other nearer lower order odd harmonic peaks.

(ii) Machine with one rotor bar broken under no-load condition

The PVR of current spectrum exhibits odd harmonics and sometimes lacks even harmonics as shown in Figure 2.24. The peaks appears for odd harmonics at 50Hz, 150Hz, 250Hz, 350Hz, 450Hz and the even harmonics at 200Hz, 300Hz. Also the amplitude of the harmonic peaks have

\[ 1^{st} > 3^{rd} \]
\[ 3^{rd} < 5^{th} \]
\[ 5^{th} < 7^{th} \]
\[ 7^{th} > 9^{th} \]

that is, the \( 7^{th} \) harmonic peak has higher amplitude compared to \( 3^{rd}, 5^{th} \) and \( 9^{th} \) odd harmonic peaks.
Figure 2.23  PVR of current spectrum for healthy rotor under no-load condition

Figure 2.24  PVR of current spectrum for one rotor bar broken under no-load
(iii) Machine with rotor having four iron strips inserted and operated under no-load condition

The PVR in current spectra exhibits only odd harmonics with amplitude of peaks of higher order odd harmonics gradually decreasing. Also these frequency peaks show more right shift with increasing frequency. The even harmonic seen at 100Hz uniquely with the rest of even harmonic frequencies are gradually vanished as seen in Figure 2.25. The expected odd harmonic frequency peaks

50Hz, 100Hz, 150Hz, 250Hz, 350Hz, 450Hz appears with right shifts as

51Hz, 103Hz, 154Hz, 260Hz, 360Hz, 463Hz. The amplitude of the harmonics are with

1\textsuperscript{st} > 3\textsuperscript{rd}

3\textsuperscript{rd} > 5\textsuperscript{th}

5\textsuperscript{th} > 7\textsuperscript{th}

7\textsuperscript{th} > 9\textsuperscript{th}

Figure 2.25 PVR of current spectrum for rotor with four iron strips at no-load
(iv) Machine with rotor having two iron strips removed and operated under no-load condition

The PVR in current spectrum exhibits only odd harmonics with lowered amplitude levels as shown in Figure 2.26. Amplitude of $50\text{Hz} > 150\text{Hz} > 250\text{Hz}$. That is

$1^{\text{st}} > 3^{\text{rd}} > 5^{\text{th}}$ harmonic and

the higher harmonics $7^{\text{th}}, 9^{\text{th}}$ etc. vanished.

The even harmonics does not exist. However it is noticed that with one rotor bar broken, PVR shows that along with the $200\text{Hz}$ component, the $5^{\text{th}}, 7^{\text{th}}$ harmonic are more pronounced in the faulty machine compared with healthy one as seen in Figure 2.27. The figure shows the PVR with spectral comparison of healthy rotor, one bar broken rotor, rotor with four iron strips intact and rotor with two iron strips removed. The difference under no-load condition between healthy and one rotor bar broken is that, one rotor bar broken has amplitude of seventh harmonic greater compared to healthy machine and also exhibits even harmonic at $200\text{Hz}$. Comparing four and two iron strips rotors, the amplitude of four strips rotor is greater than the two strips rotor with harmonic frequency shift towards the right for the higher harmonic frequency peaks.
Figure 2.26  PVR of current spectrum for rotor with two iron strips removed under no-load

Figure 2.27  PVR of current spectrum for SCIM with four iron strip, two iron strip, good rotor and rotor with one bar broken under no-load condition
2.2.2.2 Case 2 Experiment (i)-(iv) conducted under loaded condition

(i) Machine with healthy rotor and operated under half-load condition

The healthy SCIM machine used in the experiment exhibited harmonic PVR in the spectral distribution of current with strong odd harmonics 1\textsuperscript{st}, 3\textsuperscript{rd}, 5\textsuperscript{th}, 7\textsuperscript{th}, 9\textsuperscript{th} etc. and sometimes faint even harmonics as shown in Figure 2.28. The amplitude of 5\textsuperscript{th} harmonic peak is greater than 3\textsuperscript{rd} harmonic and the 9\textsuperscript{th} harmonic is greater 7\textsuperscript{th} harmonic peak.

\begin{align*}
1\textsuperscript{st} & > 3\textsuperscript{rd} \\
3\textsuperscript{rd} & < 5\textsuperscript{th} \\
5\textsuperscript{th} & > 7\textsuperscript{th} \\
7\textsuperscript{th} & < 9\textsuperscript{th}
\end{align*}

![Figure 2.28 PVR of current spectrum for healthy rotor under half-load](image)

Figure 2.28 PVR of current spectrum for healthy rotor under half-load
(ii) **Machine with one rotor bar broken and operated under half-loaded condition**

The PVR of spectral distribution of current signal exhibits the odd harmonics only with its amplitude for harmonic peaks

\[
1^{st} > 3^{rd} \\
3^{rd} < 5^{th} \\
5^{th} < 7^{th} \text{ and} \\
7^{th} > 9^{th}
\]

as seen in Figure 2.29 for machine with one rotor bar broken and energized to rotate under loaded condition. The amplitude of the peak frequencies is higher for loaded condition. But, the 7\(^{th}\) harmonic has higher amplitude than other odd 3\(^{rd}\), 5\(^{th}\), 9\(^{th}\) harmonic peaks which showed similar response to that under no-load condition as in Figure 2.24, though however, the even harmonic peaks like 200Hz, 300Hz etc. are also vanished.

