International Journal of Research and Engineering
ISSN: 2348-7860 (O) | 2348-7852 (P) | Vol. 04 No. 03 | March 2017 | PP. 86-92
http://digital.ijre.org/index.php/int_j_res_eng/article/view/266

A brief review of condition monitoring practices of induction motor

Author: Aniket Vatsa
Student M.Tech., Mine Electrical Engineering
Indian Institute of Technology (Indian School of Mines), Dhanbad, INDIA

Abstract- Since the advancement in technology many techniques have been developed to reduce the time needed for correction of faults in an induction motor as a single motor failure in an industrial scenario can lead to breakdown of a whole chain of process. In this regard technologies are needed which can online monitor the faults at an incipient stage thus reducing three downtime required for maintenances and repairs. Analysis of line current for fault detection and other signals such as vibration, power, axial leakage flux and partial discharge have been extensively explored. An effective condition monitoring algorithm using different techniques like Fourier transform, wavelet transform etc. along with the choice of the right parameter to diagnose the various faults in induction motors has been one of the key research area in this field. So keeping in mind the vast scope of this area of research, a review paper compiling the various literatures regarding the different fault monitoring machine techniques and the viable machine parameters used till date is presented.

Keywords – Induction Motor, Condition Monitoring, Fault analysis

1. INTRODUCTION

Induction Motors (IMs) are used in almost any industrial application. Therefore a single motor failure may lead to loss of production, shutdown of a generating unit, and other severe problems. It is thus beneficial to design online monitoring for such motors to detect incipient faults thereby facilitating the intended preventive maintenance to be carried out. Frequency spectrum analysis is mainly used to provide useful information regarding the nature of a machine fault. This is applied to the vibration, phase current or flux leakage signals. Studies suggest that about 80% of IM failures occur in stator, rotor and bearings [1].Basic faults occurring in IMs are classified as electrical faults, mechanical faults and external system fault or drive faults.

Mechanical faults include bearing failure, broken rotor bars, end ring crack, bent shaft and eccentricity. Drive system failure include inverter system failure, unbalanced supply, shorted or open supply lines.

Eccentric faults can be divided into two basic types namely static and dynamic. In static eccentricity, the position of minimum radial air gap length is fixed in space. Static eccentricity occurs due to stator core ovality or erroneous positioning of the rotor & stator at the time of setting up the machine. Both mechanical and electrical monitoring is used effectively for the detection of eccentricity in IMs [2],[3].Incipient bearing faults are generally detected through vibration and stator current monitoring. Stator current monitoring has the advantage of being non-invasive. Bearing misalignments can be categorized in four types as described in [4] namely outer raceways, inner raceway, ball defect, and cage defect. Rotor faults include broken rotor bars or end-rings damage. Principal cause of broken bars is direct online starting duty cycles (with 5 or 6 times the full load rotor bar currents) and mechanical loads which are pulsating in nature (like reciprocating machinery).Rotor winding faults occur primarily due to open circuit or short circuit of rotor windings. developing broken rotor bar condition if not detected magnifies as disproportionate currents flow through the adjacent bars instead of broken bars. It can shorten the life of the motor substantially. Hence the ability to sense broken rotor bars while the machine is working at normal speed and load is extremely desirable [5]. In this regard the choice of proper condition monitoring technique is critical to its cause.

This paper is organized in five sections. Section 2 enumerates various parameters used in online condition monitoring and fault analysis of IMs. Furthermore section 3 details and highlights the different fault detection techniques used thus far as evident in the available literature. Section 4 presents a brief insight of the recent use of artificial neural network and fuzzy logic as applicable in process of condition monitoring and fault diagnosis of IMs. Finally section 5 concludes the work.

