Investigation of Broken bar and Eccentricity problem in Asynchronous Machines using PDT & MCSA Technique

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Abstract— **For early detection of fault in the motor, condition monitoring is necessary. By using different analysis method with computerized data processing and acquisition has brought new areas in the condition monitoring of Induction Motor. The modern industry mainly used reliability based and condition based maintenance strategies to reduce unexpected failures. These techniques may increase the time between planned shutdowns for standard maintenance and reduce maintenance and operational cost. The operation of the machine in unsafe condition can also avoid. It is a non-invasive technique and it does not require any expensive sensors for taking measurements. Detection of broken rotor fault and air gap eccentricity fault by using Instantaneous Power Analysis method and Motor Current Signature Analysis method are discussed here. It helps in the real time tracking of various motor defects and determines the severity of it, which can be used for fast decision making. The study on healthy motor and faulty motor under different speed condition is carried out experimentally and the results are analyzed using FFT spectrum, which is obtained by interfacing National Instrument data acquisition module with the LabVIEW software.**

***Index Terms*— Broken rotor fault, Air gap eccentricity fault, Instantaneous Power Analysis, Motor Current Signature Analysis**

I. INTRODUCTION

Induction Machines are used in many applications such as paper mills, mining industry, blowers, compressors etc, because of simple structure and reliability. Failure rate of Induction Machine are generally low, therefore only basic maintenance is required. Induction Machines are most commonly built to run on single-phase or three- phase power, but two-phase motors also exist. Induction Motor's condition monitoring can be defined as a technique or process of monitoring the performance of a machine, therefore the changes and trends of the monitored signal can be used to predict the essentiality for maintenance before a break down or dangerous deterioration occurs, or to estimate the current condition of the machine. The induction motors are undergone to the occurrence of incipient faults. If these incipient faults are undetected, the occurrence of an incipient fault will cause machine failure gradually. In many industries almost all machines depends on mutual operation, and the cost of the unexpected breakdowns is very large, in such situations the breakdowns of the machines in operation usually involve huge losses in production process than the cost of machine repairs and the initial costs of the machine itself [2]. In addition, the unexpected breakdowns may have safety involved and may even unprotected human being into danger.

It should be capable of monitoring the running machines with the existence of any electrical interference, which can capable for predicting the need for maintenance before the serious deterioration or breakdown occurs, identifying and locating the defects collectively, and even estimating the life of the machine. This technique is helpful for the continuous real time tracking of the faults and used for estimating the severity through visual indication. Current and voltage transformers are placed as part of the electrical protection system in many applications. The mechanical vibrations that are connected to the stator current components at the specific characteristic frequencies. An increase in the mechanical vibrations of the motor may increase the motor current due to the modulation of the air gap by the mechanical vibration. This Causes modulation and it will appears in the inductance of the stator and finally in the motor stator current. It is a non-invasive method; therefore it can be implemented at some distances away from the place where a motor is installed.

The most widely used methods in broken rotor condition monitoring is based on measurements of vibration, acoustic noise and temperature. Stator-current based and Vibration methods seem to be most popular. Plant machines are invaluable things and are made to operate under extremely harsh condition, where a failure may be catastrophic, both in safety and economic aspects. Vibration problem identification of rotating machines, exploring the cause of repetitive failures of the machine, ensuring the safety of the equipment against vibration and shock, dynamic balancing of rotors and rotating components are the benefits of condition monitoring. The condition monitoring techniques have been classified into different techniques using different parameters .The parameters are magnetic flux. Vibration, current, induced Voltage, power, surging test, Motor Circuit Analysis, AI-based fault monitoring approaches. The main objective of this paper is to diagnose the condition of an induction motor in good and fault condition and detection of broken rotor fault and air gap eccentricity fault by using Instantaneous Power Analysis method and Motor Current Signature Analysis method is also discussed here.

