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A non-invasive technique for monitoring supply voltage variation to single phase induction motor using doppler UWB radar signal analysis

Madhusudhana Reddy Barusu[1], Nalubolu Geetha Rani[1], Yeramareddy Venkata Siva Reddy[2], Gongati Pandu Ranga Reddy[3]
[1]Department of Electronics and Communication Engineering, Ravindra College of Engineering for Women, Kurnool, India
[2]Department of Electrical and Electronic Engineering, G. Pulla Reddy Engineering College, Kurnool, India
[3]Department of Electrical and Electronic Engineering, G. Pullaiah College of Engineering and Technology, Kurnool, India

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ABSTRACT

The induction motors (IMs) are important components of various industries. The condition of IMs monitored continuously using contact and non-contact methods continuously. The contact methods are expensive, complex and difficult to implement. This paper proposes a non-contact method of fault identification in the single-phase induction motor operating in different conditions by analyzing doppler ultra-wide band (UWB) radar signal. The UWB radar generates a high frequency signal, which is transmitted on to the Induction motor form transmitter and software phase locked loop (SPLL) condition received signal from the receiver. The PLL implements as low pass filter, receives reflected signal from an induction motor along with high frequency noise. The received signal filtered to remove the high frequency noise and filtered output is analyzed to identify the different faults such as over voltage faults and under voltage faults when the motor is running with high, medium and low speed. The proposed non-invasive method has advantages compared to other such as the sensor's sensitivity will not affect with motor temperature and accuracy will not change with position of the sensor and presence of other machines.

Corresponding Author:

Madhusudhana Reddy Barusu
Department of Electronics and Communication Engineering, Ravindra College of Engineering for Women
Venkayapalle, Pasupala, NH 340C, Nandikotkur Rd, Kurnool, Andhra Pradesh 518002, India
Email: madhu.barusu@ieee.org

1. INTRODUCTION

Induction motors (IMs) are important components of various industries due to their toughness and long life. However, these devices malfunction in their duty due to various factors such as faults occurring in these machines like voltage variations, load variations etc., and environmental factors [1]. There exists number of review literature, which presented various techniques for induction motor fault diagnosis [2]–[4]. The voltage fluctuations are very frequent in day-to-day life. The frequent voltage abnormalities cause for the malfunction of these devices, which in turn causes huge losses and low working hours. The possible failure of the IMs may be identified in advance by continuous monitoring of IMs various parameters such as vibration [5], acoustic [6], [7], flux, and eddy current, current signature [8]–[13]. Due to the variation of the supply voltage to the motors, the motor vibration amplitude changes. The vibration analysis detects the different faults of the IMs using various signal processing algorithms such as fast Fourier transform (FFT), wavelet transform, and Hilbert transforms [14]. The accuracy of the fault identification affected with the sensitivity of the sensors and mounting position, as sensors must be mounted on a flat surface. Due to improper mounting, precise fault detection would be impossible [15].

The faults are classified as external faults and internal faults. The various external faults are voltage faults, frequency variation faults, and overloading faults. The different internal faults are rotor bar faults, bearing faults, and winding faults. The supply voltage variations are very frequent in the industries. The voltage variation affects the motor performance, so here different voltage related faults and techniques used for voltage variation detection are described.

The important supply voltage faults in single phase or three phase IMs are the fluctuations of supply to a high or low voltage, which is called as voltage variation faults. A motor will tolerate 10% above or below the rated voltage. The current in the IMs increases due to reduction of voltage, resulting reduced efficiency of IMs, even, over voltage applied to the motor also causes increasing current, in turn increasing winding temperature, and insulation damaging. Among these two conditions, over voltage is a critical fault for IMs, as a 10% increased voltage above the rated voltage causes excess heating of IMs and 20-30% saturation core losses [16]. There are various existing techniques for voltage variation fault detection such as ANN based [17], CNN based [18], wavelets, and IoT based [19]. Eldin *et al.* in [20] proposed an ANN-based external fault diagnosis method in the SCIM. The ANNs are trained extensively with a multilayer feed-forward algorithm to detect the under voltage, overvoltage and mechanical overload faults in the early stage. The RMS current, voltages and speed data of the SCIM are provided to the ANNs to train and analyze. The method is reliable, simple and more efficient. The limitation is that ANNs require the same level of fault all the time. Mittal *et al.* in [21] proposed a support vector machine (SVM) to detect the external faults in the induction motor. The method uses proximal SVM with RMS voltage and current as input parameters to diagnose the over voltage, under voltage and overloading fault in the SCIM. The method is more reliable to detect the external fault, but it is not suitable for online detection.