2. PARAMETERS USED FOR FAULT DETECTION

2.1 CURRENT

Motor current signature analysis (MCSA) involves the study of current frequency spectrum to identify the explicit frequency components which indicates the presence of an incipient fault. Fig. 1 describes the basic fault monitoring scheme using MCSA. Here a CT is used to lower down the current to a safe level. This scaled down current is tapped in using a data acquisition card (DAQ) for spectrum analysis.

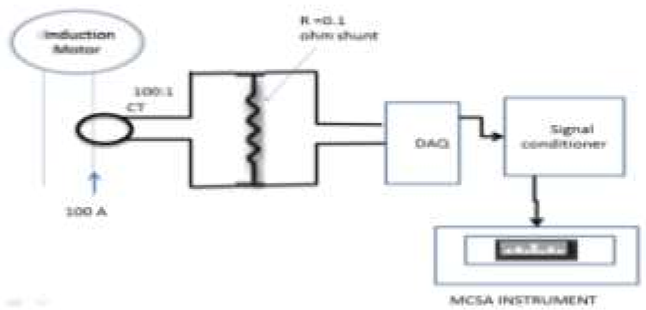


Fig.1. MCSA schematic diagram

Table 1 enumerates the various faults that occur in an IM along with the corresponding characteristic fault frequencies that occur in the current spectrum The current spectrum can be obtained through Fast Fourier transform (FFT) of the stator current under steady-state conditions. However, the stator current is a non-stationary signal whose properties continuously varies with the time-variant operating conditions of the motors such as fluctuations in load torque, power supply and machine slip which varies the fault sidebands. In some cases unloaded induction motors, for instance, the slip s is very low and the sideband components practically overlap the supply frequency. Researchers in [8-11] have demonstrated the use of spectrum analysis of machine line current (MCSA)to detect broken bar faults by investigating the sideband components around the fundamental slot harmonics. While the lower sideband is specifically due to broken bar, the upper sideband is due to consequent speed oscillation. Due to the interaction of these side band currents with flux and the inertia specific speed ripple, additional harmonics arise as shown in (7)-(8). The fault sidebands around the principle slot harmonics as obtained by FFT technique is shown in Fig. 2.

$$f_l[k] = f_1(1 - 2ks) \quad (7)$$

$$f_u[k] = f_1(1 + 2ks) \quad (8),$$

Where, k is an odd integer.

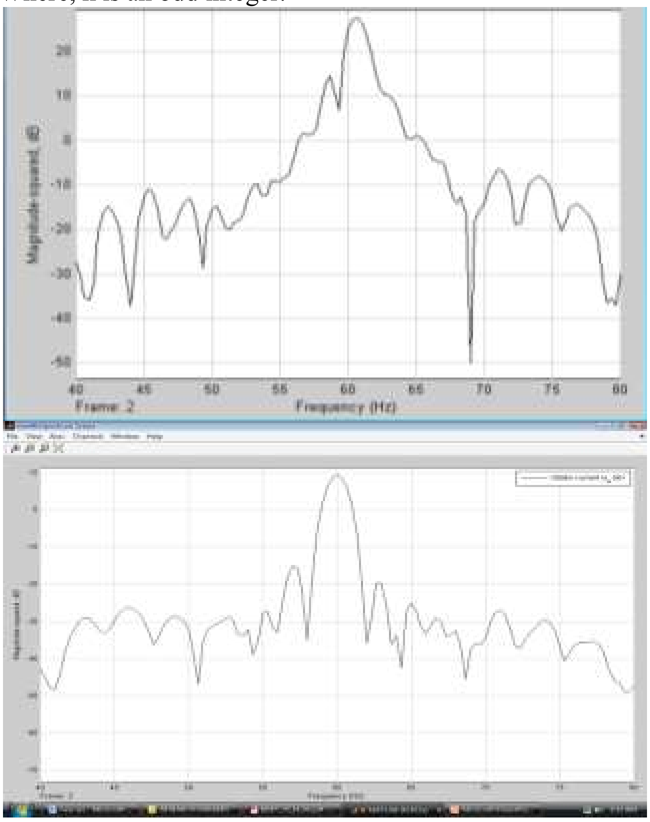
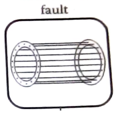
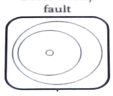
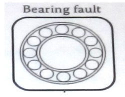
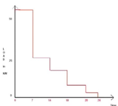