![Figure 2.29](image_url)  
**Figure 2.29** PVR of current spectrum for one rotor bar broken under half-load
(iii) Machine with rotor with four iron strips intact and operated under half-loaded condition

The PVR of current spectrum exhibits unique pattern of sidebands to the fundamental as subharmonic peaks at 40Hz, 30Hz, 20Hz, 10Hz on the LSB and 60Hz for the RSB for the motor rotating at a speed of 2690RPM and 0.6 slip as in Figure 2.30.

This response is seen also when theoretically evaluated which confirm the presence of rotor fault as shown in Table 2.4

Table 2.4 is derived from the fact that the rotating field of machine with any rotor asymmetry generates a component \((1-2ks)f\) in the stator current spectrum with the assumption of constant speed or infinite inertia (where \(f\) is the frequency of supply voltages, harmonic order \(k=1,2,3…\) and \(s\) the machine slip). In addition, frequency components at \((1+2ks)f\) also appear in the current spectrum which are observed in the experiments. The sideband frequency components are equally spaced around the peak odd harmonic frequency. These sideband frequencies shift from the corresponding main peak frequency more for increasing load due to the increased slip as in Figure 2.33.

Table 2.4 PVR for rotor with four iron strips under load

<table>
<thead>
<tr>
<th>Speed</th>
<th>Slip</th>
<th>k=1;50Hz</th>
<th>k =3;150Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>LSB</td>
<td>RSB</td>
</tr>
<tr>
<td>2690</td>
<td>0.6</td>
<td>n</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>10</td>
</tr>
</tbody>
</table>
Figure 2.30  PVR of current spectrum for rotor with four iron strips under half-load condition

(iv) Machine with rotor of two iron strips removed and operated under half-load

PVR of current spectrum for rotor with two strips removed and machine energized to operate under load exhibits only a few odd harmonics at 50Hz, 150Hz though the higher odd harmonics vanished. Also, a unique peak at 37Hz occurs which is deemed as a lower sideband peak frequency (50/1.43) of the fundamental frequency as shown in Figure 2.31 for the motor rotating at 1570RPM and 0.48 slip.

PVR with spectral comparison in rotating machine with healthy rotor, one rotor bar broken, rotor with four intact iron strips and rotor with two iron strips removed under half-load condition have been shown in Figure 2.32. The amplitude of fundamental peak for one rotor bar broken is greater, compared to that for the machine with good rotor. The amplitude of
fundamental peak for machine with intact four iron strip rotor is greater than that for machine with two iron strip rotor removed.

Figure 2.31 PVR of current spectrum for rotor with two iron strips under half-load condition

Figure 2.32 PVR of current spectrum for healthy rotor, rotor with one rotor bar broken, rotor with four iron strip and rotor with two iron strip removed all under half-load
2.2.2.3 Case 3 Experiment (v)-(vi) rotor and stator fault

(i) Machine with rotor of four iron strip intact though with stator winding short under no-load condition

This experiment (v)-(vi) has been performed with second motor to analyze the rotating motor with both rotor and stator faults i.e., multiple faults. The stator winding fault is deliberately created by shorting a tapping in R-phase with neutral and for this experiment four iron strips are fixed like for a good rotor bar simulation. The acquired stator current has been analyzed using spectrum of current. The fault frequencies are theoretically calculated for rotor fault as discussed in Section 2.2 and stator fault through Equation (2.1). The occurrence of the specific fault frequencies in the PVR of current spectrum in experiment and theoretical calculation confirms the presence of fault.

The peak response variation in spectral distribution for stator faults exhibited peaks only at odd harmonic though the fundamental has sidebands on both sides at submultiples of 50/a, where a = 2, 1.34. The LSB peaks at 25Hz and 38Hz and the RSB peaks at 62Hz and 75Hz. As the load increases the sideband frequencies shifts from the fundamental as 34Hz and 16Hz as shown in the Figure 2.33 and results are discussed in Table 2.5. By observing the previous experiments, it is noticed that the sideband frequencies 25Hz and 75Hz are due to the stator winding fault.

Frequency of 38Hz peak in due to the presence of rotor fault for the motor rotating at 1490RPM and 0.5 slip under no-load condition while under the loaded condition the sideband frequencies 16Hz and 84Hz represent the presence of rotor fault while, 33Hz and 67Hz represent the presence of stator winding fault with the motor rotating at higher speed of 1990RPM and 0.34 slip.
Table 2.5 Response calculated for rotor with four iron strip and R-phase-neutral winding short circuited in stator

<table>
<thead>
<tr>
<th>Slip</th>
<th>Speed (RPM)</th>
<th>Calculation for rotor fault sideband (Hz) n=1</th>
<th>Calculation for Stator fault sideband (Hz) n=1</th>
<th>Experimental condition</th>
<th>Figure No.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>LSB</td>
<td>RSB</td>
<td>LSB</td>
<td>RSB</td>
</tr>
<tr>
<td>0.34</td>
<td>1990</td>
<td>16</td>
<td>84</td>
<td>33</td>
<td>67</td>
</tr>
<tr>
<td>0.5</td>
<td>1490</td>
<td>38</td>
<td>62</td>
<td>25</td>
<td>75</td>
</tr>
</tbody>
</table>

Figure 2.33 PVR of current spectrum for phase and neutral winding shorted under no-load and load condition for rotor with intact four iron strips

X: 16.25, Y: -34.21  
X: 24.58, Y: -29.84
(ii) Rotor with two iron strips removed and 10% winding short in R-phase under no-load condition

Table 2.6 Response in current spectrum for rotor with two iron strips removed and stator with 10% winding short in R-phase under no-load condition

<table>
<thead>
<tr>
<th>Slip Speed (RPM)</th>
<th>Calculated Rotor fault sideband (Hz) n=1</th>
<th>Calculated Stator fault sideband (Hz) n=3</th>
<th>Experimental (Hz)</th>
<th>Condition</th>
<th>Figure No.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LSB, RSB 30, 130</td>
<td>LSB, RSB 5, 105</td>
<td>Stator 5, 105</td>
<td>no-load</td>
<td>2, 34</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>rotor 28, 128</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This experiment has been conducted to emulate stator fault short along with rotor fault by removing two iron strips out of four strips, while operating the machine under no-load condition. The stator winding fault considered is 10% winding short in R-phase.