The three-phase motor operates with three-phase supply and due to the unbalance load or unequal supply voltage to the three-phases or completely disconnecting a phase while the motor is working called voltage unbalance fault or single-phase fault respectively. The unbalance supply voltage not severe as complete loss of phase. The unbalance voltage causes for huge current to flow into the motor. Due to excess current flow, the winding temperature increases and leads to the damage of the motor winding insulation, shortened motor life and fails lubrication. The motor temperature increases at a rate twice the square of the unbalance voltage.

The single-phase fault causes for the overheating of the motor windings due to the negative-sequence current flowing. When the motor loses a phase while working, remaining phases share the load and makes the rotor to rotate continuously. The negative sequence current produced due to lost phase may be used for motor condition monitoring. The voltages generated in the lost phase due to the negative sequence current are almost same as phase voltages. So, the voltage measurement at the lost phase not able to detect the fault.

In this paper, single phase motor is considered for study of the proposed method. The fault in specific parts of motor generates specific acoustic spectrum, helps to identify faults [22], but it is difficult to analyze the acoustic signature along surrounding noise. The incipient fault can be detected by motor current signature analysis, but it requires more external circuitry and experience challenge as the frequencies and small amplitudes of harmonics generated have close resemblance, pose challenges for detection [23]. The various condition monitoring techniques employ communication cables, sensors for monitoring machine health, however the cost of installation and maintenance are difficult and expensive when the equipment are not at the same location [24]. The online diagnosis of stator winding fault and broken rotor bar fault done by high frequency signal injection. The signal injection results in the higher frequency negative sequence current, which is used to detect faults at an incipient stage [25]–[27]. The output current signal contains stator current and negative sequence carrier signal, which can be separated by digital signal processing, i.e., using filtering process, but this method restricts continuous operation, take a long time to analyze and closed rotor slot with small current spectrum is not reliable for detection of rotor fault. The contact methods for condition monitoring have complex circuitry, high cost and difficult to implement, to overtake non-contact methods is implemented in modern industries.

In this paper, a non-contact method using doppler UWB radar is proposed for voltage fluctuation's fault detection. The method uses a handheld UWB radar module, software phase locked loop (SPLL) and MATLAB software for signal analysis. In the proposed method, a high frequency signal from radar module projected and the reflected signal is captured. The captured signal analyzed for the variation of the supply voltage. The comparison of the existing methods with a proposed method tabulated in Table 1, which describes the various advantages of the proposed method and existing methods. The rest of the paper is arranged as follows: various faults and proposed method introduced in section 2. Section 3 describes the results and discussion, and section 4 concludes with a summary.

Table 1. Comparison of various existing methods for external electrical fault diagnosis

S. No	Method	Type of method	Cost (approx.)	Signal information required (Sec)	Complexity of device/method	Remarks
1	Non-contact method	Proposed method (SPLL based technique)	Low ($50)	Low (2.5 sec)	Low (UWB radar, SPLL algorithm)	It is not affected by surrounding noise or temperature
2	Non-contact method	Thermal image sensing [28]	High ($4000)	High (300-2000 sec)	High (long wave IR camera)	Interior parts are not accessible easily and adjusted manually for better images.
3	Non-contact method	Acoustic emission measurement [29]	High ($4000)	Medium (above 10 sec)	Medium (specialized lab, high-quality microphone and recording equipment)	Affected by other machine noises
4	Non-contact method	Stray flux measurement [30]	Medium ($100)	Low (10 sec)	Medium (stray flux measuring coil, data acquisition board)	The sensor coil may be influenced by adjoining electrical machines
5	Contact method	Motor current signature analysis (MCSA) [31]	Medium ($100)	Low (2.5 sec)	High (current sensors, data acquisition board, DSO)	Require large memory to store data
6	Contact method	Vibration measurement [14]	Medium (each sensor $4)	Low (2.5 to 5 sec)	Medium (MEMS-based accelerometers)	Require expertise to mount on the machine. Sensors need to replace regularly
7	Contact method	Temperature measurement [32]	High ($1000)	High (100 sec and above)	Medium (IC LM 35DZ and data acquisition card PCI 6014)	Affected by environment changes and sensor damages with high temperature
8	Contact method	Flux measurement [33]	Medium ($100)	Low (2.5 to 5 sec)	High (RFSC-radial flux sensing coil, DSO)	Stator winding need to be wound specially with RFSC and need external control