Fig.2.FFT spectrum of: (a) healthy motor, (b) faulty motor

Table1.Types of fault and characteristic fault frequencies using MCSA [4-7]

Fault condition	Frequency resolution sidebands	Approximate
For detection of broken bars $f_{sb} = f_1(1 \pm 2s)$ (1)  f_{sb} = broken bar sidebands f_1 = source (grid) frequency , s = slip	78mhz/line	
1For detection of eccentricity faults $f_{ec} = f_1\left\{(R \pm n_d)\left(\frac{1-s}{p}\right) \pm n_{\omega s}\right\}$ (2)  f_1 = electrical supply frequency R = the number of rotor bars , s = slip , p = pole-pairs , $n_{\omega s} = 1,3,5,7...$ This equation gives static eccentricity sideband frequencies components. $f_c = Rf_1$ This equation gives central frequencies	100mhz/line	
For detection of shorted turns  $f_{st} = f_1\left\{\frac{n}{p}(1-s) \pm k\right\}$ (3) f_{st} = frequency component related to shorted turn f_1 = electrical supply (grid) frequency $n = 1,2,3...$ (order of shorted coil space harmonic) p = number of pole pairs , s = slip, k = order of time harmonic	31.2mhz/line	
Bearing problems $f_l = 0.4nf_{rm}$ (4) $f_u = 0.6nf_{rm}$ (5)  f_l = lower frequency, f_u = upper frequency, n = total number of balls in the bearings f_{rm} = the rotor's mechanical frequency bearing faults can detect by detection of frequency components f_l and f_u that are for most bearings with between six to twelve balls [6, 7]	----	
Load Effects $f_{load} = f_1 + mf_r = f_1\left[1 \pm \left(\frac{1-s}{p}\right)\right]$ (6)  f_1 = electrical supply frequency f_r = rotational frequency , p = number of pole pairs s = per unit slip , m = 1, 2, 3,..	-----	

2.2 VIBRATION

Basically foremost sources of vibration in induction motors are: mechanical and electromagnetic. Electromagnetic vibration origin is based on the fact that any alteration in the regular flux distribution in the motor causes an alteration in the vibration spectrum. In abnormal condition the machine vibration will be very high. Cesar et al used MATLAB/Simulink model to implement vibration measurement and analysis instruments in real time based circuit architecture [12].Over the time a number of techniques have been developed like Hilbert transform, wavelet transform, etc. to be used while transforming vibration signals into frequency domain, but the simplest way is to perform the direct FFT of the vibration signal and analyze the frequency spectrum to make predictions about motor condition.

$$f_v = (f_{rm} + 2f_1 s) \quad (9)$$

Two sideband frequencies appear around the rotating frequency f_{rm} in the vibration spectrum. For measurement of velocity and displacement accelerometers are used. The location and proper selection of sensors is very important.

Vibration can differentiate between mechanical and electromagnetic excitation forces, which are vital in detecting root causes before they develop into failure modes, electrical machines are generally low-vibration devices. Several techniques basically based on piezoelectric and capacitive accelerometers have been applied for predictive maintenance. In Very noisy environments high EMI for instance in power plants can distort the electrical signals through the sensors which are used to detect and convey physical signals. To triumph over these problems optical fiber sensors for monitoring can be used due to the non-electrical nature of signals. The techniques used in the optical fiber grating is developed by making reflectors which are fabricated by altering the refractive index of the core of the optical fiber in a cyclic way thus creating dielectric partial mirrors, and accordingly a succession of interferences occurs as the light travels through the fiber. Hence, the Fiber Bragg grating acts as a wavelength selective reflector. The FBG fiber Bragg grating reflected wavelength λ_B satisfies the Bragg condition [13]

