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International Journal for Modern Trends in Science and Technology, 8(04):452-457, 2022

ISSN: 2455-3778 online
DOI: https://doi.org/10.46501/IJMTST0804076
Available online at: http://www.ijmtst.com/vol8issue04.html

Discovery of the stator winding inter-turn insulation degradation for condition monitoring of induction motor using the non-invasive system by harmonic analysis

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To Cite this Article
Satyanarayana Rao R.D and K.S Aprameya. Discovery of the stator winding inter-turn insulation degradation for condition monitoring of induction motor using the non-invasive system by harmonic analysis. International Journal for Modern Trends in Science and Technology 2022, 8(04), pp. 452-457. https://doi.org/10.46501/IJMTST0804076

Article Info
Received: 25 March 2022; Accepted: 22 April 2022; Published: 27 April 2022.

ABSTRACT

Due to the requirement for a modern facility for precise control phenomena, now a day's energy- efficient motors are working everywhere. Energy-efficient motors can save energy, but not avoids fault. This paper focuses on the stator winding phenomenon of 3-phase squirrel cage induction motor inter-turn insulation degradation discovery using the non-invasive system by harmonic analysis. Here induction motors of 1.5hp, 400v, and 1400rpm are utilized. Using one of the best technique Motor current signature analysis, where the current spectrum is analyzed with spectral analysis using Fast Fourier transform (FFT). Faulty & healthy conditions of the motor are properly discovered by suitable experimental results with theoretical analysis of stator winding inter-turn insulation degradation condition.

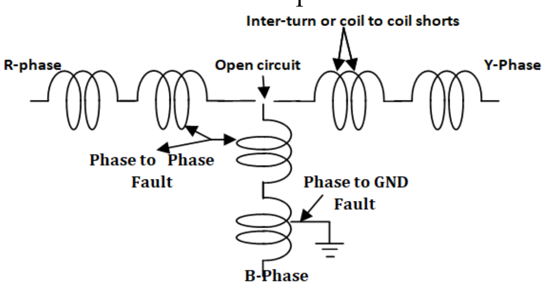
KEYWORDS: *Induction motor, Condition monitoring, Motor current signature analysis, Inter-turn insulation degradation. Harmonic analysis.*

1. INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Almost all industrial requirements from simple process operation to major applications depend on motors. If any unexpected shortcomings or weakness of motor due to any unobservable reasons may result to maximum loss towards other aspects like spares, maintenance, labor wages etc, [1].

These unexpected shortcomings are associated with stator, rotor, eccentricity etc,. Among this stator winding, failure mode contribution is nearby 30% of all other faults in induction motors. Thermal, vibration, electrical, and natural environmental stresses are also important factors causing winding failures. These types of faults can occur depending on weakness in insulation material towards turn to turn, phase to ground, phase to phase fastly circulates in a coil and expand to serious results [2].



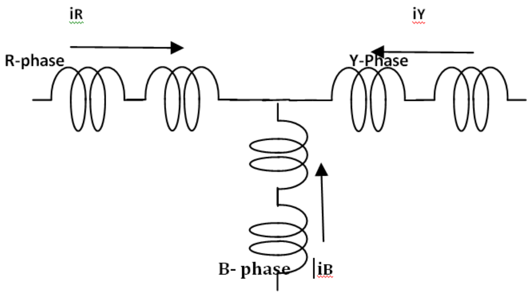


Fig 1 Schematic of the stator winding with different short circuit possibilities & circulating current

Now a days induction motors are the biggest workhorses in present industrial requirements. With the regular increase in unexpected loads, the effect of the harmonic content of power systems connected to other parts is also more important [3].

Due to the clear and accurate results and better performance operations related to recent technological revolutions, the importance of voltage harmonics presence in power systems towards three-phase induction motor has taken important attention recently[4].

One of the widely used and desirable fault detection method is called Motor current signature analysis, where fault harmonics are determined as fault indicators and current curve of the motor is observed. In general, every fault results in various harmonics [5].

For different areas of motor faults like stator, rotor etc towards various drive schemes motor current signature analysis can become a necessary & important tool. Hence by using this tool time or space harmonics will come to end by delivering the same signatures. It is formed by analyzing the current required by the machine for steady-state operation by applying Fast Fourier transform (FFT). Stator winding faults always results in harmonics [6].

An observer coil is introduced into the stator slots of the induction motor for detecting faults. A balanced sinusoidal voltage is applied. Frequency component analysis was also carried out for calculating total harmonic distortion & third harmonic component [7].