II. Faults in Induction Motor

Induction Motors are often symmetrical, therefore faults the symmetry of the motor. Reduced efficiency, unbalanced air gap voltage and line current, decreased shaft torque and increased loss are the main symptoms related to distributed symmetry**.** Most of the electrical machines uses ball and rolling bearing elements and these are one of the most important causes of failure[2]. These bearing consist of an inner and outer ring with asset of balls or rolling elements placed in raceways rotating inside the rings. Faults that are caused in the inner race way, outer raceway and rolling elements will provide unique frequency component in the measured vibrations of machine and other sensor signals. Almost 40% of all identified induction machine failures comes under stator fault category. The stator winding having coils of insulated copper wires which are placed in the stator slots. Stator winding faults sometimes caused by insulation failure between two adjacent turns in the coil. This is called a turn-to-turn fault or fault due to shorted turn[5]. The resultant induced currents produce extra heat and produce variations in the magnetic field in the machine

Rotor faults accounts for about 10% of the induction machine failure. The normal failure is a breakage or cracking of the rotor bars where they join the end-rings which can be due to the thermal or mechanical cracking of the rotor during operation [3]. This type of fault creates well-known twice slip frequency side bands in the current spectrum around the supply frequency signal.

Eccentricity occurs when the rotor is not aligned properly within the stator, producing a non-uniform air gap between them [1]. This can be caused due to the defects in bearings or manufacturing faults. The vibration in the air gap disturbs the magnetic field distribution within the motor produces a net magnetic force on the rotor in the direction of the smallest air gap. Therefore it is called as “unbalanced magnetic pull” which cause mechanical vibration.

Thermal stresses might be due to the thermal aging and thermal overloading. As Thumb rule, for every ten degree increase in temperature, the life of insulation get reduced due to thermal aging. The consequence of temperature on thermal aging can be minimized by increasing thermal insulation level or by reducing the operating temperature. The electrical stresses, which lead to winding failures, can be classified into transient voltage conditions, tracking, corona, and dielectric. The definite relationship between the insulation life and the voltage stress applied to the insulating materials should be considered when selecting the materials and establishing the coil designs for adequate design life. Those stresses can be classified as phase-to-phase, turn-to-turn and turn-to ground. If the insulation is not properly provided tracking will occurs. Mechanical stresses might be due to coil movement and due to rotor which strikes the stator. The rotor can strike the stator because of number of reasons like bearing failures, shaft deflection, rotor-stator misalignment etc.[6]

III. Condition Monitoring of Induction Motor

When the three phase Induction Motor works is in healthy condition, i.e, there is no fault, it produces a magnetic field rotates in forward direction, which rotates at synchronous speed [5]and is given by

$$Ns = f/p \quad (1)$$

Where f is the supply frequency, p is the pole pairs of

stator, p = p/2

The rotor rotates at a speed Nr, which is less than the synchronous speed. The measure of the slipping back of the rotor is termed as slip, which is given as;

$$\text{Slip, } s = (N_s\text{-}N_r)/2 \quad (2)$$

The actual difference between the speed of rotating magnetic field and actual speed of rotor is termed as the slip speed (N_2),

$$N_2 = N_s - N_r = s \times N_s \quad (3)$$

Slip frequency, f_2 is the frequency of the rotor current.

$$f_2 = N_2 \times p = s \times N_s \times p \quad (4)$$

Where, Ns is the synchronous speed.

When the machine operates in normal condition, the speed of rotating magnetic field produced by the currents flowing through the rotor conductors moves faster than the actual speed Nr. The speed of rotating magnetic field which is produced by the current carrying conductors of rotor with respect to the stationary stator winding is given by:

$$N_r + N_2 = N_r + N_s - N_r = N_s \quad (5)$$

The speed of the rotor’s rotating magnetic field equals the speed of the stator rotating magnetic field when compared to a stationary observer on the fixed stator winding that is called as the synchronous speed Ns [6].