$$\lambda_B = 2 n_{eff} \Lambda \tag{10}$$

where, n_{eff} = Effective refractivity of fiber fundamental mode on the Bragg wavelength, Λ = Period of grating , λ_B =a monochromatic light is reflected by the grating and the other lights transmit through it.The heart of this technique lies on the fact that any change in the external strain makes Λ and n_{eff} of FBG sensor change, and thus λ_B is changed. Consequently, vibration signal can be obtained by demodulating the λ_B .

2.3 PARTIAL DISCHARGE

The partial Discharge (PD) is the partial conduction of electricity that occurs in insulation systems due to high voltage stress which prevails as very high frequency pulses ranging from few kHz to several MHz As the level of degradation in condition of motor insulation like, cracking, contamination etc exaggerate, the magnitude and the pattern of PD changes. Among many methods of measuring partial discharges, PD couplers are most common. PD couplers are of many types like capacitive couplers, inductive couplers(RF& CT) or antennas, three PD couplers are used one per each phase as shown in Fig.3

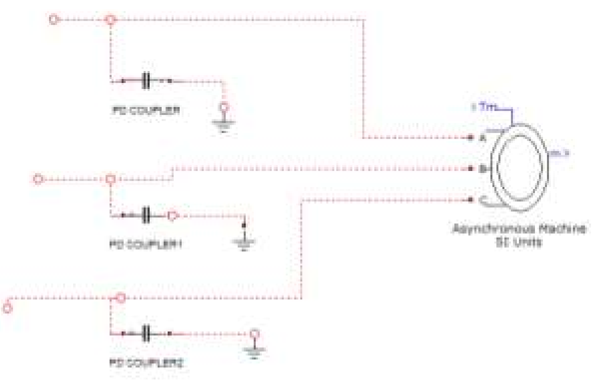


Fig .3.A typical connection of PD couplers on a 3-phase electrical motor[14]

As a condition monitoring tool, the acquirement, processing and storage of partial discharge signal [14], [15] is widely used to conclude the reliability of the insulation of electrical systems. One of the drawbacks of PD method is that it requires the installation of additional sensors and is not applicable to low voltage machines.The capacitance (C) along with dissipation factor (DF) of motor insulation can provide a good clue of motor insulation healthiness. High sensitivity differential current transformer is the sensor which has been used for detection of partial discharge[14]. In the running condition, as shown in Fig. 4, the stator insulation leakage current (I_{al}) which flows from the winding to ground is equal to the difference between the currents in the line and neutral of stator phase winding. The insulation leakage current of a phase is measured by a differential CT, which encloses both line and neutral terminals of a stator phase winding. I_{al} is made up from two components which are capacitive (I_c) and Resistive(I_r) components, which can be represented in respect to the phase to ground voltage as displayed.

(a) (b)

Fig.4. (a) corresponding circuit of insulation scheme, (b) phasor illustration of insulationLeakage current [16**]**

$$DF = \frac{I_R}{I_C} \times 100 \ \% \tag{11}$$

$$C_{eq} = \frac{2 I_C}{V \omega} \tag{12}$$

The online C_{eq}& DF measurement of small motors is successfully demonstrated on a 15hp motor [16]. These measurements are extremely load-dependent and inaccurate.The measured I_{leak} and δ are constant with respect to the load current I_{rms} , as shown in Fig.5

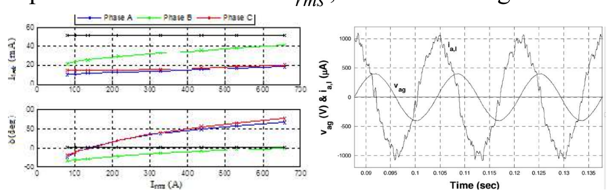


Fig.5.(a) Insulation leakage current measured on a 480V, 15hp induction motor and (b) influence of load current on online measurement of leakage current on a 12kV, 15000hp motor [16]

