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Motor Stator Winding Condition Monitoring

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Abstract

The induction motor is considered the workhorse of the industry as it is used in most of the engineering applications. It is essential to ensure a safe and reliable operation of the induction motor in every system. Among the various types of induction motor faults, stator winding insulation fault accounts for a high percentage of it. As such, being able to detect early stages of insulation faults within the equipment using the method proposed in this paper would prove to be useful in providing timely maintenance. The proposed method in this paper is the non-intrusive impedance extraction method for online stator winding fault detection of induction motor. By observing the health condition of the motor in relation with its impedance, early stages of faults can be detected and rectified. Hence, eliminating potential safety hazards, reducing motor downtime as well as lowering the cost of maintenance. Experimental results shown will prove the reliability and accuracy in which the method proposed would provide. At the same time, its installation and removal are less complicated as compared to other methods hence is cost and time efficient.

Keywords: *Induction motor, impedance extraction, stator winding, fault detection*

I. Introduction

In almost all engineering applications, the induction motors (IM) are considered the workhorse within the industry [1]. It comprises of two key components; rotor, the rotating part of the motor as well as the stationary part called the stator. By electromagnetic induction, the power is transferred from one part to another. Apart from the two main components mentioned above, an induction motor consists of other parts such as the bearings which is usually located at either end of the motor. The bearings reduce the friction between the moving parts hence increasing the efficiency of the induction motor.

Due to its rugged construction, simplicity, high efficiency and relatively low manufacturing costs, the induction motor is commonly used as a mean to power industrial equipment. They are mainly used in environment which require high operation time however are subjected to undesirable faults. As such, its health condition is essential to ensure an unwavering and dependable operation of modern industrial systems. There are various types of induction motor faults, which are common in the industry such as damaged rotor bars, dynamic or static air gap irregularities, stator windings insulation faults and bent shaft etc. However, past statistics have shown that stator winding breakdown has contributed to a large percentage of induction motor failures [2], [3].

For this paper, a non-intrusive impedance extraction online method that is based on the inductive coupling approach [4-7], is used for detecting insulation fault within the stator winding of the induction motor. A known signal generated is input into the induction motor and monitored simultaneously. The impedance obtained through the signal will be extracted. By observing the health condition and its impedance, early stages of fault can be detected and rectified. This method eliminates potential safety hazards and its installation and removal is less complicated as compared to other methods hence is cost and time efficient.

II. Methodology

Figure 1 shows the fundamental measurement setup of the circuit loop with an oscilloscope, signal generator and two clamp-on probes, namely the current injecting probe and current receiving probe. The Device Under Test (DUT), power supply as denoted by V_s in the figure below, as well as the connecting wires established a closed-circuit loop. Z_{DUT} , Z_{Wire} and Z_{Supply} , denotes the impedances of the DUT, power supply and connecting wires respectively.

Figure 1 – Fundamental Measurement Setup of the Circuit Loop.

Hence, the closed-circuit loop impedance, Z_{Loop} is obtained through the equation:

$$Z_{Loop} = Z_{DUT} + Z_{Wire} + Z_{Supply} \quad (1)$$

The signal generator simulates a known sinusoidal signal which is injected into the circuit loop through the oscilloscope CH 1. At the same time, the receiving probe will monitor and measure the same signal through the oscilloscope CH 2. A cascaded two-port network approach will be applied to draw out the unknown impedance of the DUT [8]. The resultant, M of the cascaded two-port network is given by:

$$M = M_{inject} \times M_{loop} \times M_{receive} \quad (2)$$

The general two-port network observed by the Oscilloscope is given by:

$$\begin{bmatrix} V1 \\ I1 \end{bmatrix} = \begin{bmatrix} A_{inj} & B_{inj} \\ C_{inj} & D_{inj} \end{bmatrix} \begin{bmatrix} 1 & Z_{loop} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} A_{rec} & B_{rec} \\ C_{rec} & D_{rec} \end{bmatrix} \begin{bmatrix} V2 \\ I2 \end{bmatrix} \quad (3)$$