2. METHOD

The block diagram of the proposed method presented in Figure 1. The proposed method consists of various components such as handheld UWB radar, a high frequency source, 1-phase motor which is a design under test, a data acquisition system, and signal analysis module. The high frequency signal projected on to the motor and reflected signal captured with radar module. The captured signal processed using signal processing algorithms to identify the fault.

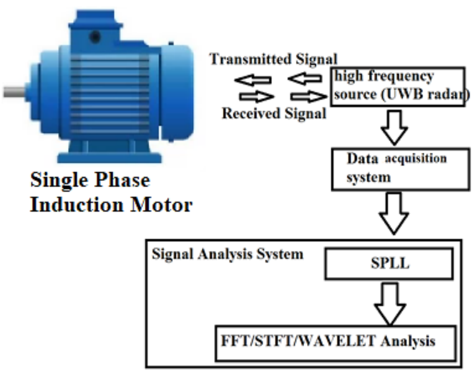

Figure 1. A framework of the proposed method

2.1. The various important components in the framework of proposed method

2.1.1. Single-phase squirrel cage induction motor (SCIM)

The motor used for testing in the proposed method is a single-phase induction motor. The Single phase SCIM used in this research is Kirloskar Mega 54S motor of the capacity 1.5 HP. The detailed parameters of 1-phase SCIM for conducting experiments are listed in Table 2.

Table 2. Single phase induction motor ratings

S. No	Parameter	Rated value
1	Power	1.5 HP
2	Current	8 A
3	Synchronous speed	1500 rpm
4	Speed	1440 rpm
5	Supply voltage	1-Phase, 240 V, 50 Hz

2.1.2. Handheld UWB radar

UWB radars are basically two types-doppler and Pulse radars. The radar transmits a signal and receives the reflected signal, which will be analyzed with signal processing algorithms to detect the characteristics of the target. Doppler UWB radar implemented on the doppler principle on the received signals, whereas pulse UWB radar works on the transmission and reception of sub-nanosecond pulses [34]. Transmitter, receiver and antenna system are the three basic sub-blocks of the radar. The receiver consists of an oscillator, pass-band filter (PBF), low noise amplifier (LNA), phase detector, intermediate frequency amplifier (IFA), and analog to digital converter (ADC) [35].

The handheld UWB radar shown in Figure 2 consists of internal blocks such as X-band mono-static dielectric resonator oscillator (DRO), transceiver module and it works with 5 V DC supply, and generates a signal of frequency 10.525 GHz. The module consists of DRO, microwave mixer and patch antenna, which radiate toward the target and the reflected wave is received via R_X patch antenna. The mixer is fed with the signal from local oscillator and received signal. It generates an output signal with intermediate frequency, which is transmitted and received signal frequency difference.

2.1.3. Software phase locked loop (SPLL)

A general block diagram of phase lock loop (PLL) shown in Figure 3. PLL is an electronic device, which reduces the phase error between the output signal and the reference signal, by controlling the phase of the output signal [36]. SPLL is implemented in digital signal processor (DSP), which is a set of instructions, realized as a computer program. SPLL operates at faster phase as operations are implemented on processor [37], and it is immune to ambient conditions, accurate and reconfigurable [38].