2.4 AXIAL FLUX

In axial leakage flux monitoring technique, a voltage is induced in a coil wound around the shaft of an electrical machine due to the axially directed fluxes. These fluxes arise due to asymmetries in the electrical and magnetic circuits of the machine.. The diameter of the search coil, is less than the tooth-width of the rotor, and is fixed to the stator usually in the air gap, and detects either the radial or circumferential component of magnetic flux.The search coil normal EMF waveform per turn of the search coil is given as (13):

$$e_{normal}(t) = A \frac{dB}{dt} \tag{13}$$

$$= \sum_{n=1,3,5} An\omega B_n \cos n\omega t \text{ (Normal MMF wave)}$$
$$+ \sum_{meven} Am\omega B_n \cos n\omega t \text{ (Normal tooth ripple MMF wave)} \quad (14)$$

where, A = the effective search coil area, Wave shape of the MMF wave in the air-gap determines the "*n*"odd harmonics which are dependent upon the spread of winding slots over the rotor pole pitch. The rotor tooth ripple that is present in the voltage waveform determines "*m*" even harmonics. A shorted turn disturbs the MMF distribution, causing low-order even harmonics or an asymmetry in the flux and search coil voltage waveforms. Moreover, it disrupts the *n*th order slot ripple harmonics.

$$e_{fault}(t) = \sum_{n=1,3,5\cdots} An\,\omega B_n \cos n\omega t \text{(Normal MMF wave)}$$
$$+ \sum_{l=2,4,6..dependent..on..fault.location} Al\omega B_l \cos l\omega t \text{(Fault asymmetric MMF wave)}$$
$$+ \sum_{m=even} Am\,\omega B_m \cos m\omega t \text{(Normal tooth ripple MMF wave)}$$
$$+ \sum_{p=\pm1,\pm3..} A(m+p)\omega B_n \cos(m+p)\omega t \text{(Fault tooth ripple MMF wave)} \quad (15)$$

Due to change in amplitudes corresponding peaks and troughs in the ripple will change making the search coil voltage unsymmetrical about zero. This is used as an effective fault indicator byAlbright in [17].Stator fault causes asymmetry which produces frequency components as [17][18].

$$f_{st} = f_1 \left\{ \frac{n}{p}(1-s) \pm k \right\} \quad (16)$$

f_{st} = Frequency component related to shorted turn, f_1 = Electrical supply frequency , $n = 1,2,3....$ Order of shorted coil space harmonic), k= order of time harmonics, p = Number of pole pairs , s = Per unit slip

Recently, external flux sensor have been used to detect stator faults in variable speed drive using an 11 kw,50hz, 4 pole squirrel cage induction motor [19]. The fault can be detected by identifying the fault frequency component given by

$$f_{st} = f_1 \left\{ \gamma \frac{R}{p}(1-s) \pm \vartheta \right\} \quad (17)$$

ϑ = Order of time harmonic, $\gamma = 1,2,3...$ Order of rotor space harmonics,R = no of rotor bars.

But there are two shortcoming of these methods. First these schemes it's not immune to voltage unbalance and secondly similar frequency components are present in case eccentricity faults of induction motor which creates a state of confusion or misperception as which fault has originally occurred.