Given that $I_2 = \frac{V_2}{50}$, Z_{loop} can be extracted as follows:

$$Z_{loop} = \frac{V1}{V2} \times \frac{1}{A_{inj} \times (C_{rec} + \frac{D_{rec}}{50})} - \frac{A_{rec} + \frac{B_{rec}}{50}}{C_{rec} + \frac{D_{rec}}{50}} - \frac{B_{inj}}{A_{inj}} \quad (4)$$

Utilising a test fixture as shown in Figure 2, M_{inject} and $M_{receive}$ can be pre-characterized. The inductive probe is fastened onto the wire of the test fixture. The ends of the wire are connected to the outer conductor and the signal terminal of the test fixture respectively. At the same time, the ground terminal of the port is connected to the outer conductor. For M_{inject} to be characterized, the injecting probe port will be connected to Port 1 of the VNA and Port 2 will be connected to the test fixture port. In the case of characterization of $M_{receive}$, the test fixture port will now be connected to Port 1 of the VNA and Port 2 will be connected to the receiving probe port.

Figure 2 – Test Fixture with Vector Network Analyzer and Inductive Probe [13]

Hence, with this setup, the VNA can measure the respective two-port parameters of the probes with the wire directly. The extracted data will be change into the ABCD parameters based on the equations shown below [9]. Given that $Z_0 = 50\Omega$.

$$A = \frac{(1+S_{11})(1-S_{22})+(S_{12}S_{21})}{2S_{21}} \quad (5)$$

$$B = Z_0 \frac{(1+S_{11})(1+S_{22})-(S_{12}S_{21})}{2S_{21}} \quad (6)$$

$$C = \frac{1}{Z_0} \frac{(1-S_{11})(1-S_{22})-(S_{12}S_{21})}{2S_{21}} \quad (7)$$

$$D = \frac{(1-S_{11})(1+S_{22})+(S_{12}S_{21})}{2S_{21}} \quad (8)$$

After pre-characterizing M_{inject} and M_{receive} , Z_{loop} can be extracted when V_1 and V_2 are obtained. A moving window Discrete Fourier Transform (DFT) algorithm is used to obtain the magnitudes and phases of V_1 and V_2 . With the window size N set at a constant value, DFT is performed to obtain the dynamic voltage equivalents at different time instances, hence obtaining V_1 and V_2 .

As shown in Figure 3, when time is equals to zero, the program begins with the samples of $v_1(t)$ and $v_2(t)$. At the same time, 'm' corresponds to the $(m+1)^{\text{th}}$ sample during the entire monitoring procedure, which is the same as multiplication of the sampling time point t and the sampling rate $\frac{1}{\Delta t}$. When $(m \geq N - 1)$, the DFT is executed and V_1 and V_2 are obtained. Acquiring of V_1 and V_2 at time t is based on the latest samples within the time domain, which is from $(m - N + 1) \Delta t$ to $m \Delta t$. Therefore, the N samples are determined and are relative to the sampling time instance t . Once achieving V_2 at time instance t , the corresponding I_2 can also be extracted. Thus, Z_{SUM} at that time point t can be calculated and subsequently Z_{TVN} is determined. Lastly, the algorithm will compare whether the sampling time point t has reached the last sampling time point (t_{end}). The algorithm will end when $t \geq t_{\text{end}}$ otherwise the same process is repeated till the condition is fulfilled.

Figure 3 – Moving Window Discrete Fourier Transform Algorithm

Hence the DFT can be used to monitor Z_{loop} in real time [7]. Once V_1 and V_2 are obtained, Z_{loop} can be obtained through the equation stated above. By de-embedding the components Z_{Wire} and Z_{Supply} from Z_{loop} , Z_{DUT} can be extracted. In the case where Z_{Wire} and Z_{Supply} values are small and negligible, they can be ignored.