The PVR of current spectrum exhibited the odd harmonics with corresponding left sideband peaks at 25Hz, 125Hz, 225Hz and the corresponding expected right sideband peaks at 75Hz, 175Hz, 275Hz vanished for the respective 1\textsuperscript{st}, 3\textsuperscript{rd}, 5\textsuperscript{th} harmonic peaks. Interestingly the even harmonic peaks appear instead as RSB peaks as discussed in Table 2.6.
This section has discussed on PVR for rotor bar broken under no-load and half-load condition as single fault type and with stator winding short circuited to emulate multiple fault type.

### 2.3 DETECTION OF FAULTS IN BEARINGS COUPLED TO ELECTRIC MOTORS

Installation problems are often caused by improperly forcing the bearing onto the shaft or in the housing. This produces physical damage in the form of brinelling or false brinelling of the raceways, which leads to premature failure. The impact of the bearing vibration on the stator current spectra can be determined since any air-gap eccentricity produces anomalies in the air-gap flux density. Since ball bearings support the rotor, any bearing defect will produce a radial motion between the rotor and stator of the machine. Misalignment of the bearing occurs in four ways namely inner race, outer race, ball or cage fault. Most condition monitoring techniques for rolling element bearings are designed to detect (due to race, bearing etc) four
characteristic-fault’ frequencies. This has lead to the common practice of categorizing bearing faults according to fault location. The stator current of the three phase induction machine has been analyzed through statistical methods, time domain and frequency domain methods to detect various types of bearing faults. The theoretical results are verified experimentally with a variable speed drive whose shaft is coupled with the bearing.

2.3.1 Literature on Methods for Bearing Fault Detection

Al Kazzaz & Singh (2003) discussed the treatment of raw data obtained from physical machine parameters. The implementations of various DSP and analysis techniques in time and frequency domain with different machine variables are given. Signal detectors such as mean square value and crest factor are used with the voltages, currents and vibration signals in time domain. In addition, signal filtering, signal averaging and correlation are used in time and frequency domain simultaneously. FT and STFT are used to present the time domain signal in frequency domain. The obtained vibration spectrum is analyzed using narrow band, variable band, selected band and spectrum masking approaches. The data implemented with mentioned techniques covers different operating conditions of the machine under test.

Stack et al (2004) presented a method for performing stator-current-based bearing condition monitoring. A review of the sources of significant frequency components observed in a typical stator current spectrum was presented, which allows the significant nonbearing fault components to be removed from the stator current. The sources removed included, supply voltage fluctuations, cyclical load torque variations, and other nonbearing faults sources. The need for an efficient and compact spectral representation was then motivated, and the autoregressive spectrum estimation technique was reviewed to fill this need. A bearing fault index was developed based on the mean spectral deviation. In this method, the frequency content of the
filtered stator current was modeled. A baseline or reference model was computed while the bearings were healthy. As the bearing health degraded, the deviation in spectral content from its baseline measurement increased. This increase in spectral deviation was then used as the fault index.

Zarei & Poshtan (2007) discuss detection of incipient bearing defect (A - Healthy, B-1mm outer race, C – 1mm inner race, D – 3mm inner race and E- 2 holes in outer race) using the stator current analysis via Meyer wavelet (high frequency resolution, 8 levels) in wavelet packet structure, with energy comparison as the fault index. In this study a three-phase, 1.2kW, 380V, 50Hz, 1400RPM, four pole induction motor was used. In all the tests, the machine is connected to a line directly. Stator current is sampled at Fs=2kHz before and after the defects are made. The average periodogram of signals with a sample number of N=80,000, Hanning window with length L=4000 and 50% overlap have been used for signal analysis.

Gunal et al (2009) present a new approach to induction machine condition monitoring using Notch Filtered Motor Current Signature Analysis (NFMCSA), which is performed in time domain to extract features of energy, sample extrema, third and fourth cumulants evaluated from data within sliding time window. The experimental verification of the proposed method are shown to be done with six identical induction motors of which one is healthy motor and other five are with synthetic faults such as bearing faults, broken bar (3, 5 nos.) and arbitrarily shorted stator winding faults. All motors are rated at three phase, 2.2kW, 4 pole, 50Hz, 380V_{LL}. Tests were conducted at various loading condition of 5A, 4.7A and 4.1A corresponding 5% overload, full load and half load. Load test is accomplished by coupling induction motors with a single-phase permanent magnet synchronous generator connected to an adjustable resistive load bank. The classification of faulty motors with the proposed parameters is performed using three well
known classifiers namely Bayesian, Gaussian Mixture Model (GMM), and Fisher’s Linear Discriminant Analysis (LDA) to verify the effectiveness and the success of the proposed feature set.