2.5 TEMPERATURE MONITORING

Temperature sensors like resistance temperature detectors (RTD) or thermocouples are used for the purpose of temperature monitoring. The base resistance of RTD deviceis $100\,\Omega$ at 0^0C .It has also has the benefit of being linear over a wide operating range which makes it a high precision device. However,it has the disadvantage of low sensitivity. They are generally used asa four-wire configuration of Wheatstone bridge, but two-wire or three-wire operation is also possible. The change of resistance is converted into the change of output voltage by these circuits [20. The temperature measurements have been mostly applied on the on stationary parts of the electrical machine. But in many machines the rotor is a critical component, particularly larger induction motors.Stationary temperature monitoring techniques cannot be applied on it. If it gets jammed or blocked the rotor draws very large current which can rise temperatures to very high values that might damage the rotor. several techniques have been developedfor measuring rotor temperatures for experimental purposes, using heat-sensitive papers or paints, or thermocouples connected through slip rings. Still recently, there has not been a method sufficiently reliable to use for monitoring purposes. Siyambalapitiya *et al.* [21] have described a device for monitoring eight thermocouples, multiplexing the signal on the rotor, then optically coupling to the stator and decoding in a digital signal processor.Alternative type of temperature transducer is the thermistor, which provides a rough but very sensitive response in contrast to RTD which has accurate but less sensitive response in comparison with the thermistor.. In thermistorschange in resistance is expressed as a function of temperature [18].Along with advantage of being sensitive, they also have the advantages of high stability, fast response and small physical size. Due to small size the time constant of thermistors operated in sheaths is small. But the size reduction also decreases the heat dissipation capability and so makes the self-heating effect of greater importance. Highest temperature of Thermistors is generally limited to 300 ◦C, above which level the stability reduces. Output of thermistor is nonlinear. It is for this reason, it is also intricate to control the consistency among samples of thermistors, implying that the correctness achievable is comparatively small.

3.FAULT DETECTION TECHNIQUES

Several methods are used in preprocessing stage for extracting features of the measured motor parameters for assessment of motor health condition.

3.1 FAST FOURIER TRANSFORM

Fast Fourier Transform (FFT) is the most trivial method which is employed in the process of fault detection[1]. FFT of a given signal returns the information about the frequencies present in the signal of contention.The process of analyzing a signal begins with acquiring the signal in time domain. The signal is tapped down to a lower value using a current transformer. Thereafter, analog-to-digital conversion is performed. The digital signal is further getting discrete and is represented by x (t). For N discrete samples, it can be expressed as a sum of N sinusoidal components of frequencies ω_i , and phase shifts

$$x(t) = A_0 + \sum_i^N A_i + \sin(\omega_i t + \theta_i) \quad (18)$$

$$\omega_i = \frac{2\pi f_s i}{N} \quad (19)$$

where ω_i = circular frequency and f_s = signal sampling rate.

Same signal can be expressed in sine and cosine terms as follows-

$$x(t) = A_0 + \sum_i^N (a_i \cos(\omega t) + b_i \sin(\omega t)) \quad (20)$$

Values of coefficients can be determined by Discrete Fourier Transform, [22],[23]

$$a_i = \frac{2}{N}\sum_{i=1}^{i=N} x(t)\cos(\omega_i t)$$

$$b_i = \frac{2}{N}\sum_{i=1}^{i=N} x(t)\sin(\omega_i t)$$

$$A_i = \sqrt{a_i^{\,2} + b_i^{\,2}} \quad \text{(FFT magnitude)}$$

(23)

FFT phase angle

$$= phase\ [FFT\ (A)] = \arctan\ gent\left(\frac{b_i}{a_i}\right)$$

where, a_i =cosine term, b_i = sine term and A_i = Amplitude for frequency component i.

FFI is a computational efficient version of Discrete Fourier Transform algorithm that greatly reduces the necessary number of computations. After applying FFT to stator current, normalization of amplitudes of resulting frequency components is done to reduce influences of motor's load conditions [24]. FFT is suitable for characterization of stationary signals. However it is not suitable for signals with transitory characteristics[25].