III. Experiment Validation

A. Verification of Accuracy of Proposed Setup

To verify the precision of the suggested measurement setup, several components such as resistors, capacitors and inductors with known values are used to represent different DUTs. In this validation experiment, the following parameters are set at a fixed value:

$$F_{\text{Signal}} = 100\text{kHz} \quad (9)$$

$$F_{\text{Sampling}} = 1\text{MHz} \quad (10)$$

$$N = 100 \quad (11)$$

For the suggested method, selecting a suitable F_{Signal} is essential. To extract the impedance accurately, the intervals between the period of N samples should be smaller than that of the impedance change. Hence,

$$F_{\text{Sampling}} = N_p \cdot F_{\text{Signal}} \quad (12)$$

$$N = N_p \cdot N_c \quad (13)$$

where N_p is the number of samples for each cycle of F_{Signal} , N_c is the number of cycles of F_{Signal} to carry out the DFT. In this paper, both N_p and N_c will be set at a constant value of 10 for all experiment. Thus, utilizing the proposed method, the circuit loop is injected with the test signal, F_{Signal} and the real time impedances of the various DUTs are computed. The following figures below shows some of the measured impedances of the various DUTs (Resistors, Capacitors & Inductors) using the suggested method. The solid line represents the measured value and the dashed line represent the calculated value. For a resistor with resistance of $1\text{ k}\Omega$. From Figure 4, for a resistor with impedance of 1000Ω , the measured magnitude values can be observed to be at approximately 1000Ω . Real time data statistics of the resistor show that measured impedance is given at 1008Ω as shown in Figure 5. And the phase of the same resistor is given at approximately 0° as seen in Figure 5 and Figure 6 below. The measured value can be considered accurate as it is within 5% tolerance level of the calculated value. This discrepancy is due to the manufacturing of the individual components.

Figure 4 – Measured Magnitude of 1000Ω Resistor at given parameters

Figure 5 – Data Statistics of 1000 Ohms Resistor

Figure 6 – Measured Phase of 1000Ω Resistor at given parameters

In the case of a capacitor, the impedance can be obtained through the formula:

$$Z = \frac{1}{2\pi f c} \quad (14)$$

For a capacitor with capacitance of 82nF, the corresponding impedance is given by:

$$Z = \frac{1}{2 \times \pi \times (100 \times 10^3) \times (82 \times 10^{-9})} \approx 19.5 \Omega \quad (15)$$

Phase of a capacitor is given at -90°.

Figure 7 – Data Statistics of 82nF Capacitor

The data statistics of the 82nF Capacitor state that the measured impedance magnitude is at 19.5Ω and phase is at -91.31° as shown in Figure 7. These results can also be observed in the magnitude and phase waveform obtained as shown in Figure 8 and Figure 9, respectively. The measured value is almost the same as the calculated value.

Figure 8 – Measured Magnitude of 82nF Capacitor at given parameters

Figure 9 – Measured Phase of 82nF Capacitor at given parameters

In the case of an inductor, the impedance can be obtained through the formula:

$$Z = 2\pi fL \quad (16)$$

For an inductor of inductance $82\mu\text{H}$, the corresponding impedance is given by:

$$Z = 2 \times \pi \times (100 \times 10^3) \times (82 \times 10^{-6}) \approx 51.5\Omega \quad (17)$$

Phase of an inductor is given at 90° .

Figure 10 – Measured Magnitude of 82uH Inductor at given parameters

Figure 11 – Data Statistics of 82uH Inductor

For an inductor with inductance of 82μH, its impedance calculated from the formula is 51.5Ω and its phase is 90°. Based on the Figure 10 and Figure 11 above, it is observed that the measured value is within the 5% tolerance level. The phase value can also be seen to be close to the theoretical value as seen in Figure 12.

Figure 12 – Measured Phase of 82uH Inductor at given parameters

As seen from the figures above, the determined impedances utilizing the suggested method display close agreement with the values calculated through theoretical formulas. This prove that the suggested method can extract the impedance of the DUT with good precision.

B. Healthy State of an Induction Motor

For the monitoring of the online condition of a single-phase induction motor, the same oscilloscope and current probes as seen in the earlier experiment will be used. Figure 13 below shows the basic configuration for the online monitoring.