As discussed in Bellini et al (2008) about 40–50% of induction motor faults are related to mechanical defects. Among them a rough classification includes: damage in rolling element bearings, due to static and dynamic eccentricity. Most electrical machines use either ball or rolling-element bearings, which consist of two rings namely the outer and inner rings. Balls or rolling elements rotate in raceways inside the rings. Bearing faults may be reflected in defects of outer race, inner race, ball, or train. Even under normal balanced operation with good shaft alignment, fatigue faults can take place. Vibrations, internal stresses, inherent eccentricity, and bearing currents due to electronic drive systems have strong influence on developing such faults. In a general way, a fault in the load part of the drive gives rise to a periodic variation of the induction motor load torque. Examples for such faults causing torque oscillations include: general fault in the load part of the drive system, e.g. load imbalance, shaft misalignment, gearbox faults, bearing faults. Torque oscillations already exist in a healthy motor due to space and time harmonics of the air-gap field, but the considered fault related torque oscillations are present at particular frequencies, often related to the shaft speed. Shaft vibration frequencies associated with different ball bearing faults were given as in Equation (2.2)-(2.5).

In the following the symbol \( F_C \) will be used for the cage fault frequency, \( F_I \) for the inner raceway fault frequency, \( F_O \) for the outer raceway fault frequency, \( F_B \) for the ball fault frequency, \( F_R \) for the shaft rotating frequency, \( D_b \) for the ball diameter, \( D_c \) for the pitch diameter, \( N_B \) for the number of rolling elements, \( \beta \) for the ball contact angle.
Typically, bearing faults are detected through vibration signals. The use of electrical signals is, however, preferable in many applications. Al Kazzaz & Singh (2003), Stack et al (2004), Zarei & Poshtan (2007), Gunal et al (2009) and Bellini et al (2008) discuss on the analysis of the current of the induction machine. The link between vibration and current components can be presented as follows: the vibration component at one of the mechanical characteristics frequency of the defect $f_{car}$ acts on the electrical machine as a torque ripple $\Delta T(t)$ that produces a speed ripple $\Delta \omega(t)$. The consequent mechanical angular variation produces an angular fluctuation in the magnetic flux. Hence the vibration is seen as a torque component that generates in the current two components at frequencies at $F_{be}$:

$$F_{be} = \left| f \pm kf_{car} \right|$$ (2.6)

where $f$ is the supply frequency and $k$ is harmonic order. Therefore bearing faults generate stator currents at predictable frequencies $F_{be}$, related to the mechanical characteristics frequency and electrical supply frequency.
2.3.2 Experimental Test bed for Bearing Fault Diagnosis

The schematic of the test bed for bearing fault diagnosis is shown in Figure 2.35. A single phase, 230V, 50Hz supply has been given to 11kW, single phase to three phase inverter used for Variable Speed Drive (VSD), which feeds the three phase, 50Hz, Δ415V, 4.6A, 2.2/3kW, 1400 RPM induction motor. The test rig contains a shaft connected to the motor with a flexible coupling arrangement. The shaft is supported by two bearings (NACHI 6006 ZZ, single row deep groove ball bearing mounted in plummer block) at its mid portion. The flexible coupling between motor and shaft ensures that the shaft is not affected from any of the vibrations from the motor, accommodating any misalignments present in the assembly. The type of bearing used for testing is SKF 6307 2Z whose dimensions are discussed in Table 2.7. Photograph of experimental test bed for bearing fault emulation is shown in Figure A1.5.

The loading of the bearing is done through hydraulic load arrangement with a pressure gauge of two Ton capacity operated with manual pressure pump and load cell. After allowing the bearing an initial run, motor current is acquired for operating conditions of no-load and load of 1000N. After collecting current data from machine under healthy bearing as shown in Figure 2.36, various defective bearings namely bearing with ball fault, inner
and outer race are shown in Figure 2.37 and Figure 2.38 and are tested at no-load and load condition at variable speed. Figure 2.36 to Figure 2.38 show the snapshots for the bearing at various conditions used for experimental analysis.

**Test bearing**

The test bearing used in this experiment is SKF 6307 2Z, single row deep groove ball bearing [22]. The specifications of bearing are given in Table 2.7. Here, single point damage is created on bearing, typically by drilling the outer race surface, with punch mark on the ball and by Electric Discharge Method (EMD) on the inner race.

**Table 2.7 Specifications of bearing**

<table>
<thead>
<tr>
<th>Bearing Parameters</th>
<th>Make : SKF 6307 2Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearing OD (mm)</td>
<td>80</td>
</tr>
<tr>
<td>Bearing ID (mm)</td>
<td>35</td>
</tr>
<tr>
<td>Bearing width (mm)</td>
<td>21</td>
</tr>
<tr>
<td>Ball diameter (mm)</td>
<td>14.5</td>
</tr>
<tr>
<td>Pitch diameter (mm)</td>
<td>57.5</td>
</tr>
<tr>
<td>No. of balls</td>
<td>8</td>
</tr>
<tr>
<td>Dynamic load ratings (kN)</td>
<td>33.2</td>
</tr>
<tr>
<td>Static load ratings (kN)</td>
<td>19</td>
</tr>
<tr>
<td>Speed rating with grease (rpm)</td>
<td>8500</td>
</tr>
</tbody>
</table>
Figure 2.36 Good bearing assembly

Figure 2.37 Bearing with ball fault

Figure 2.38 Bearing with inner and outer race fault
2.3.3 Results and Discussions

Using the above discussed experimental test bed the induction motor single phase current has been acquired under no-load and load condition at variable speed. The acquired motor current has been analyzed through time and frequency domain under different fault conditions like ball fault, inner and outer race fault and the same has been compared with a good bearing as discussed in the following section.