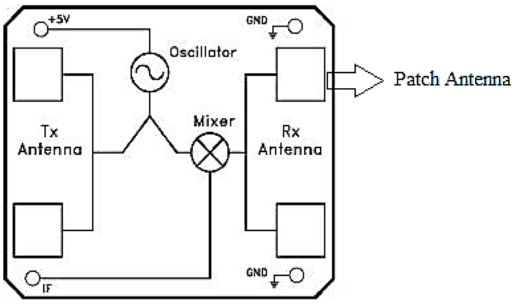

Figure 2. Block diagram of the UWB radar module

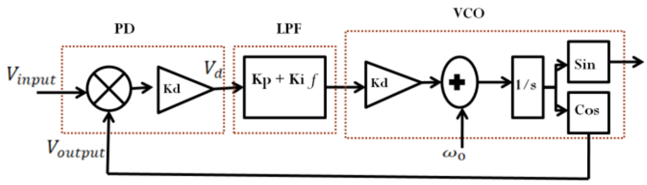

Figure 3. General block diagram of PLL

3. RESULTS AND DISCUSSION

Figures 4 and 5 shows the hardware requirement and set up for the implementation of the proposed method respectively, which consists of 1-phase motor, UWB radar module, and data acquisition system with SIGVIEW software. The proposed method works as given below based on [39], [40]. The UWB radar module is kept at 30 cm from IMs. The radar projects the high frequency signal of 10.525 GHz on to the motor and receives the reflected signal. The reflected signal is combination of motor vibration frequency and transmitted signal. The reflected signal received by the radar and a mixer along with a local oscillator removes a high-frequency transmitted signal and gives the output signal with intermediate frequency, i.e., motor vibration signal frequency alone sent out, along with some noise. The radar output signal is recorded with SIGVIEW software (data acquisition system). The data acquisition system stores signal by sampling at a rate of 10 kHz (sampling period of 0.1 msec). The sampled and recorded signal feed to SPLL, implemented in MATLAB to remove the unwanted noise. In the proposed method, only the first 2.5 sec of the recorded signal is used in the analysis with FFT to detect the faults in the motor. The obtained results are presented in the below section.

In the proposed method, the UWB radar is held at a fixed distance from the motor and the signal received by the radar while motor working with normal supply voltage and running normal speed is sown in Figures 6 and 7 shows transmitted and received signal, the error signal from the SPLL, and final output system. When the motor is running without any deviations with voltage and speed, the output signal will be a proper sine wave. When the motor experiences a transient fault, the received signal is shown in Figure 8, which consists of spikes at different locations based the fault condition. During transient conditions, as shown in Figure 9, the spikes are seen in the received signal, and also in the error signal, which is the output of the SPLL. Finally, in the output, it is seen that frequency of output signal varies, wherever fault is occurring. In this paper, along with testing motor under normal and transient condition, it is also tested under different conditions of voltage such as low voltage, high voltage and normal voltage with motor running at high operating speed condition. The received signals and output signals are shown as from Figures 10 to 15.

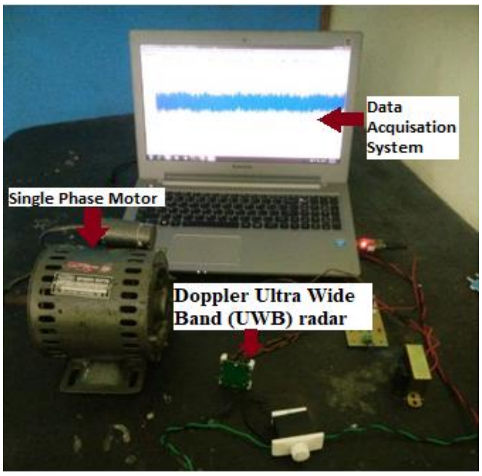

Figure 4. Hardware requirement for the proposed method of single-phase induction motor supply voltage variation fault identification

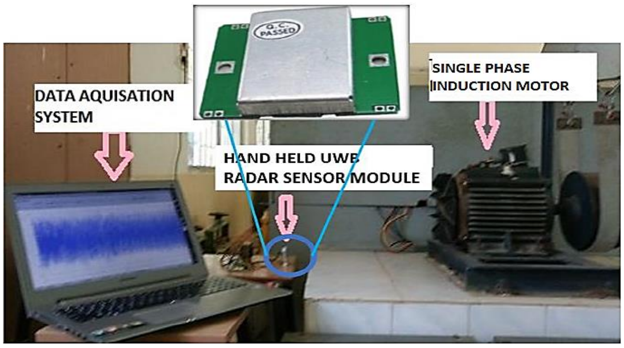

Figure 5. Hardware experimental arrangement for the proposed method of single-phase induction motor supply voltage variation fault identification