In[8], authors presents a developed method for overcoming difficulties in the early detection of inter-turns stator short circuit condition arising from low voltage motors.

In[9], A multiple coupled circuit of a 3 phase squirrel cage induction motor based model on exact stator winding layout, skewing of rotor bars and the linear rise in the stator slot MMF, consolidated the space harmonics associated within the motor in the presence of a fault.

Motor current signature analysis is applies to the characteristic nature of different frequencies corresponding to detect turn to turn shorts, static/dynamic eccentricities, broken rotor bars, and also identification of gradual degradation of the machine insulation [10].

In [11], presents to investigate of the collective effect of thermal and voltage stresses on intrinsic shortcomings of induction motor insulation can be founded using fuzzy logic applications. In [12], the author introduces a method to predict the insulation lifetime of real-time temperature measurements based on theoretical background developments. In [13], explains the necessary results related to major types of tests of squirrel cage induction motor malfunctions like misalignment, unbalance, looseness, broken rotor bars etc. In [14], author gives stator winding short circuit fault that happens due to the destruction of the turn insulation based on Motor current signature analysis diagnostics with zero-crossing time signal of the stator current. In [15], introducing a new method called NI-Compact RIO-based online stator winding fault identification method for proper discovery of partial degradation and stator winding insulation failure.

By studying the above literature survey, all these research works are focused mainly on different load torque conditions for the healthy and faulty motors with fault-specific harmonics for various methods. These harmonics are arising due to stator inter-turn shorts and mainly voltage unbalances in the three- phase supply, losses in the rotor slot harmonics, and static or dynamic eccentricities. In the view of these phenomena, there is the gradual degradation of machine insulation belonging to shortcomings of thermal, mechanical, electrical or environmental stresses. The present work is mainly focused on stator winding insulation degradation detection using the non-invasive method of harmonic analysis.

2. THEORETICAL ANALYSIS FOR INTER-TURN FAULT CURRENT HARMONICS

As per fig.1, stator winding short circuit possibilities of 3 phase induction motor can produce fault currents generating a high amount of heat & temperature. The stator & rotor equations which describe stator windings turn to turn fault of induction machine can be expressed as follows [22]:

$$V_s = R_s I_s + \frac{d\psi_s}{dt} \quad (1)$$

$$0 = R_r I_r + \frac{d\psi_r}{dt} \quad (2)$$

$$\psi_s = L_s I_s + L_{sr} I_r \quad (3)$$

$$\psi_r = L_r I_r + L_{rs} I_s \quad (4)$$

Where $Vs = \left[v_{as} v_{bs} v_{cs} v_{sc} \right]^t$ (5)

$$Is = \left[i_{as} i_{bs} i_{cs} i_{sc} \right]^t \quad (6)$$

$$Ir = \left[i_{ar} i_{br} i_{cr} \right]^t \quad (7)$$

$$\psi_s = \left[\psi_{as} \psi_{bs} \psi_{cs} \right]^t \quad (8)$$

$$\psi_r = \left[\psi_{ar} \psi_{br} \psi_{cr} \right]^t \quad (9)$$

However stator & rotor parameters are represented as s and r and three stator phases are indicated as a, b and c respectively. Also, V, I, & Ψ are voltage, current & flux linkage of the winding. From the above equations due to inter-turn insulation failure of stator winding of circulating current produces a new MMF rotating at synchronous speed but in the opposite way. As a result of this faulty current, new harmonic components will appear in the stator current spectrum which enables to detect the insulation deterioration [22].

It is well-known fact that, when three-phase induction motor received unbalanced line voltages, the resultant currents in the stator windings also change. Due to this fact, a small percentage of voltage unbalance will result in a much larger percentage of current unbalance [3].

As per Fourier analysis, any non-sinusoidal periodical waveform can be transformed into a different order harmonic waveform. Therefore, the non-sinusoidal current and voltage waveform can be expressed as [4]:

$$i(t) = \sqrt{2}[I_1 \sin \omega_0 t + \sum_{k=2}^{\infty} I_k \sin(k\omega_0 t + \theta_k)] \quad (10)$$

$$v(t) = \sqrt{2}[V_1 \sin \omega_0 t + \sum_{k=2}^{\infty} V_k \sin(k\omega_0 t + \phi_k)] \quad (11)$$

Where I_1, V_1 is the fundamental current and voltage, I_k V_k are the K^{th} order harmonic current and voltage, θk and φk, are the phase angles of the harmonic current and voltage and ω0 is the radian frequency. When a nonsinusoidal voltage source is supplied to a three-phase induction motor, the corresponding slip Sk to the various harmonics can be expressed as[4];

$$S_k = \frac{kN_s + (1-S)N_s}{kN_s} = \frac{k+(1-S)}{k} \quad (12)$$

Faults connected to stator winding have a certain amount of harmonics. So the stator turn to turn or inter-turn fault indication is given by equation (13)[10].

$$f_{stator} = f\left\{\frac{n}{p}(1-s) \pm k\right\} \quad (13)$$

As per the above discussions, Equ(13) is employed for the detection of insulation degradation due to inter-turn fault current harmonics.