2.3.3.1 Time domain analysis

The machine is mounted with the various bearings for various experimental study. The machine is allowed to operate upto rated speed and the current is acquired using DAQ discussed in Section 1.6. In time domain analysis, RMS and crest factor discussed in Section 1.7.1 are evaluated on current signal and plotted for various slip values. The RMS value for a healthy bearing is observed to be 4.2A at 0.7 slip. The RMS value changes as 4.6A for inner and outer race fault and to 4A for ball fault as shown in Figure 2.39 for no-load condition. Similar response is experimentally observed for the three phase squirrel cage induction motor under load condition as shown in Figure 2.41. The crest value is calculated and is as 0.2 for a slip of 0.7 for good bearing which changes to 1.7 for inner and outer race and as 2 for ball fault as seen in Figure 2.40.

RMS and crest factor values are higher for inner and outer race fault compared to healthy bearing. For healthy bearing the RMS value is higher and Crest factor is lesser compared to the values for ball fault. Similar response is observed for both no-load and load condition as presented in Figure 2.40 and Figure 2.42.
Figure 2.39  Slip Vs RMS of the motor current for bearing with healthy ball fault, inner and outer race fault bearings under no-load condition

Figure 2.40  Slip Vs Crest factor of the motor current for bearing with healthy, ball fault, inner and outer race fault under no-load condition
Figure 2.41  Slip Vs RMS of the motor current for bearing with healthy, ball fault, inner and outer race fault under load condition (2000N)

Figure 2.42  Slip versus crest factor of the motor current for bearing with healthy, ball fault, inner and outer race fault under load condition (2000N)
2.3.3.2 Frequency domain analysis

The bearing fault diagnosis through frequency domain analysis has been discussed in this section. By substituting Equation (2.7) in Equation (2.2)-(2.5) the Equation (2.9)-(2.12) can be obtained as reported in Nandi et al (2005).

\[
\frac{D_b \cos \beta}{D_c} \approx 0.2
\]  

(2.7)

which implies that

\[
\cos \beta \approx 1; \frac{D_b}{D_c} = 0.2
\]  

(2.8)

\[
F_o = 0.4N_b f_r
\]  

(2.9)

\[
F_l = 0.6N_b f_r
\]  

(2.10)

\[
F_b = 4.8f_r
\]  

(2.11)

\[
F_c = 0.4f_r
\]  

(2.12)

By substituting for \( f_r = \text{(speed/60)} \) in Hz and \( N_b = 8 \) in the Equation (2.9)-(2.12) and then substituting these values in Equation (2.6) the fault frequencies are calculated.

Case 1 – Machine with healthy bearing

The PVR has spectrum with peaks each at harmonic values \( n=1, 5, 7 \) with the third harmonic vanished, but fifth harmonic is pronounced. The harmonic peaks have LSB lower in amplitude than RSB. Thus fundamental frequency has amplitude of 25Hz < 75Hz, third harmonic has 125Hz < 175Hz and fifth harmonic has 225Hz < 275Hz etc. Similar response is seen for both
load and no-load operation of the SCIM. Table 2.8 discusses the PVR for healthy and ball bearing fault. Figure 2.43 represents the PVR in stator current spectrum for good bearing under no-load and load condition. The PVR in current spectrum exhibits peaks at 1\textsuperscript{st} (50Hz) and 5\textsuperscript{th} harmonic (250 Hz) for load and no-load condition for healthy bearing.

![Figure 2.43 PVR in spectrum of stator current for good bearing under no-load and load of 2000N](image)

Table 2.8 PVR for healthy and ball fault bearing under no-load and load condition

<table>
<thead>
<tr>
<th>Bearing condition</th>
<th>Machine operation</th>
<th>PVR in spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy bearing</td>
<td>Machine operation</td>
<td>PVR in spectrum</td>
</tr>
<tr>
<td></td>
<td>Noload LSB, n, RSB</td>
<td>Same but with 10dB lower LSB compared to RSB in amplitude levels for loaded condition</td>
</tr>
<tr>
<td></td>
<td>Load</td>
<td>Same third harmonic 150Hz is almost vanishing</td>
</tr>
<tr>
<td>Bearing holding</td>
<td>Machine operation</td>
<td>PVR in spectrum</td>
</tr>
<tr>
<td>Ball fault</td>
<td>Noload LSB, n, RSB</td>
<td>Same third harmonic 150Hz is almost vanishing</td>
</tr>
<tr>
<td></td>
<td>Load</td>
<td>Third harmonic 150Hz is almost vanishing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LSB &lt; RSB in amplitude</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Loading lowers amplitude of peaks</td>
</tr>
</tbody>
</table>
Case 2 – Machine with ball bearing fault

Experimental analysis for machine with ball bearing fault is done with various faults induced on the bearing. Stator currents’ spectrum for bearing with ball fault under no-load condition rotating at 1409RPM is shown in Figure 2.44. The PVR from DSP analysis of current has spectral distribution exhibit subband frequencies for $1^{st}$, $3^{rd}$, $5^{th}$ and $7^{th}$ harmonics etc. The harmonic peaks have side band peaks shifting more away from their respective peak frequencies as load increases. Even if load is increased by 1000N to 2000N causing speed change from 1413RPM to 1424RPM. The PVR showed both the LSB and RSB shifted as follows for harmonic peaks with shift as $3^{rd}$ +12Hz, $5^{th}$ +24Hz, $7^{th}$ +36Hz as presented from theoretical calculation using Equation (2.11) shown in the Table 2.11.

