Influence of rotor position on frequency response of induction motor

Sagar Shah
Dept. of Electrical Engineering
Institute of Technology
Nirma University,Ahmedabad
sagarshah.s8397@gmail.com

Hormaz Amrolia
Department of Electrical Enginering
Gujarat Technological University
hormaz.amrolia@gmail.com

Santosh C. Vora
Dept. of Electrical Engineering
Institute of Technology
Nirma University,Ahmedabad
santoshvora@yahoo.com

K.P Badgujar
Dept. of Electrical Engineering
L. D. College of Engineering
Gujarat Technological University
Ahmedabad
dr.ketanbadgujar@gmail.com

Ajit Kumar
General Manager
Dept. of Electrical operation and maintenance
Adani Power Ltd,Mundra
ajit.kumar@adani.com

***Abstract*—The Frequency response analysis is a widely used tool to diagnose mechanical fault(s) in power transformers. The induction motor operates based on the same principle as the transformers, especially windings are inductively coupled. Except for a few constructional differences between transformers and induction motors, there is a high possibility to consider the frequency response analysis on induction motor for the mechanical fault detection. Here, variation in frequency response of induction motor due to rotor position is studied by employing various terminal connections. These connections are compared with among themselves in terms percentage impedance deviation and the best is suggested for frequency response analysis of induction motor to avoid rotor position dependency. A connection arrangement is proposed which makes the deviation in frequency response for different position ≤ 2%.**

Keywords—Frequency Responses Analysis, Induction Motor, Effect of Rotor Position, Diagnostics

I. Introduction

Induction machines are the workhorse of many industries and they account for 85% of all rotating machines used. This is because of its low cost, ruggedness, dependability, simplicity, durability, and efficiency [1]. The induction motor plays a very crucial role in power plants, petroleum refineries, process industries and numerous manufacturing facilities. In power generation plant, induction motors are used to drive bowl mills, feed water pumps, conveyor belts etc. having power ratings of 1000 kW and beyond. If an induction motor of such rating fails due to mechanical faults, ageing of parts or electrical faults, will lead to high replacement costs and/or loss of production or even a shutdown of the unit. The health assessment of large rated high voltage (HV) induction motors has a significant impact on reliable performance and serious financial consequences. Thus, early fault detection of induction motor is very crucial to the various industries.

Major failures in induction motors can be attributed due to bearing issues, stator winding damage, broken rotor bar etc. A complete list of motor failures is available in [3]. A survey [4] carried out shows that 50% of induction motor failure is due to stator and rotor faults. A lot of research has been done on condition monitoring of induction motor such as vibration analysis, zero sequence voltage component (ZSVC) and motor current signature analysis (MCSA) [5-7].

A method is proposed where high-frequency signals and an impedance analyser are used to diagnose an AC machine's turn-to-turn insulation [8]. A technique viz. Frequency Response Analysis (FRA), proposed in [9], is employed for power transformers. It is a well-known and standardized technique for the detecting mechanical deformations in power transformer [10]. This method is based on the frequency response of an equivalent RLC ladder network of the circuit / network / device (in frequency domain). Such a network exists in the transformer as well as in the induction machine, the major difference among the two is the induction motor contains rotating parts. To check the FRA feasibility and to avoid influence of the rotor position in a hydro generator, experiments were carried out without rotor [11]. An induction motor without a rotor is tested for insulation failure using FRA measurement [12]. According to [13], frequency response of salient-pole synchronous machines are influenced by rotor position, but squirrel cage induction motors will not be affected by the rotor position as the latter has a constant air gap. Study has been carried out where stator turn short is diagnosed by frequency response method [18].

This paper is divided in the following sections. The section II presents overview of the frequency response analysis technique. Section III discusses the experimental methodology and section IV focuses on results.

II. Frequency response analysis

The frequency response analysis is a well-established and studied method used for diagnosing mechanical deformations / faults in power transformers. Here, voltage signal (excitation) is injected at one of the winding terminal and the response to the injected signal is recorded at the other end of the winding. The measured response can be either voltage or current. The ratio, response to excitation, provides a system transfer function, which is plotted and frequency response curve is obtained. The magnitude and the phase angle of the frequency response are the quantities of interest and are treated as the signatures of the winding under consideration. Comparison of the base signature and the present signature highlights the anomalies.