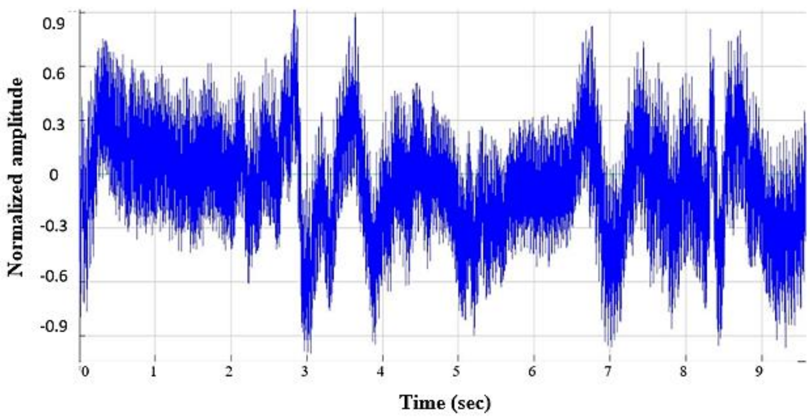

Figure 6. Normalized UWB radar Signal received during normal supply voltage, and running at normal speed

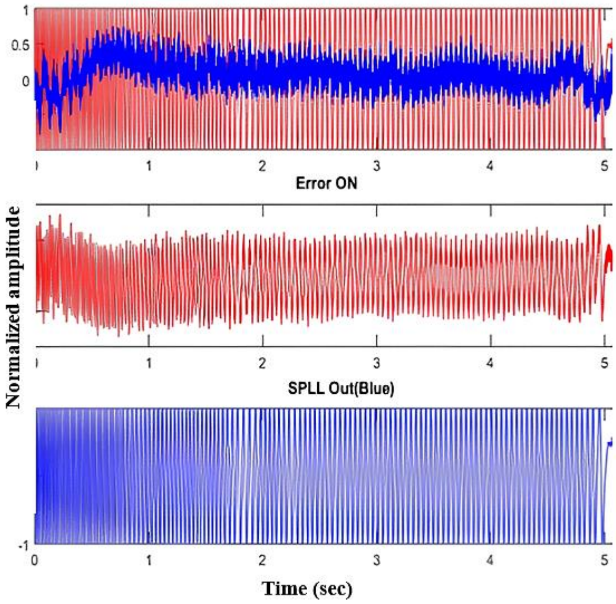

Figure 7. SPLL output during ON condition of induction motor

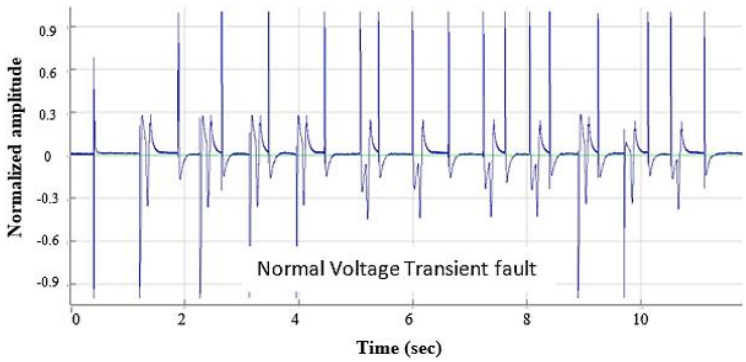

Figure 8. Normalized UWB radar signal received during normal supply voltage, and running at normal speed with transient fault