3.1 Detection of Broken rotor bar fault

Magnetic field between rotor and stator varies, when a broken bar present or an eccentricity in the gap occurs, which causes a slight deviation from the fundamental field. This deviations produce current in the rotor and stator with a frequency slightly different from the fundamental frequency called sidebands. There is an additional rotating magnetic field produced due to broken rotor bars. It produces a backward rotating magnetic field at slip speed (i.e, in -ve direction ((N_s - N_r) = s × N_s)) with respect to rotor

Backward rotating speed of the magnetic field produced by the rotor due to broken bars,

N_b is given by

$$\begin{aligned} N_b &= N_r - N_2 \\ &= N_r - s\,N_s = N_s\,(1 - s) - s \times N_s \\ &= N_s - 2 \times s \times N_s\, N_b \\ &= N_s\,(1 - 2\,s) \end{aligned} \quad (6)$$

i.e the stationary stator winding produce a rotating field at:

$N_b = N_s\,(1 - 2\,s)$, It can be expressed in terms of frequency as

$$f_b = f\,(\,1 - 2\,s\,) \quad (7)$$

The rotating magnetic field at that frequency cuts the stator windings and prevail a current at that frequency (f_b). It means that f_b is a twice slip frequency component spaced 2sf1 down from f1. The speed and torque oscillation occurs at 2sf1 and this induces an upper sideband at 2sf1 above f_1.[7]

Hence twice slip frequency sidebands occur at ± 2sf1 around the supply frequency.

$$f_b = (\,1 \pm 2s)\,f\ \text{Hz} \quad (8)$$

The lower side band frequency is specifically due to broken bar and upper side band frequency is due to consequent speed oscillation. The magnitude of the f (1-2s) sideband is reduced by the speed of oscillation. Due to the rotor oscillation, the upper sideband component of current at f(1+2s) is induced in the stator winding. The third harmonic flux enhances upper sideband. The broken bars actually produce a sequence of such sidebands given by

$$fb = (1 \pm 2ks)f,\ \ k = 1, 2, 3\ldots \quad (9)$$

The appearance in the harmonic spectrum produced by the sidebands frequencies given by equations (1) and (2) clearly indicates a rotor fault of the induction machine.

3.1.1 Motor Current Signature Analysis [MCSA] Technique

In ideal cases, that is when the motor is working in good condition with no abnormalities in stator windings, the instantaneous power p(t) can be represented[3]as

$P(t) = V_{LL}(t)*i_L(t)$ Where $V_{LL}(t)$ is the voltage between any two of the stator terminal.

$i_L(t)$ is the terminal current input.

By considering a perfectly healthy motor running with a constant speed as reference, The equation for voltage $V_{LL}(t)$, current $i_L(t)$ and power p(t) can be written as:

$$V_{LL}(t) = U_m\cos(2\pi ft)$$
$$i_{LL}(t) = I_m\cos(2\pi ft - \psi)$$
$$p_o\,(t) = V_{LL}(t)\, i_{LL}(t)$$

Where U_m is the amplitude of the supply line to line voltage.

I_m is the amplitude of the supply line to line current.

f is the supply frequency, ψ is the motor load angle.

The current spectrum of the healthy motor is only having a fundamental component at the frequency f, while the instantaneous power spectrum has a DC component because of average power or input active power and the fundamental component at 2f. Harmonic torques is generated in the motor if a rotor cage fault occurs. This harmonic torques is accompanied by slip and speed oscillations. The speed oscillations around the medium value ω_r give rise to another frequency in the stator windings. It induce emf which modulate the current main frequency component at twice the slip frequency given as

$$f_s = 2*s*f$$

Frequency characteristics for this type of faults will appear in the stator current spectrum. These components location helps in identifying the abnormality. The rotor cage fault causes sinusoidal modulation of the stator current amplitude, but the load angle does not change significantly. [8] The modulated current can be expressed as

$$I_L(t) = I_{LL}(t)\,(1 + m\cos\,(2\pi f_s t))$$
$$= I_{LL}(t) + \frac{mIm}{2}\cos(2\pi(f - f_s)t - \psi) + \frac{MIm}{2}\cos(2\pi(f + fs)t - \psi).$$

