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A NEW METHOD FOR DETECTION OF UNBALANCE VOLTAGE SUPPLY IN THREE PHASE INDUCTION MOTOR

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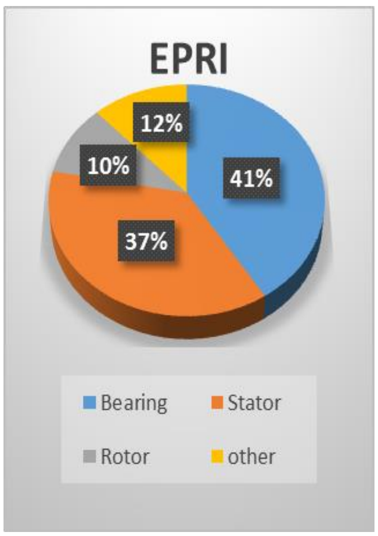
Graphical abstract



Abstract

Induction motors are associated with various techno-economic advantages; therefore these are widely used in residential, commercial and industrial systems. Cost effective and reliable process of condition monitoring of induction motor is very important. It is found that unbalance voltage supply is one of the major factors that produce uneven heating due to reverse current and leads to inter-turn short circuit. The issue regarding unbalanced voltage supply has attracted the attention of researcher and engineers in recent past. In this paper, a new effective non-invasive (online) method is proposed that only use rotor harmonic current signature for the detection of unbalance voltage supply instead of main line current signature. This is a sensor-less and online approach that accomplishes the reliable and accurate analysis of the induction motors. Moreover, it allows a continuous real time tracking without disturbing the normal operation and guarantees the overall production process. Additionally, this method recognizes the unbalance and estimate the severity of the unbalance in the voltage source. The effects of unbalance voltage supply are investigated through experiments. In order to perform the analysis and detect the asymmetry due to unbalance voltage, an experimental set up is designed that can accurately repeat the measurements. In the proposed work, unbalance voltage supply is diagnosed through experimental hardware setup. To validate the propose methods an experiment is performed that confirm that motor operating under unbalance voltage supply give a significant rise in the rotor harmonic while under balance voltage supply there is so such a rise in the rotor harmonic.

Keywords: Diagnosis, condition monitoring, inter-turn short circuit, insulation failure, induction motor, rotor slot harmonics, winding insulation.

1.0 INTRODUCTION

Induction motors are prime component of many industries and are frequently integrated into commercial and industrial equipment. Although induction motors are reliable electric machines, they are susceptible to many electrical and mechanical faults due to installation issues and environmental factors. Induction motors are subject to different types of faults [1-5]. Condition monitoring in an induction motor must concentrate on the root causes of the failure modes that exhibit a slow failure sequence. According to the published surveys, two-fifths of the faults are due to bearing failures. Inter-turn short circuit faults in stator windings are approximately responsible for one-third of the motor faults. Ten percent faults are due to end rings and broken rotor bars. Figure 1 summarizes the sum of faults in an induction motor. The figure presents the surveys conducted by Electric Power Research Institute (EPRI) about the fault of induction motor[6, 7]. The effects of such faults in induction motors include unbalanced stator voltages, currents, torque, efficiency reduction, oscillations, excessive vibration, overheating, and torque reduction. Besides, these faults affect the magnitude of certain harmonic.

In induction motors the insulation is potentially the weakest components. Insulation in stator winding of induction motor is a laminated system that consists of numerous layers of mica-paper tape on a fiberglass backing material impregnated and consolidated with a synthetic resin[8]. The main class of stator winding faults is short-circuiting of a few turns (inter-turn) in a phase winding. It found that the unbalanced voltage supply is one of the major factors that produce uneven heating in the stator winding and damage the insulation. Under unbalanced voltage supply the induction motor face opposing positive and negative phase sequence components. The positive sequence voltage generates positive torque, while the negative sequence voltage produces the air gap flux that rotates against the rotor, thus generate reversing torque (unwanted). Due to the reversing torque, net speed and torque of an induction motor are reduced and the pulsations of speed and the torque increase motor noise. In addition, the unbalanced voltages negative sequence generates large negative sequence current, this increase the motor losses and temperatures. The main focus of this work is to detect, diagnose unbalanced supply and then to distinguish from the balanced supply.