Stator currents spectrum for ball fault under 1000N load condition rotating at 1413RPM is shown in Figure 2.45. The PVR of current spectrum exhibits RSB sideband frequencies representing the ball fault, which appears at 164Hz and 291Hz, with a magnitude of -39dB and -35dB.

Stator current’s power spectrum for ball fault under 2000N load and rotating at a different speed of 1424 RPM is shown in Figure 2.46. The PVR of spectrum exhibits sideband frequencies representing the ball fault, which appears at 177Hz and 291Hz with a magnitude of -35dB and -36dB represents the ball fault. Table 2.9 discusses PVR for machine with ball bearing fault.

<table>
<thead>
<tr>
<th>Figure No.</th>
<th>condition</th>
<th>Sideband frequencies (theoretical) (Hz)</th>
<th>Sideband frequencies (experimental) (Hz)</th>
<th>Speed (RPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.44</td>
<td>No-load</td>
<td>161.7, 387.2</td>
<td>161, 385.7</td>
<td>1409</td>
</tr>
<tr>
<td>2.45</td>
<td>1000 N</td>
<td>162, 290</td>
<td>163.6, 290.5</td>
<td>1413</td>
</tr>
<tr>
<td>2.46</td>
<td>2000 N</td>
<td>178.8, 292.8</td>
<td>177, 290.5</td>
<td>1424</td>
</tr>
</tbody>
</table>
Figure 2.44  PVR in spectrum of stator current for machine operating with bearing holding ball fault under no-load condition

Figure 2.45  PVR in spectrum of stator current for machine operated with bearing holding of ball fault under 1000N load
Case 3 - Machine with bearing of inner and outer race faults

The experimental test bearing has hole of 4mm diameter both in inner and outer race. The fault frequencies for inner race and outer races have been calculated separately. Table 2.10 presents the values calculated theoretically for the specifications of the test sample as given in Table 2.7. The presence of corresponding sidebands frequencies for both inner and outer race faults has been verified using the spectrum of the acquired current signal.

Figure 2.47 represents the stator current spectrum for inner and outer race fault under no-load condition with motor rotating at 1410RPM. The innerrace fault mimic ball fault. But the PVR shows the fault with larger energy for the peaks, particularly for the first, fifth harmonic compared to that for ball fault. The peaks show LSB, RSB of 25Hz shift on either side from the corresponding main peaks at n = 1, 3, 5, 7.

Spectrum of current for bearing with inner and outer race fault is discussed here. PVR of currents’ spectrum exhibits sideband frequencies similar to no-load condition, but the higher harmonic peaks at n = 3, 5, 7, 9
have sidebands vanished under 2000N load and rotating at 1480RPM as seen in Figure 2.49 and for 1000N load rotating at 1385RPM the higher harmonic peaks with respective sidebands are totally vanished as seen in Figure 2.48.

Inner-outer race has PVR in current spectrum exhibits odd harmonics. Each of the harmonic peaks has LSB and RSB which mimic similar to ball fault. The third and seventh harmonics are of very low value. Even though compared to ball fault the amplitude level of all the PVR are similar, it is observed that odd harmonic peaks were similar for race fault. This pattern is observed for both no-load and load condition as discussed in Table 2.10 and in Figure 2.47 to Figure 2.49.

### Table 2.10 PVR for machine with bearing of inner and outer race fault

<table>
<thead>
<tr>
<th>Figure No.</th>
<th>Inner and outer race Bearing fault Condition</th>
<th>Sideband frequencies (Hz) Experimental</th>
<th>Sideband frequencies theoritical (Hz)</th>
<th>Speed (RPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.47</td>
<td>No-load</td>
<td>24.4, 177</td>
<td>26.21,176.6</td>
<td>1410</td>
</tr>
<tr>
<td>2.48</td>
<td>Load (1000N)</td>
<td>23, 68(inner race) Higher order harmonic Vanished</td>
<td>24.8, 69.4 (inner race)</td>
<td>1385</td>
</tr>
<tr>
<td>2.49</td>
<td>Load (2000N)</td>
<td>24 Higher order appear again</td>
<td>24</td>
<td>1480</td>
</tr>
</tbody>
</table>

Inner race mimic ball fault since both have same pattern. But spectrum shown for inner race has larger area under 1\textsuperscript{st}, 5\textsuperscript{th} harmonic compared to ball fault. Table 2.11 lists the estimated fault frequencies through Equation (2.2)-(2.12) for ball fault, inner race fault and outer race fault under no-load and load condition and its PVR.
Figure 2.47  PVR in spectrum of stator current for inner and outer race under no-load

Figure 2.48  PVR in spectrum of stator current for inner and outer race under 1000N load
Figure 2.49  PVR in spectrum of stator current for inner and outer race under 2000N load