A wide range (10 Hz to 2 MHz) of frequencies are injected to a terminal of machine using two methods, viz. 1) Impulse signal 2) Sinusoidal signals of fixed magnitude but as a sweep of frequencies. The first is identified as the impulse response analysis. This method will give us a quick response, but suffers from poor signal to noise ratio and non-uniform frequency resolution over the range. The second method is identified as the sweep frequency response analysis (SFRA). Here, fixed magnitude sine signals with frequency incremented either linearly or logarithmically is fed to the machine winding and response is captured. This method is time-consuming, but offers good frequency resolution, repetitive outcome as well as good signal to noise ratio. The SFRA is employed for the discussions in rest of the paper.

III. Experimental Setup

The authors of the paper are investigating the effect of rotor position on frequency response signature of induction motor and then suggest a method which minimizes the rotor position effect.

To investigate, the induction motor (Table I), shaft is divided in 8 positions, of 45° (mechanical angle). The frequency response is recorded using SFRA kit (PFRS-25, Table II) for each position using two connection methods viz. winding measurement and line measurement. Transfer Impedance transfer function is used for study.

TABLE I. Nameplate Data of Measured Induction Motor

Specification of 75 kW, 3 - ϕ Squirrel Cage Induction Motor		
1	Rated Voltage (V)	415
2	Rated Power (kW)	75
3	Speed (RPM)	989
4	Rated current (A)	134
5	Insulation class	H/F
6	Frequency (Hz)	50

TABLE II. Specification of PFRS-25 SFRA Kit

PDIC-PFRS-25 SFRA KIT		
1	Frequency-Range	0.1 Hz – 25 MHz
2	Number of Data Points	Default 1046, Up to 32000 points
3	Input Impedance	50 Ω
4	Output Impedance	50 Ω
5	Compliance Voltage	0.2 – 24 Vp-p
6	Measurement voltage at 50 Ω	0.1 - 12 Vp-p
7	Dynamic- range	-0.0 to -70.0 dB with accuracy of ±1dB
8	Sampling-Rate	100.0 MS/sec

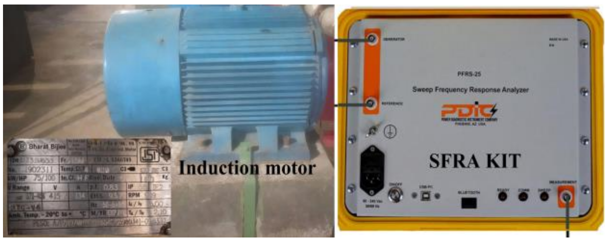

Fig. 1. Induction motor and SFRA Kit

In winding measurement connection (Fig. 2), the frequency response of single winding is recorded i.e. The voltage (excitation) is injected and measured at U1 terminal and the voltage (response) signal is captured at opposite terminal U2. Terminals not used for measurement are kept open.

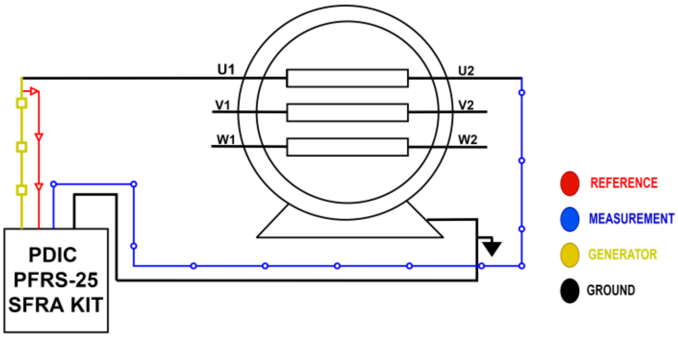

Fig. 2. Connection diagram of winding measurement

In line measurement (Fig. 3), two winding are connected in series and frequency response is recorded i.e. The voltage (excitation) is injected and measured at U1 terminal and the voltage (response) signal is captured at terminal V1. Terminals not used for measurement are kept open.

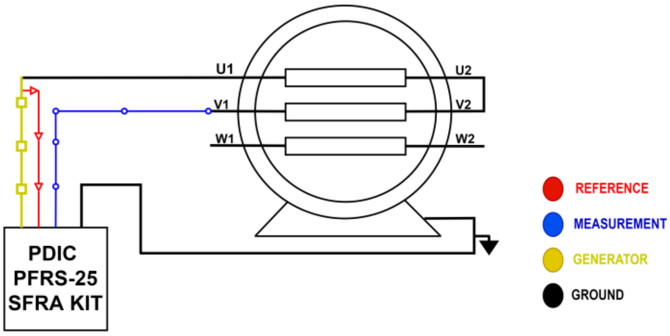

Fig. 3. Connection diagram of line measurement

IV. Results and Discussion on Frequency Response

The response recorded at different position for winding measurement is shown in Fig. 4 and line measurement is shown in Fig. 5.