The resultant unbalance voltage supply causes a significant circulating current to propagate through the coil and leads to deterioration and failure in winding. The unbalance voltage supply tends to be very destructive. Figure 2 shows the symptoms of the faults that are produced in the stator winding. If an unbalance voltage supply, not diagnosed at early stages, can lead to larger section of the winding failure, such as coil-to-coil or phase-to-phase short circuit and finally phase-to-ground faults [9, 10]. Insulation failure leads to the burning of insulation and localized melting of the copper winding and core.

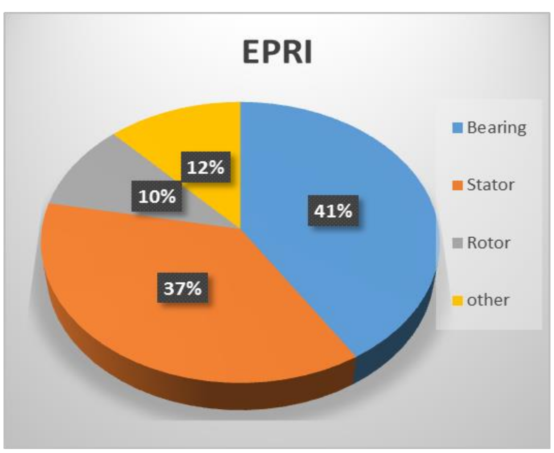


Figure 1 Percentage fault of each component of induction motor

2.0 VOLTAGE VARIATIONS AND UNBALANCE

Voltage unbalances are random variations in the magnitude of voltage, mostly due to load, frequent motor operations concerning speed variations etc. The term voltage unbalance refers to the non-equality among the magnitudes or angles of the applied voltage at three different phases at particular time, mostly it is due to the occurrence of the unequal single-phase load distribution, impedance asymmetry in transformer and line winding, variation in single-phase loads, fuses blown out in banks, large reactive load etc. The most significant cause for voltage unbalance is a mismatch between the generation and utilities of power demand in industries. Due to variation in the operation times of single-phase and three-phase loads, there are definite chances for existing of voltage variations below and above the rated voltage value. Hence, unbalance voltage are classified four different categories:

I. Balanced overvoltage
II. Balanced undervoltage
III. Unbalanced overvoltage
IV. Unbalanced undervoltage

Balanced overvoltage refers to the state where the individual voltage and the voltage in three-phases are greater than the rated voltage value. Balanced under-voltage refers to the state where the individual voltage and the voltage in three-phases are lesser than the rated voltage value. Unbalanced voltage refers to the state where the voltages in three phases are different from each other and their positive sequence is greater than the rated voltage. Unbalanced under voltages refer to the state where the voltages in three phases are different from each other and their positive sequence is lesser than the rated voltage.

Due to number of factors as mentioned in introduction, there is less probability that the voltage in all three-phase remain constant at all times, hence in this paper analysis are carried on unbalanced overvoltage and unbalanced under voltage. Further, these both states are diagnosed and distinguished from healthy motor.

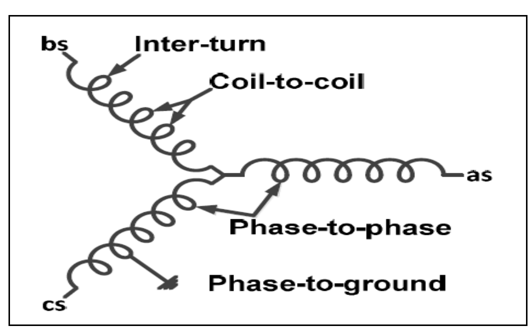


Figure 2 Schematic of stator winding failure modes [10]

3.0 VARIOUS DEFENITIONS OF UNBALANCE VOLTAGE

According to different standard there are some definitions for unbalance voltage:

By NEMA:

The NEMA defines unbalance voltage by the line voltage unbalance rate (LVUR), which is given as:

$$\% \, LVUR = \frac{\text{Max.deviation of volt from the avg.line volte}}{\text{Avg.line volt}} * 100 \quad (1)$$

By IEEE:

The IEEE defines unbalance voltage through the phase voltage unbalance rate (PVUR), which is given as:

$$\% \, \mathrm{PVUR} = \frac{\text{Max.deviation of volt from the avg.phase volt}}{\text{Avg.phase volt}} * 10 \quad (2)$$

By IEC:

According to IEC unbalance voltage defined as the ratio of negative sequence voltage component to the positive sequence voltage component. The percentage unbalance factor (VUF), which is given as:

$$\% \, \mathrm{VUF} = \frac{\text{Negative sequence voltage component}}{\text{Positive sequence voltage component}} * 100 \quad (3)$$

4.0 MOTIVATION DEFINITIONS OF UNBALANCE VOLTAGE

The traditional off-line or invasive testing methods are inconvenient and do not permit frequent testing of the stator winding insulation. Non-invasive schemes are more desirable and cost-effective because these techniques do not require additional sensors and the motor faults can be diagnosed in an environment, where installation of sensors are very difficult. Based on the identification and challenging issues for accurate description of an induction motor performance under asymmetry, such as, unbalanced supply voltage, require a non-invasive technique that involves more details to achieve a good fault diagnosis. Main focus of this work is to follow the recent trend and to develop effective unbalance supply voltage detection method. In this research work non-intrusive methods is proposed that only use voltage and current measurements and does not require additional sensors.

This proposed method is insensitive to unbalanced supply voltage, intrinsic asymmetry in the motor. The approach will accomplish reliable and accurate analysis on induction motors. Furthermore, an experimental set up and an experimental procedure is designed that can accurately repeat the measurements of signals and will be able to detect a particular fault. In this technique, it will be possible to simulate an induction motor under various conditions of unbalance voltage supply. The asymmetry caused by the unbalanced supply voltage is measured through current. The unbalance voltage supply is detected through this analysis can are visualized through computer. In this technique, traditional third order MCSA will not be used as a fault indicator. In MCSA method current mostly third order current harmonics help to diagnose the fault or unbalance voltage supply. In MCSA, each fault creates its own harmonics. Similarly, the harmonics of stator unbalanced supply voltage correspond to the same third harmonics. Thus, in this case it is difficult to diagnose and distinguish between stator winding faults and voltage unbalanced supply. In this research work new approach is proposed to diagnose unbalanced supply voltage. In these techniques we have not consider the main current signature harmonics instead; we have analyze the rotor current harmonics that flows due to the voltage induced by the rotor slot harmonics. Further, the unbalance voltage supply is diagnosed the current signature by rotor slot harmonics obtained from the proposed method.

A Voltage Induced In Stator Winding Due To Rotor Harmonics

In an induction motor, the magnetic field of rotor is generated through stator side. Under ideal condition there is single harmonic for rotor magnetic field. While in the case of squirrel cage, there are extra harmonics in magnetic field of rotor in addition to fundamental component. These harmonics induce voltage in stator winding are called rotor harmonics. These harmonics can be determined at frequencies discussed in [11].

$$f_{RH} = \left[k \, \frac{2N_r}{p}(1-s) \pm 1\right] F_s, \quad k = 1,2,3 \dots \dots \dots \quad (4)$$

In equation (1), N_r represents the rotor slots, p represents the total number of poles, s is a slip, and F_s refers to the main line frequency. It is seen from the equation that in addition to the main line frequency the rotor harmonics frequency depends on the number of poles and the number of rotor slots

B Response of Stator Current For Unbalanced Supply

Harmonic components even exist for perfectly symmetrical ideal induction motor. The asymmetry in a motor at manufacturing process will also develop third harmonic with small magnitude. Therefore, the third harmonic will not be considering a significant indicator for induction motor faults. The effect of unbalanced supply may be observed from current spectrum [12]. It can be concluded that the unbalanced supply generate third-order harmonic. In fact, the traditional techniques have used the third order harmonic to diagnose the unbalance supply voltage, third order harmonic even exits for perfectly aligned motor. Thus, classical technique of current signature is not feasible.