Where m is the modulation Index

f_s =2sf; is the modulating frequency.

s is the slip. In the current spectrum two sideband components appears around the fundamental component at frequencies

$$f_1 = f - f_s \text{ and } f_2 = f + f_s \quad (10)$$

3.1.2 Instantaneous Power Analysis [IPA] Technique

The motor current signature analysis is non-intrusive and economical for the broken rotor fault calculation. But the changes in amplitude values of the current signals are very difficult to detect mainly at no-load conditions. Broken rotor fault defects at no-load and full load conditions can be able to detect at incipient stages by using instantaneous power analysis method [3]. Consider a perfect healthy motor running with a constant speed as reference, the equation for voltage $V_{LL}(t)$, current $i_L(t)$ and power p(t) can be written as

$$V_{LL}(t) = U_m\cos(2\pi ft)$$
$$i_{LL}(t) = I_m\cos(2\pi ft - \psi)$$
$$p_o\,(t) = V_{LL}(t)i_{LL}(t)$$
$$= \frac{UmIm}{2}\cos\,(2(2\pi ft) - \psi) + \frac{UmIm}{2}\cos\,(\psi) \quad (11)$$

Where $V_{LL}(t)$ is the voltage between any two of the stator terminal. $i_L(t)$ is the terminal current input. The healthy motor's current spectrum is only having a fundamental component at the frequency f, while the instantaneous power spectrum has a DC component because of average power or input active power and the fundamental component is occur at a frequency of 2f. Due to the fault a change will occur at the air gap between stator and rotor, which causes a variation in the magnetic flux. Because of this variation modulation will occur in the stator current, but the stator voltage will not affect that much. The obtained stator voltage and current signal are used for getting the power spectrum. By analyzing the sideband frequency of the obtained spectrum, the severity of the fault can be detected. [9]

The rotor cage fault causes sinusoidal modulation of the stator current amplitude, but the load angle does not change significantly. The modulated current can be expressed as

$$I_L(t) = I_{LL}(t)\ (1+m\cos(2\pi f_s t))$$
$$= I_{LL}(t) + \frac{mIm}{2}\cos(2\pi(f\text{-}fs)t\text{-}\psi) + \frac{mIm}{2}\cos(2\pi(f+f_s)t\text{-}\psi). \quad (12)$$

Where m is the modulation Index, f_s =2sf; is the modulating frequency. The instantaneous power is obtained is expressed as

$$P(t) = p_o(t) + \frac{mUmIm}{4}\cos[2\pi\ (2f\text{-}f_s)\ t\text{-}\psi]$$
$$+ \frac{mUmIm}{4}\ \mathrm{Cos}\ [2\pi\ (2f+f_s)\ t\text{-}\psi]$$
$$+ \frac{mUmIm}{2}\ \mathrm{Cos}\ (\psi) + \cos\ (f_s t). \quad (13)$$

3.2 Detection of air gap eccentricity fault

There are three types of air gap eccentricity fault namely dynamic, static and mixed eccentricity fault. Air gap eccentricity related fault of a three phase squirrel cage Induction Motor is given by,

$$f_{ac} = f_1\{(R\pm n_d)\frac{(1-s)}{p}\pm n\} \quad (14)$$

Where, f_1 is the fundamental frequency, R is the number of rotor bars,n_d is the eccentricity order, (0, for static eccentricity, 1, 2, 3... for dynamic eccentricity), p is pole pairs of the motor, n is the harmonics present in the motor supply.[10]