Visually inspecting the figures, we find that the deviation in impedance value is more for different positions in frequency range of 20 Hz to 10 kHz for both the connection methods whereas for frequency greater than 10 kHz, the deviation vanishes.

The deviation observed in the results lies in the range of frequency which is dominated by inductive parameter of system [20]. This variation in inductive parameter is due to skewed rotor [16], residual magnetism [17]. Even the IEEE std. 1415-2006 suggests, measurement of inductance at multiple rotor positions. [19].

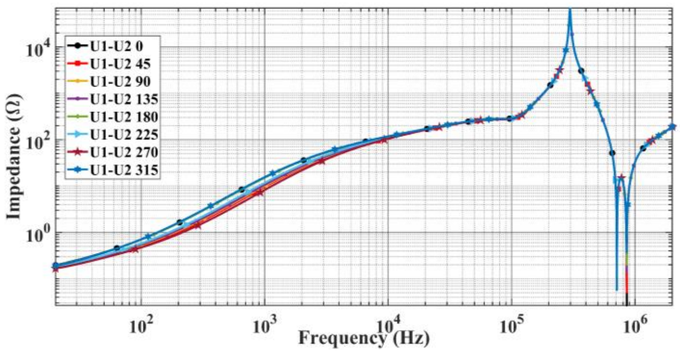

Fig. 4. Frequency response for winding measurement at different rotor position

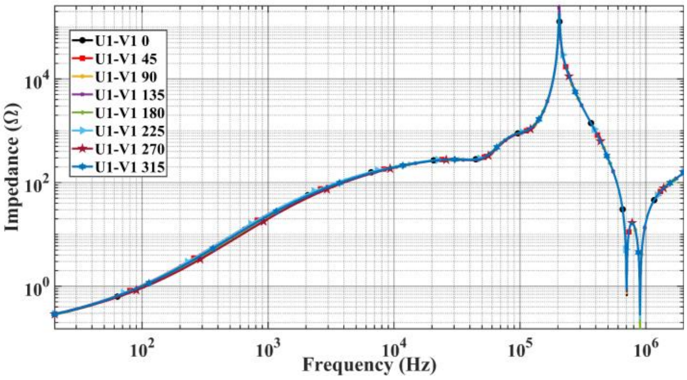

Fig. 5. Frequency response for line measurement at different rotor position

In this work, the authors are proposing a connection method which makes the rotor position dependency less dominant for frequency response measurement. The connection diagram for the proposed method is shown in Fig.6. In this connection all the windings are connected in series, and the frequency response is captured for different positions.

In winding and line connection, the airgap is not energized completely as the winding are distributed. Thus a few winding slots are excited dominantly at time of recording and as the rotor position changes the effect of above-mentioned factor are reflected in frequency response. Thus, to avoid this, the all the slots need to be energized simultaneously such that the impedance observed will be same, even the rotor positions changes.

Thus, authors of this paper proposes, connecting all the winding in series which recording the frequency response of induction motor. This is usually feasible as for large rated machines all the terminals are available in the terminal box. The connection diagram is shown in Fig. 6 and the response is shown in Fig. 7.