3.2 WAVELET ANALYSIS

Fourier series expansion only gives frequency resolution and this is one of the major disadvantages of FFT. Wavelet transformation breaks a signal into a family of wavelets, called approximate and detail signals which gives a sense of time of the signal in contrast to sinusoids which is only time based analysis [25].Wavelets can be used for processing those signal whose spectra changes over time. The Continuous Wavelet Transform (CWT) for a continuous signal *x (t)* is defined by following equation[26]

$$CWT_x(\tau, a) = \frac{1}{\sqrt{2}}\int x(at)g^*\left(\frac{t-\tau}{a}\right)dt$$

(25)

Where ,*g(t)* = the mother or basic wavelet,* =denotes complex conjugate,*a* = the scale factor, and *τ*= time shift.For signal analysis using CWT, the complex-valued Morlet's wavelet is used generally it is defined As

$$g(t) = e^{j2\pi f_0 t} e^{\frac{-t^2}{2}}$$

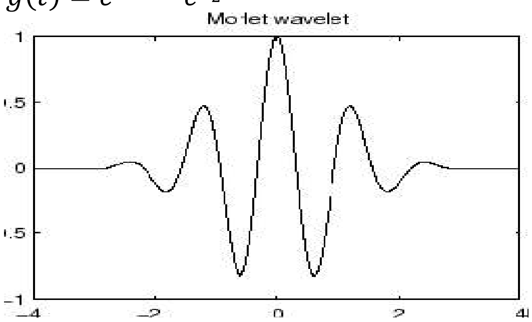


Fig.6.*Morlet wavelet*

Since in practical scenario we work with discrete (sampled) signals along with Discrete Wavelet Transform (DWT) . in DWT wavelets are discretely sampled and it decomposes a sampled signal as [27]

$$X[n] = \sum_j a_{i_o,j}\varphi_{i_0,j}[n] + \sum_{i=i_0}^{I-1}\sum_j d_{i,j}\psi_{i,j}[n]$$

(26)

Where, $\varphi[n]$ is the scaling function and $\psi[n]$ denotes the mother wavelet. $\varphi_{i_0,j}[n] = 2^{i_0/2}\varphi(2^{i_0}n - j)$ denotes the scaling function at a scale of $s = 2^{i_o}$ shifted by j and $\psi_{i,j}[n] = 2^{i/2}\psi(2^i n - j)$ denotes the mother wavelet at a scale of $s = 2^i$ shifted by j . $a_{i_0,j}$ is the coefficient of approximation at a scale same as that of the scaling function and $d_{i,j}$ is the detail coefficient at a scale same as that of the mother wavelet [28]. (21) (22)

3.3 PARK'S VECTOR METHOD

In this approach current on all the three phases is sensed, from the symmetrical three-phased current system, having the components: i_a , i_b and i_c from which Park's vector components are obtained(i_d and i_q) (24)

$$i_d = \sqrt{\frac{2}{3}}i_a - \frac{1}{\sqrt{6}}i_b - \frac{1}{\sqrt{6}}i_c$$

(27)

$$i_q = \frac{1}{\sqrt{2}}i_b - \frac{1}{\sqrt{2}}i_c$$

(28)

In case of no faults , the Park's vector current components are expressed as (29, 30),

$$i_d = \frac{\sqrt{6}}{2}i_M \sin \omega t$$

(29)

$$i_q = i_M \sin\left(\omega t - \frac{\pi}{2}\right)$$

(30)

where, i_M = The maximum value of the supply phase current and ω = frequency. In a vector plane, components i_d and i_q generate circular pattern. In case any fault occurs due to the presence of sideband components in supply current, the circular pattern is distorted [29]. The distortion suffered by circle of Park Method is directly related to the type and intensity of damage.