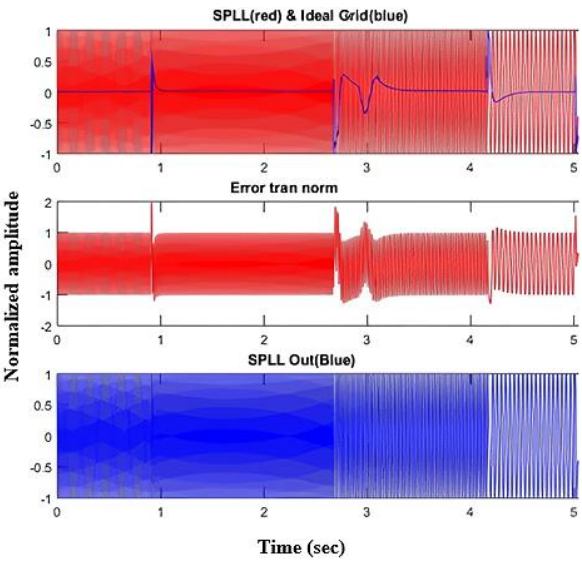

Figure 9. SPLL output with transient fault in induction motor

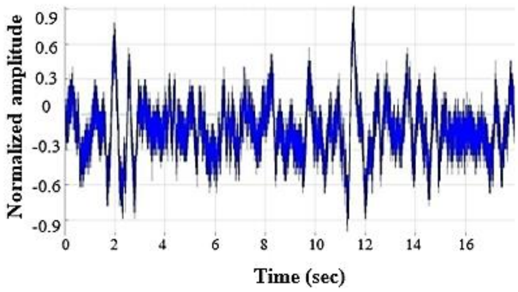

Figure 10. Normalized UWB radar signal received during boosted supply voltage and running at high speed

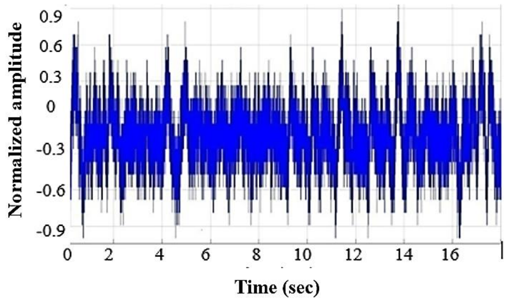

Figure 11. Normalized UWB radar signal received during normal supply voltage, and running at high speed

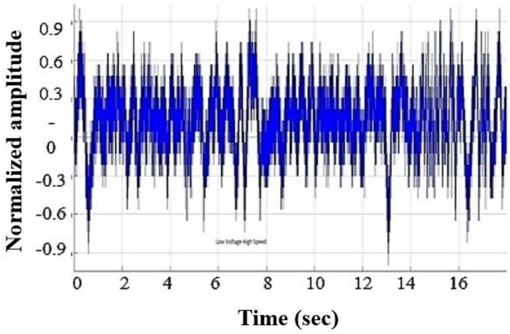

Figure 12. Normalized UWB radar signal received during low supply voltage, and running at high speed

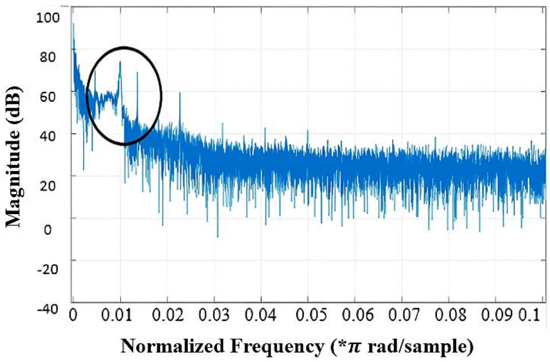

Figure 13. Frequency analysis output for induction motor operating with high voltage and high speed

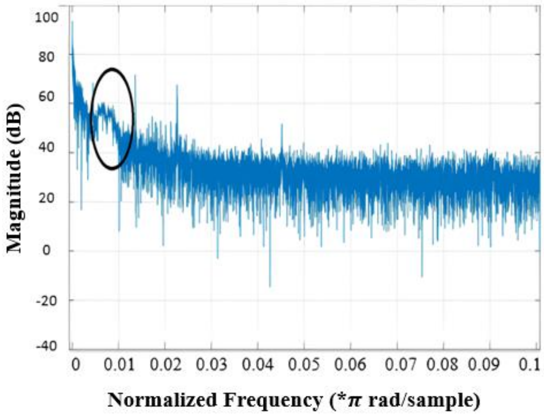

Figure 14. Frequency analysis output for induction motor operating with normal voltage and operated at high speed