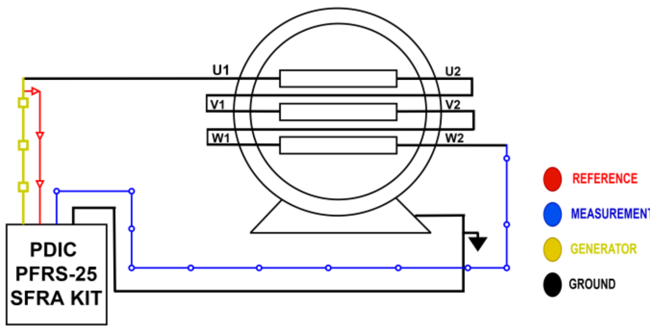

Fig. 6. Connection diagram of series measurement

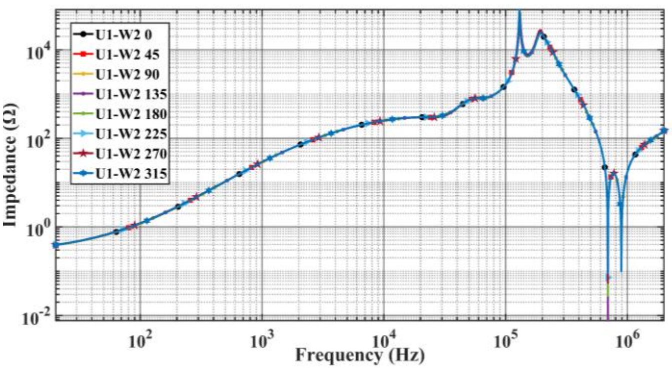

Fig. 7. Frequency response of series measurement at different rotor position

Evident from Fig. 7 that the value of impedance is same throughout different positions. Authors have compared the variation of impedances for all three connections at one frequency i.e.

$$Z_{diff} = \frac{Z_{max} - Z_{min}}{Z_{min}} \times 100 \text{ at 'f' frequency} \quad (1)$$

This impedance variation is tabulated for winding measurement (Table III), line measurement (Table IV) and series measurement (Table V). As well it is plotted using bar graph for visual comparison (Fig. 8).

TABLE III. MAX. AND MIN. IMPEDANCE DIFFERENCE OF WINDING MEASUREMENT (U1-U2)

Freq (Hz) → / **Impedance ↓**	**20**	**100**	**1k**	**10k**	**100k**	**1M**	**2M**
Min. impedance (Ω)	0.16	0.47	8.2	104.9	288.2	32.5	189.9
Max. impedance (Ω)	0.19	0.71	15.5	118.1	297.8	32.8	191.3

TABLE IV. MAX. AND MIN. IMPEDANCE DIFFERENCE OF LINE MEASUREMENT (U1-V1)

Freq (Hz)→ / **Impedance ↓**	**20**	**100**	**1k**	**10k**	**100k**	**1M**	**2M**
Min. impedance (Ω)	0.28	0.92	19.9	193.5	882.2	17.33	157.9
Max. impedance (Ω)	0.29	1.04	24.7	203.2	926.3	17.52	158.7

TABLE V. MAX. AND MIN. IMPEDANCE DIFFERENCE OF SERIES MEASUREMENT (U1-W2)

Freq (Hz) → / **Impedance ↓**	**20**	**100**	**1k**	**10k**	**100k**	**1M**	**2M**
Min. impedance (Ω)	0.39	1.19	28.9	251.55	1572.9	26.29	173.54
Max. impedance (Ω)	0.39	1.21	29.2	253.49	1592.7	27.65	177.56

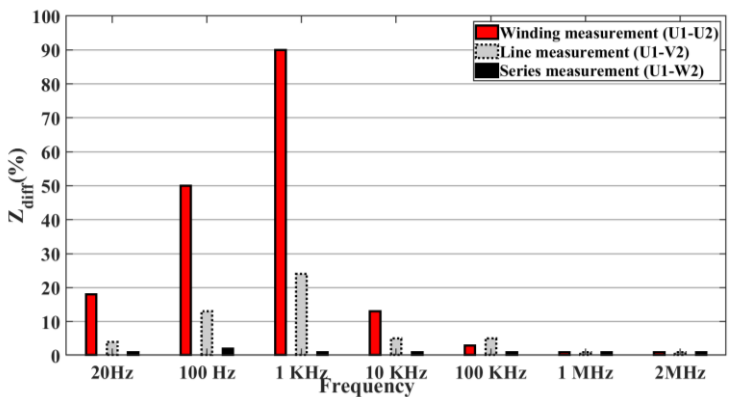

Fig. 8. Impedance difference for three arrangements (Left: winding measurement, middle: line measurment, right: series measurment)

As observed, the impedance deviation in series connection for all the frequency is ≤ 2%, which is within the tolerance limit for any measurement.

V. CONCLUSION

In this paper, effect of rotor position on frequency response of a 75-kW induction motor winding is studied using three different possible connections viz. winding measurement, line measurement and series winding measurement. Out of these, series connection measurement, exhibits lower frequency response variation for different position at different frequencies. The variation is ≤ 2%, which is ideal for any measurement. The connection gives the overall health of the machine; however, it does not replace individual winding measurement owing to sensitivity consideration and individual winding fault identification.

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