Figure 13 – Setup for Monitoring of Single-Phase Induction Motor

For online CM of the induction motor, the healthy state condition is essential. Hence, the first step of the suggested method is to retrieve the impedance of the IM in its healthy condition with no faults. For this part of the experiment, we will extract the healthy state impedance of the induction motor with light load and heavy load at 3 different frequencies, 100kHz, 200kHz and 400kHz respectively. Under the following conditions, the impedance of the IM in its healthy state is extracted.

When light load is attached to the induction motor,

$$F_{\text{Signal}} = 100\text{kHz}, 200\text{kHz}, 400\text{kHz} \text{ respectively} \quad (18)$$

$$N = 100 \quad (19)$$

Figures 14-16 show the measured magnitude of the impedance of the induction motor with light load in their healthy state at the stated frequencies.

Figure 14 – Light Load Healthy State Magnitude, F_{sig} is 100kHz, F_s is 1MHz

Figure 15 – Light Load Healthy State Magnitude, F_{sig} is 200kHz, F_s is 2MHz

Figure 16 – Light Load Healthy State Magnitude, F_{sig} 400kHz, F_s 4MHz

When heavy load is attached to the induction motor,

$$F_{Signal} = 100\text{kHz}, 200\text{kHz}, 400\text{kHz} \text{ respectively} \quad (20)$$

$$N = 100 \quad (21)$$

Figures 17-19 show the measured magnitude of the impedance of the induction motor with heavy load in their healthy state at the stated frequencies.

Figure 17 – Heavy Load Healthy State Magnitude, F_{sig} is 100kHz, F_s is 1MHz

Figure 18 – Heavy Load Healthy State Magnitude, F_{sig} is 200kHz, F_s is 2MHz

Figure 19 – Heavy Load Healthy State Magnitude, F_{sig} is 400kHz, F_s is 4MHz

Despite a heavy load attached to the induction motor, the impedance extracted is of close agreement with that of the induction motor with a light load attached at the same frequency level. This is proven from the waveform above as well as the data statistics table shown in Figure 20 and Figure 21. Based on the real time data extracted, it is shown that the impedances for both low load and heavy load does not differ much in comparison.

Data Statistics ...				Data Statistics ...				Data Statistics ...			
Statistics for 100kHz_LowLoad Ma...				Statistics for 200kHz_LowLoad Ma...				Statistics for 400kHz_LowLoad Ma...			
Check to plot statistics on figure:				Check to plot statistics on figure:				Check to plot statistics on figure:			
	X		Y		X		Y		X		Y
min	0		3534	min	0		1482	min	0		725
max	0.999		3922	max	0.4995		1550	max	0.2497		766.5
mean	0.4995		3724	mean	0.2497		1513	mean	0.1249		747.9
median	0.4995		3727	median	0.2497		1511	median	0.1249		751.6
mode	0		3534	mode	0		1482	mode	0		725
std	0.2884		75.03	std	0.1442		17.09	std	0.0721		11.23
range	0.999		387.8	range	0.4995		67.8	range	0.2497		41.48
Save to workspace... Help Close				Save to workspace... Help Close				Save to workspace... Help Close			

Figure 20 – Data Statistics for Low Load Healthy State (Magnitude)

Figure 21 – Data Statistics for Heavy Load Healthy State (Magnitude)

As such, we can conclude that load does not affect the high frequency impedance of the induction motor. This part is essential as it ensure that any changes in the impedance is a result of a potential fault and not due to the change in load.

C. Stator Winding Insulation Faults Detection

After obtaining the healthy state impedance of the induction motor, simulation for the emulated inter-turn short circuit and coil-to-coil short circuit faults under the same conditions are conducted. The inter-turn short circuit fault is when the two turns of the same phase are shorted together as shown in Figure 22. Coil to Coil Short Circuit fault occurs when two coils of the same phase are shorted together as shown in Figure 23.

Figure 22 – Emulated Inter-Turn SC Fault

Figure 23 – Emulated Coil to Coil SC Fault

Under the following conditions, the impedance of the induction motor in its emulated fault conditions are extracted.