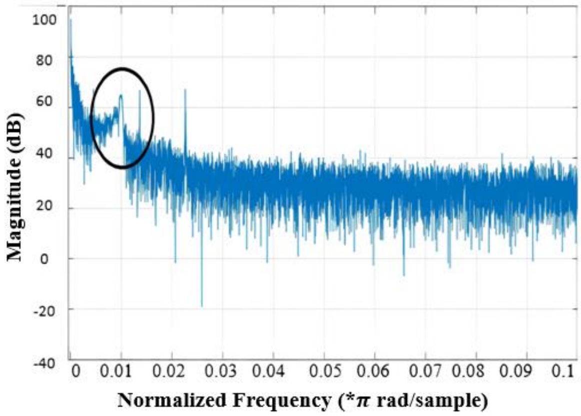

Figure 15. Frequency analysis output for induction motor operating with low voltage and operated at high speed

Figures 16 and 17 show the comparison of leakage factor and side lobe attenuation of different operating conditions of the motor. The proposed method tested with different voltages and different speeds and the obtained values are tabulated in Table 3. The Table 3 give the comparison of leakage factor (%), relative side lobe attenuation (dB) and main lobe width (-3dB) for motor operation in three different supply voltages, i.e., normal voltage (206 V), low voltage (170 V), and boosted voltage (230 V). The change of voltage (low and high voltages) is applied to changing voltage stabilizer.

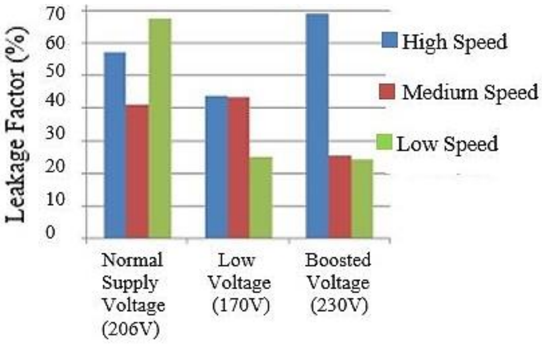

Figure 16. Comparison of leakage factor

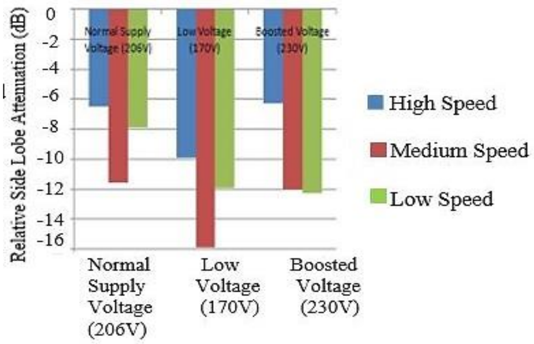

Figure 17. Comparison of different fault condition error signal obtained from SPLL

From the given Table 3, the following conclusions can be drawn. During normal supply voltage condition, leakage factor is increasing from high-speed operation (57.3%) to low-speed operation (67.69%) and medium speed lies in between (41.24%). Similarly, the relative side lobe attenuation, the magnitude increases from high-speed operation (-6.5 dB) to low-speed operation (-11.6 dB). When an induction motor is operated with boosted voltage (Figure 16) (230 V), the leakage factor flows in the opposite direction as normal supply voltage. The leakage factor is high (69.29%) when the motor is running with high speed, low during low-speed operation (24.08%) and it is medium during medium speed operation. The relative side lobe attenuation, the magnitude is low at high-speed operation (-6.3 dB) and higher during low-speed operation. Induction motor is running at low supply voltage (170 V), leakage factor is approximately same during high (43.99%) and medium (43.57%) speed and reduces when machine is running at low-speed (24.88%). The relative side lobe attenuation shown in the Figure 17, the magnitude is low at low-speed operation (-11.9 dB) and higher during the medium speed operation.