3. EXPERIMENTAL SETUP OF THE PRESENT WORK

The present work uses a non-invasive method to observe the abnormalities in the induction motor. It is a simple method to make use of the LEM-LA25-NP - Hall effect current transducer connected to all of its RYB Channels to incoming 3 phase supply from the output side of autotransformer. By using FFT (Fast Fourier Transform) algorithm, a better signature of healthy & faulty conditions of the motor can also be found. During its preliminary work, Tektronics 70 MHZ, 1 Giga samples/sec digital oscilloscope, which has default FFT analysis, is made use. By setting the FFT option, it can be used to capture and save the signals in the memory of the oscilloscope. Later it can be downloaded to personnel computer using an RS-232 communication cable.

An experimental setup of the present work is shown below in Fig 2 for the detection of the stator winding insulation degradation of motor such as normal running with various loadings such as zero or no load, half load and full load conditions using motor current signature analysis. The test setup consists of motor-1, a 3 phase,50Hz,1.5hp,1415rpm,400V squirrel cage induction motor with the mechanically loaded brake drum and motor-2, a 3 phase,50Hz,1.5hp,1400rpm,400V squirrel cage induction motor with mechanically loaded brake drum. The instrumentation for current analysis includes LEM-LA25-NP, 3 Channel, 0-10A Input, 0-5V Output, Hall Effect current transducer, a better resolution digital oscilloscope & a personnel computer connected with the help of an RS-232 communication cable.

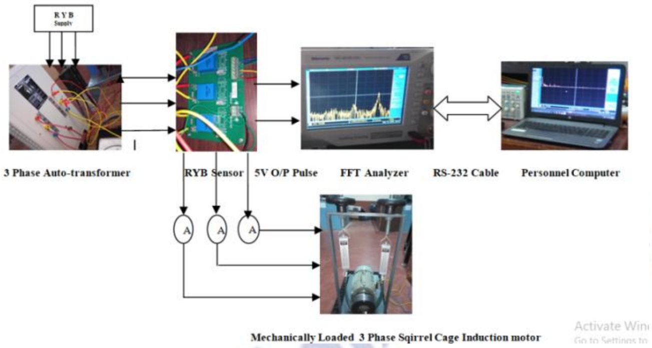


Fig: 2 Schematic of the Experimental setup

Motor Specifications	Motor-1	Motor-2
Performance Frame & make	IS/IEC 60034 ,Crompton Greaves	IS/ 375, Vinayaka Electricals,B'lore.
K.W(H.P)	1.10(1.50)	1.10(1.50)
Voltage	415±10%	415
RPM	1415	1400
Insulation class	F	B
HZ	50±5%	50
A	2.55	2
Efficiency Full load	78.00	76.00

Table 1. Motor Specifications.

Fig: 3 Experimental setup used in the laboratory

4. RESULTS AND DISCUSSIONS

A. Under No load & healthy condition

A balanced three-phase supply is applied to a healthy induction motor during no-load condition, thus motor gives uniform & accurate running. Comparison of results of the motor under healthy and faulty motor stator winding inter-turn degraded condition during no load is shown in fig 4. It shows a dominant fundamental frequency component f_s only at 50.55Hz and -6.59dB, due to the presence of some minor error which is an acceptable limit. This shows a better indication of the healthy motor. But due to faulty conditions, the motor draws more current resulting in excessive heat due to losses in stator & rotor. The spectral analysis clearly shows fundamental frequency component (f=50Hz) was not an accurate position. But 3rd harmonic=150.4Hz, 5th harmonic=250.3Hz, 7th harmonic=350.2Hz & 9th harmonic=451.3Hz goes to peak level and also backward position. This curve gives a clear indication of the faulty motor during no-load condition.