Table 2.11 PVR for bearing fault analysis

<table>
<thead>
<tr>
<th>Ball fault</th>
<th>n</th>
<th>NoLoad</th>
<th>Load (1000N)</th>
<th>Load (2000N)</th>
<th>PVR</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSB</td>
<td>1</td>
<td>64</td>
<td>64</td>
<td>65</td>
<td>1\textsuperscript{st} + 12</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>176</td>
<td>177</td>
<td>179</td>
<td>3\textsuperscript{rd} + 24</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>289</td>
<td>290</td>
<td>293</td>
<td>5\textsuperscript{th} + 36</td>
</tr>
<tr>
<td>RSB</td>
<td>1</td>
<td>162</td>
<td>162</td>
<td>163</td>
<td>3\textsuperscript{rd} + 12</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>274</td>
<td>275</td>
<td>277</td>
<td>5\textsuperscript{th} + 24</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>387</td>
<td>388</td>
<td>391</td>
<td>7\textsuperscript{th} + 36</td>
</tr>
<tr>
<td>Outer race</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LSB</td>
<td>1</td>
<td>26</td>
<td>25</td>
<td>30</td>
<td>1\textsuperscript{st} – 25</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>101</td>
<td>99</td>
<td>109</td>
<td>3\textsuperscript{rd} – 50</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>177</td>
<td>173</td>
<td>188</td>
<td>5\textsuperscript{th} – 75</td>
</tr>
<tr>
<td>RSB</td>
<td>1</td>
<td>124</td>
<td>123</td>
<td>128</td>
<td>3\textsuperscript{rd} – 25</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>199</td>
<td>197</td>
<td>207</td>
<td>5\textsuperscript{th} – 50</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>275</td>
<td>271</td>
<td>286</td>
<td>5\textsuperscript{th} – 75</td>
</tr>
<tr>
<td>Inner race</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LSB</td>
<td>1</td>
<td>64</td>
<td>62</td>
<td>69</td>
<td>1\textsuperscript{st} + 12</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>177</td>
<td>173</td>
<td>188</td>
<td>3\textsuperscript{rd} + 24</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>289</td>
<td>283</td>
<td>306</td>
<td>5\textsuperscript{th} + 36</td>
</tr>
<tr>
<td>RSB</td>
<td>1</td>
<td>162</td>
<td>160</td>
<td>167</td>
<td>3\textsuperscript{rd} + 12</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>275</td>
<td>271</td>
<td>286</td>
<td>5\textsuperscript{th} + 25</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>387</td>
<td>381</td>
<td>404</td>
<td>7\textsuperscript{th} + 36</td>
</tr>
</tbody>
</table>
Case 4 – Machine operated with mechanical asymmetry

Figure 2.50 represents the stator currents’ spectrum for motor with mechanical asymmetry i.e., the load side bolts of the motor is not fixed. The left and right sidebands are at equal displacement from the fundamental with each frequency component pair occurring as LSB and RSB peaks are displaced by nearly 10Hz with same amplitude levels. The presence of fault frequencies at 20Hz, 30Hz, 40Hz, 50Hz, 60Hz, 70Hz, 80Hz etc. affirm the presence of mechanical asymmetry.

Figure 2.50 PVR in spectrum of current for induction motor with mechanical asymmetry (load side bolt of the motor is not fixed)

The previous discussions are an attempt with an initial step to investigate the efficiency for monitoring bearing fault diagnostic based on PVR in current spectrum. The related frequencies are theoretically determined for bearing with healthy, ball fault, inner and outer race fault as presented in Table 2.11. The same has been experimentally verified through time and frequency domain analysis.
2.4 DETECTION OF FAULTS IN GEARS COUPLED TO ELECTRIC MOTORS

Gears form a critical part of many electromechanical systems. Gear faults cause vibrations, and hence their reliable diagnostics are very important.

Gears are used to transmit motion from one shaft to another or between the shafts. In most systems, the gear forms a part of the mechanical load that is coupled to an electrical device, which usually is an electric motor. Several faults can occur in the gear arrangement. Faults in gears can cause discontinuities in production schedules in industries, thus lowering the productivity. The critical importance of a gear in most systems (for instance in aircrafts, helicopters) has led to the development of gear condition monitoring as an active research area. However, most of the diagnostic strategies have focused on vibration analysis and the monitoring of gear health has not attracted much attention from the electrical engineering community. This section discusses the need for detecting faults in gears coupled to induction motors by monitoring the motor current. It is observed that gear faults create unique spectral components in the current spectra that can be used to track and detect these faults.

Kar & Mohanty (2006) suggested DWT to decompose the current signal, and FFT analysis is carried out with the decomposed current signal to trace the sidebands of the high frequencies of vibration. The signals were decomposed using Daubechies 8 (Db8) as the mother wavelet which is orthogonal and its scaling function matches the transient motor current.

Rafiee et al (2007) presented that the vibration signals were recognized as the reliable source to extract the feature vector which were synchronized by Piecewise Cubic Hermite Interpolation (PCHI) and
preprocessed using standard deviation of wavelet packet coefficients. The experimental test bed consisted of a four-speed motorcycle gearbox, an electrical motor with a constant nominal rotational speed of 1420RPM and a load mechanism. A multilayer perceptron (16 input: 20 hidden neuron: 5 outputs) structure had been used in the paper.

Rajagopalan et al (2006) proved theoretically and validated experimentally that faults in gears coupled to electric motors can be detected by monitoring either the voltage or the current in the motor driving the gear. This offers an inexpensive and novel alternative to vibration-based diagnostics that require accelerometers and associated sensor wiring. Three kinds of faults are experimentally implemented namely localized teeth damage, scoring (loss of lubricant), and debris in the gear lubrication.

Experimental and theoretical discussions are done in this thesis and results demonstrate that motors’ current signature analysis is a viable technique to detect the gear faults as it is a cheaper alternative than vibration based fault detection scheme.

2.4.1 Theoretical Analysis of Motor Current for Fault Gear

A gear often consists of a pinion and a driven wheel. The motor is coupled to gear box. A gear defect such as a damaged tooth produces an abnormality in the load torque “faced” by the motor. This abnormality is transferred to the motor current from the load. Depending on the abnormality unique frequencies can be seen in the frequency spectrum of the current signal. Mechanical oscillations in gear box changes the air-gap eccentricity which results in air-gap flux waveform change. Consequently this can induce stator current components given by Equation (2.13)

\[ f_e = |f \pm mf_r| \] (2.13)
where $f$ is fundamental frequency in Hz

$f_r$ is rotational speed frequency of the motor in Hz.