3.2.1 Motor Current Signature Analysis [MCSA] Technique

If an air gap eccentricity fault occurs in SCIM, characteristics frequency component due to fault is appeared at $f_1 \pm mf_r$ in the stator current, which is given by

$$i_a = I_m \cos\omega_1 t + \sum_{m=1}^{\infty}\{I_m\cos[(\omega_1\text{-}\ m\omega_r)t\ \text{-}\psi] + I_m\cos[(\omega_1+m\omega_r)t\ \text{-}\psi]\} \quad (15)$$

Where, ω_r is the angular frequency of the rotor

f_r is the frequency of the rotor, ψ is the phase angle

3.2.2 Instantaneous Power Analysis [IPA] Technique

Because of the air gap eccentricity fault, in addition to a dc component, a frequency component will occur at $2f_1$ and frequency components occur at $2f_1 \pm mf_r$. At frequencies of mf_r, the instantaneous power spectrum contains an additional component. This component is called eccentricity's characteristic component, which provides information about the state of the motor.[11]

$$p(t) = \frac{\sqrt{3}}{2}\{U_m I_m[\cos(2\omega_1 t - \psi) + \cos\psi] + \sum_{m=1}^{\infty}\{I_m U_m[\cos((2\omega_1\text{-}\ m\omega_r)t\text{-}\ \psi) + \cos(m\omega_r t + \psi)] + I_m U_m[\cos((2\omega_1 + m\omega_r)t\text{-}\ \psi) + \cos(m\omega_r t\ \text{-}\psi)]\}\}$$

IV. Hardware Implementation

A stator current contains potential fault information. The most suitable measurements for diagnosing the faults under consideration, in terms of easy reliability, accessibility and sensitivity are stator current amplitudes. Fig. 4.1 shows the block diagram of the developed experimental test rig.

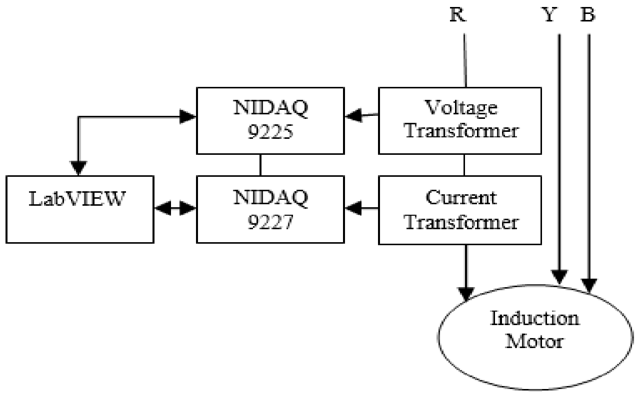


Fig.1 Block diagram of the developed experimental test rig

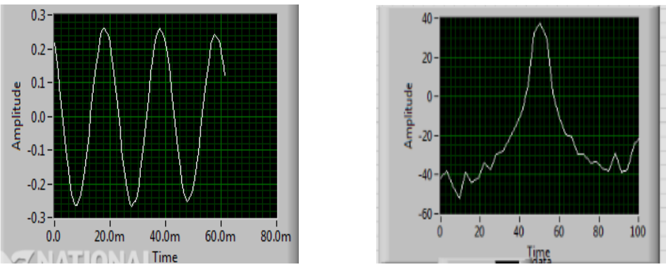
If a motor is working in good condition, the air gap between rotor and stator will not change, therefore there is no variation in the magnetic flux. If any fault occurs, it will affect the radial movement of rotor. Due to this air gap between rotor and stator changes to cause magnetic flux variations. This defect disturbs the symmetry of flux between stator and rotor which creates Oscillation in stator current and can be observed at different frequencies. The signal from the stator current was acquired through Current Transformer and was given to DAQ. The voltage signal was acquired through Potential Transformer that was also given to the DAQ. DAQ module converts the analog data to digital data. DAQ module is interfaced with LabVIEW software to acquire and process the current and voltage measurements to calculate the FFT spectrum.NI DAQ 9225 is used for acquiring voltage signal. NI DAQ 9227 is used for acquiring current signal. 0.5hp, 440V, 1500 rpm, three phase squirrel cage induction motor is used here.