C Current Monitoring In Three Phase Of Induction Motor

It is found that classical third order current signature harmonic technique is not feasible to diagnose unbalanced voltage supply. In order to solve the problem related to unbalanced supply, new approach is presented to detect and diagnose unbalance voltage supply. In the proposed method, current spectrum of each phase will be monitored. The unbalance supply voltage will produce asymmetry in induction motor. Moreover, the parameter of unbalanced motor differs from healthy one. To find out the parameter, we should look to the conductor under healthy and unbalanced supply voltage condition as expressed in the following equations.

$$l_a(\theta) = \sum_k l_{ak}[\theta - \theta_k] \quad (5)$$

$$l_b(\theta) = \sum_k l_{bk}\left[\theta - \theta_k - \frac{2\pi}{3}\right] \quad (6)$$

$$l_c(\theta) = \sum_k l_{ck}\left[\theta - \theta_k + \frac{2\pi}{3}\right] \quad (7)$$

In these equations, l, is the number of conductors, where θ is angle with the stator, and k is the index. For ideal motor without any fault, the number of conductors will be equal, i.e., $l_{ak} = l_{bk} = l_{ck}$.The Faraday rule, can be used to find out the induced voltage by rotor harmonics as[11]:

$$V(t) = \omega . L . B_r(\theta, t) . l_a(\theta) \quad (8)$$

$$V_a(t) = \sum_g V_{ag} Sin\left(\left[g\frac{N_r}{P}(1-s)+1\right]\omega_1 t - \emptyset_{ag}\right) \quad (9)$$

$$V_b(t) = \sum_g V_{bg} Sin\left(\left[g\frac{N_r}{P}(1-s)+1\right]\omega_1 t - \emptyset_{bg}\right) \quad (10)$$

$$V_c(t) = \sum_g V_{cg} Sin\left(\left[g\frac{N_r}{P}(1-s)+1\right]\omega_1 t - \emptyset_{cg}\right) \quad (11)$$

where V_{ag}, V_{bg}, V_{cg}, are the magnitudes of an induced harmonic voltage. ω_1 is the angular frequency, L represents conductor length, B_r is the rotor field, and l_a, l_b, l_c are the placement of conductors in three phases. For healthy motor the harmonics in all the phases should have the same magnitude. This is because of the symmetrical conductor distribution as shown in (Eq. (5-7)) and the voltage equation (Eq. (9-11)). For healthy motor, assume that the three phases have the same impedance, such as, $Z_a = Z_b = Z_c$ and the same amount of current is flowing through each phase.

Consider the situation where the supply voltage is unbalanced and the stator winding is healthy. Under Unbalanced supply voltage, the number of conductors will be not affected at incipient stage which means that the harmonics of induced voltage not differ from healthy motor but the difference is in the magnitude of the voltage at stator winding due to unbalance applied voltage thus, different current will flow in all the three phases as shown in (Eq. (12-14)).

Table 1 Experimental variation in voltage supply

	Phase 1 Volt. (V1)	**Volt. variation among phase (V1 & V2)**	**Phase 2 Volt. (V2)**	**Volt. variation among phase (V2 & V3)**	**Phase 3 Volt. (V3)**	**Volt. variation among phase (V3 & V1)**
Under Balance voltage supply	415 V	0%	415 V	0%	415 V	0%
Under Unbalance Voltage supply	415 V	10%	375 V	6%	350 V	15%

$$Z_a = Z_b = Z_c \quad (12)$$
$$V_a \neq V_b \neq V_c \quad (13)$$
$$I_a \neq I_b \neq I_c \quad (14)$$

Our aim is to detect an unbalanced voltage supply. When motor is healthy, the magnitude of the current is same in all three phases, while, under unbalanced supply voltage condition the magnitude of the current will not be the same in all three phases. In order to detect the unbalanced supply voltage, ordinary MCSA and Park's Vector approach will not be helpful. In proposed method, third harmonic of stator current are not considered. In this method the rotor harmonic are considered that flows through stator. Therefore, the challenging issue can be solved by proposed method.