$m = 1, 2, 3...$ harmonic number

$f_e$ is current component due to air-gap changes in Hz.

As seen above, mechanical oscillations will give rise to additional current components given by Equation (2.13) in the frequency spectrum. Gear boxes may also give rise to range of frequencies similar to those observed for broken bar. Specifically, slow revolving shafts will give rise to frequency ranges on current spectra around the supply frequency components as prescribed by Equation (2.14), where $f_r$ is the rotational speed frequency in Hz which can be calculated as

$$f_r = \frac{f}{n.p}$$

(2.14)

Where

$n$ is gear ratio

$p$ is the number of pole pairs.

### 2.4.2 Experimental Test bed for Gear Fault Detection

The schematic diagram for gear fault diagnosis is shown in Figure 2.51. The experimental setup consists of rigid base plate on which two electric motors are mounted, in between which the gearbox is coupled. One motor (AC motor) is connected to the driving side that acts as a driver and the other (separately excited Direct Current (DC) generator) is connected to the driven side. The base of the base plate is fixed with the ground. Gearbox consists of a pair of spur gears as shown in Figure 2.52 and the driver and driven spindles are supported by two bearing housings. Photograph of experimental test bed for gear fault emulation is shown in Figure A1.6
Transmission from driving motor to driven motor has been done by flexible coupling. The driven motor is connected to the heater for applying the load on the gear. Heater which is having four plates, two plates were switched on for half load condition and all four plates were switched on for full load condition. The defect has been created at the driven gear in the direction of rotation by grinding one of the teeth.

**Figure 2.51 Schematic of gear fault diagnosis experimental test bed**

**AC motor**

The AC motor is directly connected to the main power supply. It has been used for driving the gear. Specification of the motor is single phase, 2hp, 220V AC, 50Hz, 10.5A, 1420RPM.

**DC Generator**

The DC generator has been connected to the driven side. This also serves as a load to the gear by supplying the current to a heater load. The specification of the DC generator is 2 hp, 180V, 11.1A, 1500RPM.

**Test gear pair**

Test gear pair consists of small drive gear and driven gear with 25 teeth. The specifications of the gears are given in Table 2.12.
Table 2.12 Specification of the gear

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Driver Gear</th>
<th>Driven Gear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Carbon steel</td>
<td>Carbon steel</td>
</tr>
<tr>
<td>Number of teeth</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Module</td>
<td>2.16 mm</td>
<td>2.16 mm</td>
</tr>
<tr>
<td>Pressure angle</td>
<td>20°</td>
<td>20°</td>
</tr>
<tr>
<td>Pitch circle diameter</td>
<td>54 mm</td>
<td>54 mm</td>
</tr>
<tr>
<td>Tooth thickness</td>
<td>20 mm</td>
<td>20 mm</td>
</tr>
</tbody>
</table>

Electrical load

An electrical heater has been used as load to the generator. It has four heater plates. Load can be set from 347.5 Watt to 681.2 Watt.

Figure 2.52 Faulty gear with a notched tooth

2.4.3 Results and Discussions

As per Equation (2.14), by substituting n=1, f=50Hz, p=2 gives the theoretical estimation as \( f_r = 25 \) Hz by substituting this in Equation (2.13) gives \( f_c \) as 75 Hz, 100 Hz (RSB) and DC Hz, 25 Hz (LSB) for m=1,2.
No-load (without heater) and load (with heater connected) test has been conducted using the above experimental test bed for a healthy and a fault gear (notched tooth). AC motors’ current has been acquired for analysis through currents’ spectrum as discussed below. The spectrum of healthy and fault gear under no-load and full-load conditions are shown in Figure 2.53 and Figure 2.54.

At no-load condition, the sideband peak frequencies are not predominant in spectrum, but it is well pronounced with higher amplitude under full-load condition for the presence of the gear fault. From experiment it is observed that PVR in current spectra exhibits all odd harmonics at n=1, 3, 5, 7 as 50Hz, 150Hz, 250Hz, 350Hz each with dual sidebands of 25Hz peaks as LSB and RSB for each corresponding peak. Also at loaded condition of the machine the amplitude of the peak are higher and the fundamental frequency 50Hz presents sidebands at 25Hz, 75Hz and the even harmonic peak occurs uniquely at 100Hz as seen for faulted gears which are also validated using estimation through Equation 2.14.

![Figure 2.53](image)

**Figure 2.53** PVR in current spectrum of motor coupled to healthy and fault gear at no-load condition
Figure 2.54  PVR in current spectrum of motor coupled to healthy and fault gear at full-load condition

It has been theoretically and experimentally verified that a fault in the gear coupled to electric motor can be detected by monitoring the PVR in spectrum of signal current. This offers an inexpensive and novel alternative to vibration-based diagnostics that require accelerometers and associated sensor wiring. The gear-fault-frequency components are visible in the motors’ current spectrum for faulty gear. They change with the presence of fault in the gear and tracking of these frequencies components in the current spectrum can help to monitor the health of the gears.

2.5 CONCLUSION

This chapter has discussed on mechanical and electrical fault detection in rotating machines like the three-phase SCIM using PVR in current and voltage signals. The next chapter discusses on fault detection in static electric equipments like the distribution transformers through spectral analysis to track the peak variations in response on the acquired current and voltage signal.