When light load is attached to the induction motor,

$$F_{\text{Signal}} = 200\text{kHz} \quad (22)$$

Figures 25 and 26 show the magnitude of the measured impedance of the induction motor under the two emulated faults, respectively.

Figure 24 - Light Load Inter-Turn SC Magnitude, $F_{\text{sig}}200\text{kHz}$, $F_s2\text{MHz}$

Figure 25 - Light Load Coil to Coil SC Magnitude, $F_{\text{sig}}200\text{kHz}$, $F_s2\text{MHz}$

Figure 26 – Data Statistics for the Different Conditions at frequency 200kHz

From Figures 24 and 25, they represent the magnitude at healthy state, inter-turn SC condition and coil to coil SC condition respectively, the online impedance deviates when a fault occurs. This can also be observed from the data statistics of the individual conditions as shown in Figure 26. At the same time, when the inter turn SC fault was identified, the fault has not escalated into a major breakdown, which

distinctly prove the importance of the suggested technique in the maintenance process of an induction motor. Subsequently, the same procedure is repeated for the induction motor at 100kHz and 400kHz to validate the capability of the suggested method to function at different frequencies. Figures 27 and 28 below show the results obtained.

Figure 27 - Light Load Inter Turn SC Magnitude, $F_{sig}100kHz$, F_s1MHz

Figure 28 - Light Load Coil to Coil SC Magnitude, $F_{sig}100kHz$, F_s1MHz

Figure 29 - Data Statistics for the Different Conditions at frequency 100kHz

At 100kHz frequency level, the induction motor healthy state impedance is 3724Ω. When the motor encounter inter turn SC fault, the impedance falls to 3224Ω. At the same time, when the motor encounters a coil to coil fault, the impedance increases to 3931Ω as shown in the data statistics table in Figure 29. The waveform of the impedance magnitude also shows signs of the deviation during fault

condition as seen in Figure 27 and Figure 28. The following figures below shows the same results at frequency level of 400kHz. At 400kHz frequency level, the induction motor healthy state impedance is 747.9Ω . When the motor encounter inter turn SC fault, the impedance deviates to 759.8Ω . At the same time, when the motor encounters a coil to coil fault, the impedance increases to 854.2Ω as shown in the data statistics table in Figure 32. The waveform of the impedance magnitude also shows signs of the deviation during fault condition as seen in Figure 30 and Figure 31.

Figure 30 - Light Load Inter Turn SC Magnitude, $F_{sig}400kHz$, F_s4MHz

Figure 31 - Light Load Coil to Coil SC Magnitude, $2F_{sig}400kHz$, F_s4MHz

Data Statistics ...			Data Statistics ...			Data Statistics ...		
Statistics for Healthy State			Statistics for Inter Turn SC			Statistics for Coil to Coil SC		
Check to plot statistics on figure:			Check to plot statistics on figure:			Check to plot statistics on figure:		
	X	Y		X	Y		X	Y
min	0	725	min	0	737.4	min	0	843.2
max	0.2497	766.5	max	0.2497	778.7	max	0.2497	869.9
mean	0.1249	747.9	mean	0.1249	759.8	mean	0.1249	854.2
median	0.1249	751.6	median	0.1249	763.4	median	0.1249	853.2
mode	0	725	mode	0	737.4	mode	0	843.2
std	0.0721	11.23	std	0.0721	11.6	std	0.0721	5.032
range	0.2497	41.48	range	0.2497	41.3	range	0.2497	26.71
Save to workspace... Help Close			Save to workspace... Help Close			Save to workspace... Help Close		

Figure 32 - Data Statistics for the Different Conditions at frequency 400kHz

As seen from the figures, the proposed method can detect faults in the stator windings of the induction motor despite the frequency level.

IV. Conclusion

The non-intrusive impedance extraction technique as proposed in this paper has shown good potential in detecting stator windings fault within the induction motor. It does not require any direct electrical connection with the power supply connecting to the induction motor. Hence it removes any safety hazards when conducting condition monitoring. At the same time, it is more cost and time efficient as its installation and removal is less complex as compared to other methods.

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