Table 3. Comparison of different fault condition error signal obtained from SPLL

S.NO	Supply voltage	Motor condition	Error signal (frequency domain analysis) Leakage factor (%)	Relative side lobe attenuation (dB)	Main lobe width (-3dB)
1	Normal supply voltage (206 V)	On condition	29.5	-1.1	9.16e-3
2	Normal supply voltage (206 V)	Transient fault condition	1.16	-1.9	2.12e-2
3	Normal supply voltage (206 V)	Low speed	67.69	-7.9	1.90e-05
4	Normal supply voltage (206 V)	High speed	57.3	-6.5	2.47e-05
5	Normal supply voltage (206 V)	Medium speed	41.24	-11.6	3.24e-05
6	Low voltage (170 V)	High speed	43.99	-9.9	2.28e-05
7	Low voltage (170 V)	Medium speed	43.57	-15.9	9.11e-03
8	Low voltage (170 V)	Low speed	24.88	-11.9	1.90e-05
9	Boosted voltage (230 V)	High speed	69.29	-6.3	2.1e-05
10	Boosted voltage (230 V)	Medium speed	25.31	-12	2.48e-05
11	Boosted voltage (230 V)	Low speed	24.08	-12.3	9.09e-3

4. CONCLUSION

In this paper, a technique based on Doppler UWB radar signal analysis for voltage variation fault identification implemented successfully. The motor tested with different voltage conditions like low (170 V), normal (206 V), and high (230 V) operating voltage in combination of running the motor at different speeds like high, medium and low speeds. The output results show SPLL based proposed noninvasive method is suitable for identifying voltage fluctuations. The error signals obtained from SPLL analyzed in the frequency domain and proved that analysis of UWB radar signal is useful in identifying faults in induction motor. The contact methods have drawbacks such as sensors sensitivity affected with motor temperature and position. Being a non-contact method, it overcomes all the above shortcomings. However, the proposed method may affect with the distance of radar module and sensitivity. The proposed method is yet to test on 3-phase motors, which may differ with the proposed method.

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BIOGRAPHIES OF AUTHORS

Madhusudhana Reddy Barusu received a Master's degree from the Satyabhama University, Chennai, India and received a doctoral degree from Anna University, Chennai, India in 2009 and 2020 respectively. He is working as a professor and head of the department in Department of Electronics and Communication Engineering, Ravindra College of Engineering for Women, Kurnool, Andhra Pradesh, India since 2020. His area of interest includes power electronics and drives, signal processing and VLSI design. He can be contacted at email: madhu.barusu@ieee.org.

Nalubolu Geetha Rani received a Master degree in Nano Technology from JNTUH, Hyderabad, India and received a has obtained Ph.D. degree in Nano Science and Technology from JNTUH, Hyderabad, India. She is working as Associate Professor in the Department of Electronics and Communication Engineering Ravindra College of Engineering for Women, Kurnool, Andhra Pradesh, India since 2013. Her areas of research are nano electronics. She can be contacted at email: drgeetharaniece@recw.ac.in.

Yeramareddy Venkata Siva Reddy received B.Tech., M.Tech., and Ph.D. degrees from JNT University, Anantapur in the year 1995,2000 and 2010 respectively. He is presently working as Professor in the Electrical and Electronics Engineering Department, G. Pulla Reddy Engineering College, Kurnool, Andhra Pradesh, India. His research areas include power systems and electrical drives. He can be contacted at email: yvsreddy.eee@gprec.ac.in.

Gongati Pandu Ranga Reddy received B.Tech. degree in Electrical and Electronics Engineering from Jawaharlal Nehru Technological University, Hyderabad, M.Tech degree in Control Systems from Jawaharlal Nehru Technological University Anantapur, Anantapuramu and a Ph.D. degree in Electrical Engineering in the field of Renewable Energy Sources from Jawaharlal Nehru Technological University Anantapur, Anantapuramu. Currently working as HOD and Associate Professor in the Department of EEE in G. Pullaiah College of Engineering and Technology, Kurnool and has 17 years of experience in Teaching and Research. Research interests include matrix converters, power quality, conventional energy sources, intelligent techniques, and optimization techniques. He can be contacted at email: pandurangaeee@gpcet.ac.in.