Figure.2.Complete Hardware Setup

V. Results and Discussions

5.1) Healthy Motor

In the case of a healthy motor, the current is not modulating. Its amplitude is same for every cycle as in Fig. 3(a).The power spectrum of the healthy motor is shown in Fig. 3(b). In that, there is no sideband frequency. It has only the supply frequency at 50Hz.



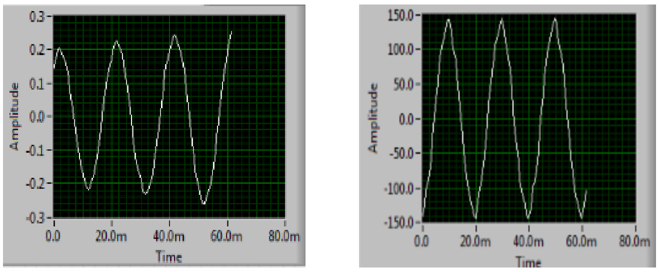
(a) (b)

Fig 3(a): current waveform of the healthy motor, (b): power spectrum of the healthy motor

5.2) Faulty Motor

In the case of a faulty motor, the current waveform is modulating, as shown in Fig: 4(a).But the voltage is not affected.

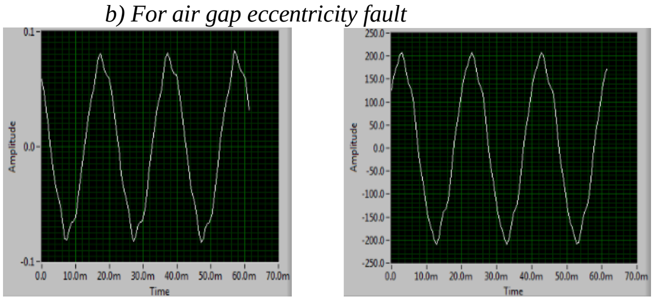
a) For broken rotor fault



(a) (b)

Fig (4) Broken rotor fault (a)current waveform (b) voltage waveform

b) For air gap eccentricity fault

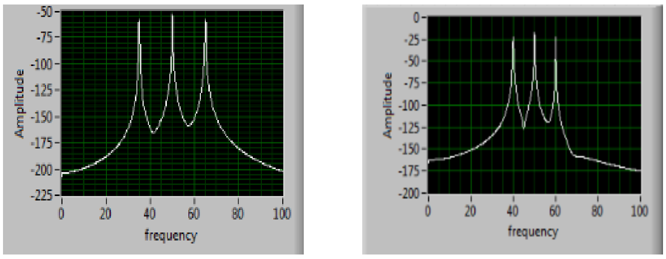


(a) (b)

Fig (5) Air gap eccentricity fault (a)current waveform (b) voltage waveform

5.2.1 Faulty Motor [Motor Current Signature Analysis]

a) Broken rotor fault



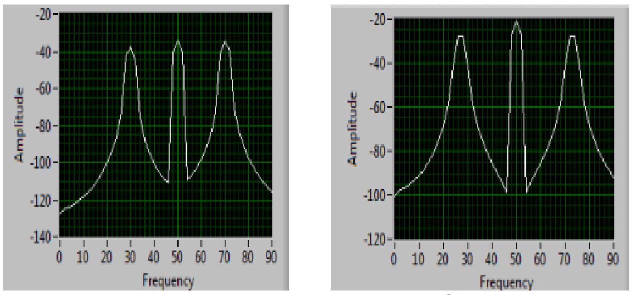
(a) (b)

Fig.(6) power spectrum of the broken rotor fault motor (a) at a speed of 1275 rpm (b) at a speed of 1350 rpm using MCSA method.