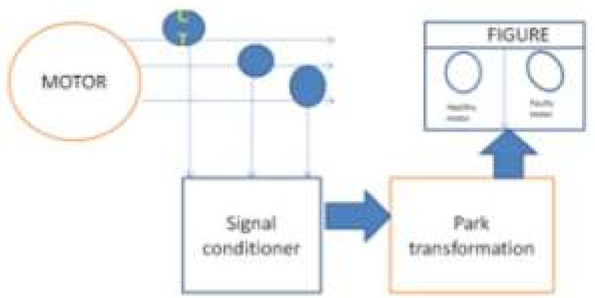


Fig.7. Block Diagram of MCSA using Park's vector approach

4. CONDITION MONITORING: RECENT ADVANCES

4.1 Artificial neural networks (ANN)

Artificial neural networks *(ANN),* fuzzy or neuro-fuzzy systems are broadly utilized for speed, torque estimation, solid state drive [30]. They are predominantly suited for ac machines' in which the relationships between motor current and speed are non-linear.Fig. 8 shows a basic schematic of fuzzy system used for condition monitoring of 3 phase IM.

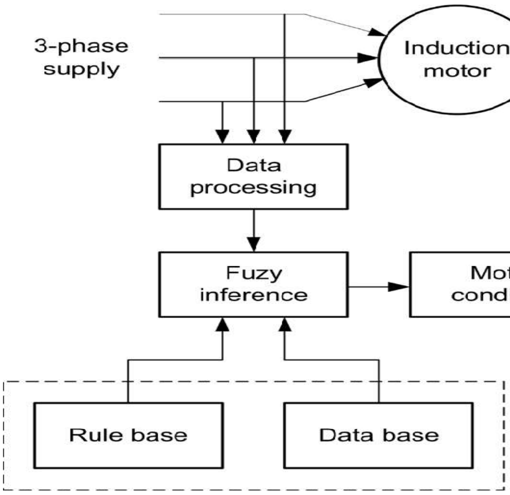


Fig.8.Fuzzy logic applied to MCSA

Once Fault signature is obtained, it is used for fault diagnosis using artificial Intelligence (AI) which takes the final decision either based on the training of the neural network, or the pre-defined rule based.A tool can be used called Support Vector Machine (SVM) which is learning process effectively functional to a broad variety cataloging and pattern identification situation. It is most useful in the cases where the dimension of problem is high. The use of SVM in MCSA in described in [31].

4.2 Wireless Sensor Networks (WSN) in partial discharge (PD) monitoring

Uses of WSN abolish the requirement of sensor power cable and sensor communication cables. Although publications regarding the application of WSNs for condition monitoring system in a high voltage environment[32-34], are substantial but little work has been done on the actual network performance assessment of any WSNs employed for PD detection. Since a lot of information are continuously transmitted and received in a typical WSN system, timing and data download synchronization are of utmost importance. Thus there is a need of synchronization of all the acquired data from the nodes before downloading the data to the coordinator.There is a constraint in WSNs regarding the packet size. With increase in packet size the signal output increases in a proportional manner. As the packet size increases, the packet error probability $P_e$too increases according to (31).

$$P_e = 1 - (1 - b_e)^L \tag{31}$$

where, b_e =Bit-error probability, L = The length of the packets in bits and P_e =Packet error probability

Bit-error probability is dependent on various parameters at the physical level of the sensor operation for instance propagation path loss and multipath reflection.

5. CONCLUSION

The present work describes a brief study of the different faults in an IM along with the available monitoring techniques and the various working motor parameters used thus far in the available literature. In this regard, a detailed review of the prevailing fault monitoring technique for the effective condition monitoring and fault diagnosis used till date are presented. The literature survey reveals that FFT spectrum method allows fast failure state estimation. The more detailed investigation to point out the difficult conditions of the machine under different stator fault conditions of induction motor can be performed as well as it is a non-invasive fault detection technique which can detect incipient faults accurately moreover it's a selective, and economical means for online monitoring of an electrical motors in any industry. However, the non-applicability to non-stationary signals and resolution problem renders FFT useless in the real time condition monitoring scenario. In this regard, wavelet transform immerges as a viable replacement for the FFT based technique. Furthermore since electromagnetic forces are proportional to square of the flux density in an induction motor hence, the vibration from unique electromagnetic forces is a second order effect compared to current components which directly induced from the specific rotating flux waves, therefore, the fault has to be severe to be detected

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