5.0 MOTOR UNDER EXPERIMENTATION AND RESULTS

The experimental laboratory setup was adopted on a three-phase induction motor. Fig.3 shows the experimental setup that was carried out in machine lab on three phase induction motor connected to 415 volt, 3-ø ac supply, star connection, 50 Hz frequency, 2-poles and 30 rotor slots. To introduce the effect of unbalanced voltage supply, Lab-Voltage variable source device was used. For the performance of motor different cases are represented in Table 1 under unbalanced voltage. Power supply model 8821-2A was used in experiment and the equipment for data acquisition includes current transformer, FLUKE 435 II series power quality and energy analyzer and a personal computer PC to analyze the behavior of the motor through the current spectrum and the rotor harmonics.

Figure 4 shows the current spectrum of three phase induction motor for balanced voltage supply. Refer to Eq. (1), the harmonic at 625Hz and 675Hz are the rotor harmonic and these rotor harmonic induces voltage at stator winding. The presence of harmonics at 625Hz and 675Hz are the indication of voltage induced at stator winding from rotor side. It if found that under balance voltage supply there is not so much change in the amplitude of rotor harmonic at 625Hz and 675Hz

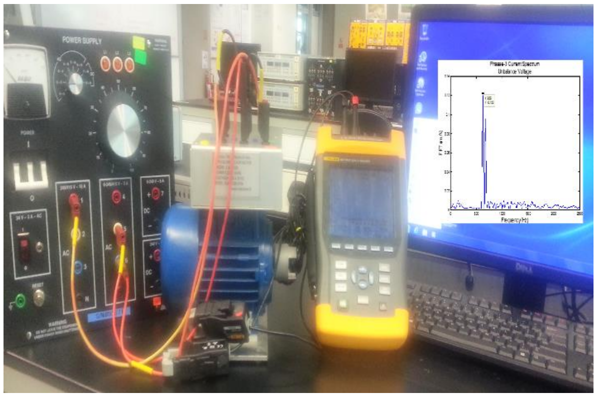


Figure 3 Experimental setup for the proposed method

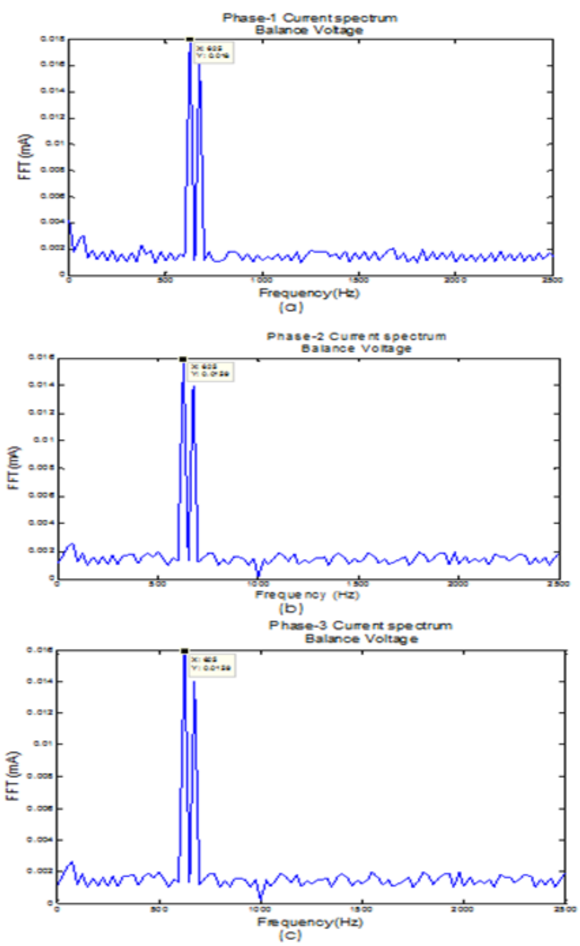


Figure 4 Current spectrum for balanced voltage supply in all the three phases

Figure 5 shows the current spectrum of three phase induction motor for unbalanced voltage supply. Refer to Eq. (1), the harmonic at 625Hz and 675Hz are the rotor harmonic and these rotor harmonic induces voltage at stator winding. It is found that there is a enormous change in the amplitude of rotor harmonic. The change in the harmonic amplitude under unbalanced voltage is due to the asymmetry caused by the voltage supply. The unbalanced voltage supply will generate reverse rotating magnetic