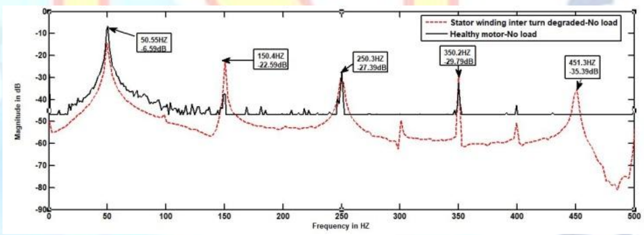


Fig.4 Comparison of FFT curve of healthy & faulty motor during zero or no load condition

B. Half load condition

By applying half load to a faulty motor, we know that there is a further decrease in speed and increase in current magnitude. The voltage unbalance condition was also observed. It is observed that increase in humming nature, slight vibration, and motor temperature as compared to no-load condition. Fig 5 shows the comparison of the spectral curve of a healthy & faulty motor under half load condition. Finally, it is also observed that a nearby similar set of frequency components appeared as compared with no load curve of the motor.

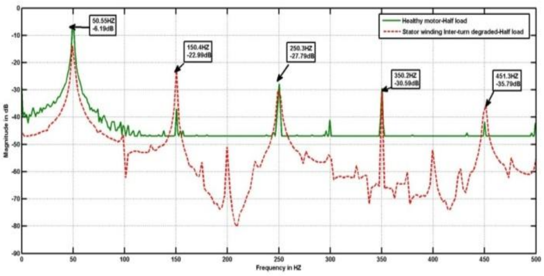


Fig.5 Comparison of FFT curve of healthy & faulty motor during half load condition.

C. Full load condition

By applying full load to a faulty motor, due to weak condition & poor performance, there is a sudden reduction in speed and increase in current magnitude. Due to unbalanced supply voltage, more vibrations, gradual humming sound and noise have been observed. The FFT analysis of motor under this condition shows in fig 6. The appearance gives a similar set of frequency components as compared with earlier no- load and half-load conditions with increased magnitudes. Table 2 shows a comparison of Experimental & Theoretical fault frequencies & their % Error differences.

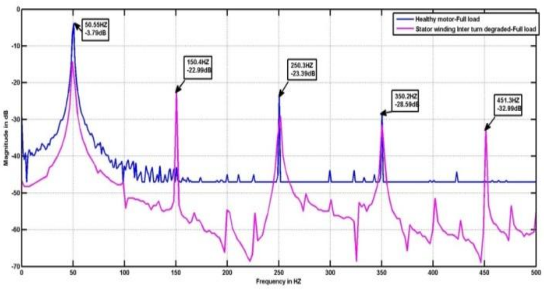


Fig.6 Comparison of FFT curve of healthy & faulty motor during full load condition.

	Experimental fault frequencies in Hz		
Fault frequencies	No load	Half load	Full load
fs	49.32	49.32	49.32
3fs	150.4	150.4	150.4
5fs	250.3	250.3	250.3
7fs	350.2	350.2	350.2

Table 2a . Experimental fault frequencies in Hz.

Theoretical computed fault frequencies in Hz using Eq(13).			% Error bet. Theoretical & Experimental values		
No load	Half load	Full load	No load	Half load	Full load
52.06	52.7	52.00	2.74	3.38	2.68
151.0	152.7	152.0	-0.6	2.3	1.6
252.2	251.3	251.1	1.9	1	0.8
353.2	352.1	351.1	3	1.9	0.9

Table 2b. Comparison of Theoretical computed fault frequencies and % Error bet. Theoretical & Experimental values

5. CONCLUSIONS

Comparison of results of the motor under healthy and faulty motor stator winding inter-turn degraded condition during no load is shown. It shows a dominant fundamental frequency component f_s only at 50.55Hz and -6.59dB, due to the presence of some minor error which is an acceptable limit. This shows a better indication of the healthy motor. But by observing its faulty condition, the motor itself draws more current resulting in excessive heat due to losses in the stator & rotor. The spectral analysis clearly shows fundamental frequency component (f=50Hz) was not an accurate position. But 3rd harmonic=150.4Hz, 5th harmonic=250.3Hz, 7th harmonic=350.2Hz & 9th harmonic=451.3Hz goes to peak level and also backward position. A curve gives a clear indication of the faulty motor during no-load, half load & full load conditions. Table 2 shows a comparison of Experimental & Theoretical fault frequencies & their % Error differences.

6. ACKNOWLEDGEMENTS

The author gives thanks for this work supported by the Electrical & Electronics department, U.B.D.T College of Engineering, Davanagere & also the Electrical & Electronics department, Adichunchanagiri Institute of Technology, Chikkamagaluru, Karnataka, India.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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