The power spectrum of the broken rotor fault motor at a speed of 1275 rpm has an amplitude of -50db and the side band frequencies are obtained at $f \pm f_s$, i.e at 35Hz and at 65Hz.When operating at a speed of 1350rpm, the amplitude of the supply frequency is less than -25db and the side band frequencies occur at 40 Hz and at 60Hz.

b) Air gap eccentricity fault

The power spectrum of the air gap eccentricity fault motor at a speed of 1210 rpm has an amplitude of -30db and the side band frequencies are obtained at $f \pm mf_r$, i.e at 30Hz and at 70Hz.When operating at a speed of 1380rpm, the amplitude of the supply frequency is -20db and the side band frequencies occur at 27 Hz and at 73Hz.



(a) (b)

Fig.(7) power spectrum of the air gap eccentricity faulty motor (a) at a speed of 1210 rpm (b) at a speed of 1380 rpm using MCSA method.

5.2.2 Faulty Motor [Instantaneous Power Analysis]

a) Broken rotor fault

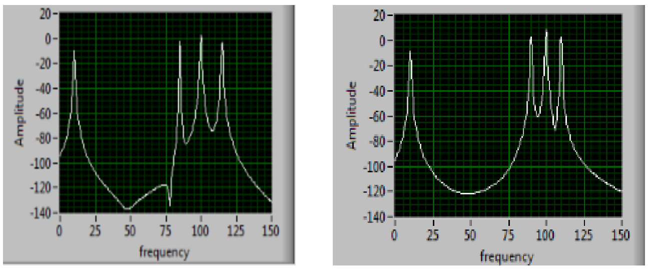


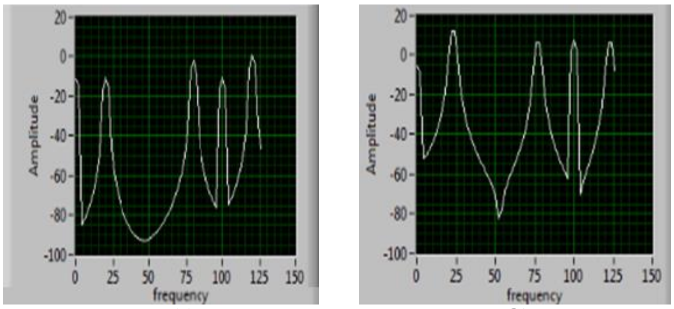
Fig (8) power spectrum of the broken rotor fault motor (a) at a speed of 1275 rpm,(b) at a speed of 1350 rpm using IPA method.

For a speed of 1275 rpm, sideband frequencies occur at 85Hz and at 115Hz. The value of f_s is 15Hz. For a speed of

1350 rpm, sideband frequencies occur at 90Hz and at 110Hz. The value of f_s is 10Hz. i.e at $2f \pm f_s$ .The supply frequency has an amplitude is around 5db.

b) Air gap eccentricity fault

When comparing the IPA method and MCSA method, IPA method is giving more accurate result. The variation of current spectrum, when a fault occurs is very low; therefore sometimes we are unable to detect the fault. But in the case of power spectrum we can easily detect the sideband frequency because the variation of power signal is very large, and can easily detect the severity of fault.



(a) (b)

Fig (8) power spectrum of the air gap eccentricity fault motor (a) at a speed of 1210 rpm ,(b) at a speed of 1380 rpm using IPA method.

I. Conclusions

Both Instantaneous Power Analysis and Motor Current Signature Analysis are good for fault detection of motor in harsh environment especially in the region where motor access is very difficult. The proposed IPA method possesses some features like real time monitoring of fault and helps to detect the severity of the fault. This help in the advancement of automatic decision making. IPA provides more information than that of MCSA method, because the variation in the side band frequencies is more visible and reliable in the IPSA method, especially when the fault occurs in the no-load conditions. The IPA technique would enhance the accuracy and reliability of on-line detection of broken rotor fault and air gap eccentricity fault.

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