field in correspondence to the positive rotating filed. This reverse rotating will generate negative sequence current therefore there is difference between the current spectrums for both condition. From the Figure 4 and 5, it is seen that under healthy condition when three phase voltages are same there is no such a difference among the magnitude of the rotor harmonics while in case of unbalance voltage supply there is huge rise in the amplitude of rotor harmonic.

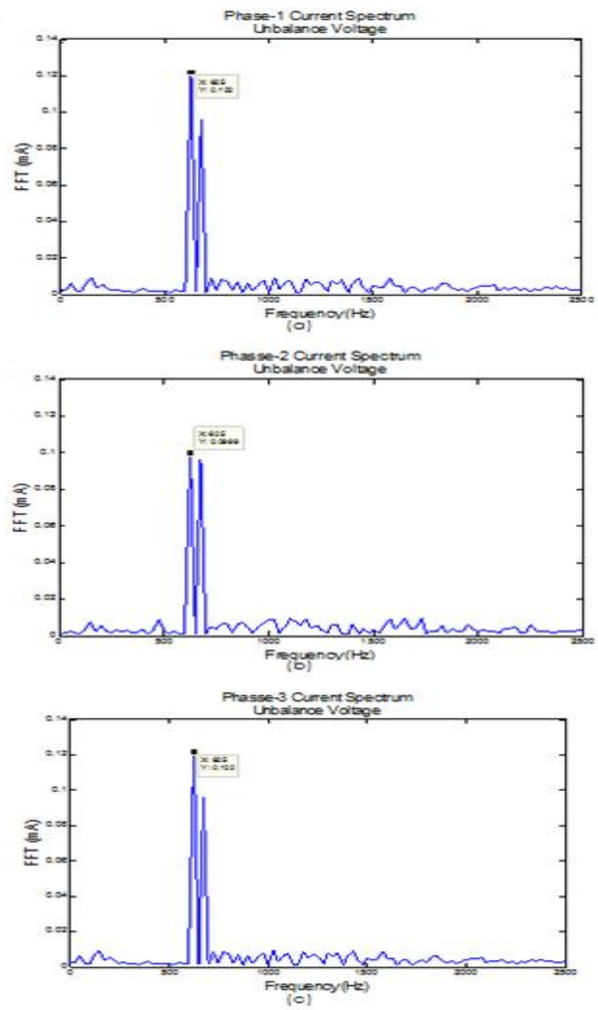


Figure 5 Current spectrum for unbalanced voltage supply in all the three phases

5.0 CONCLUSION

In this work, performance of a three phase induction motor under balanced and unbalance applied voltage has been taken in account. As the unbalance in the voltage source can cause excessive losses, heating, noise, vibration, torsional pulsations, slip, and motor accelerating torque, detecting of unbalancing in the voltage applied is important. In this paper a new method has been proposed to diagnose unbalance voltage supply and also to distinguish between balanced and unbalanced voltage supplied motor. This is a sensor less and online approach that accomplishes the reliable and accurate analysis on the induction motors. Moreover, it allows a continuous real time tracking without disturbing the normal operation and guarantees the overall production process efficiently. Additionally, this methods permit to recognize the unbalance and estimate the severity of the unbalance in the voltage source. The effects of unbalance are investigated through experiments. The results for balanced voltage supply and unbalanced voltage supply was illustrated via the significant rise in the magnitude of rotor harmonic in the motor current spectrum. It was found that the motor operating under unbalance voltage supply give a significant rise in the rotor harmonic while under balance voltage supply there is so such a rise in the rotor harmonic.

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