Study the performance of three-phase induction motor under imbalanced non-sinusoidal supply

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Abstract. The rising of single-phase distributed generators and imbalanced loads in the electrical power grid can cause the three phases voltage to unbalance, causing in risen losses and overheating in motors. As a consequence of the growing usage of electronic equipment and non-linear load, the waveform of the voltage source of the electrical system is becoming distorted and variations appear among the phases. This work explores the negative impacts of imbalanced of 10 HP three phase induction motor squirrel-cage fed by three phase IGBT inverter at full load. The drive system has been designed and simulated by MATLAB /Simulink. The inverter switches are controlled by a pulse controller, which consists of two level pulse width modulation (PWM). The results represent the effects on the performance of the motor. The results of the Simulation show the negative impacts of imbalanced non-sinusoidal voltages which are higher than the case of balanced non-sinusoidal voltages. Also, the computation of voltage unbalance factor (VUF) depending on positive and negative sequence components are considered.

keywords: voltage unbalance factor (VUF), induction motor, Pulse width modulation (PWM), IGBT inverter, MATLAB /Simulink.

1. Introduction

As a consequence of the growing usage of electronic techniques and additional nonlinear load, the waveform of the voltage source of electrical energy is becoming distorted and differences occur between the phases. This drop is related to electromagnetic unsuitability difficulties, and load efficiency drops like motors. Consequently, application to VSI fed three-phase induction motors (3PIM) can be considered because these motors are a simple and rugged electrical machine with adaptation to several load situations. The motor should undertake a mixture of voltages above and below with imbalance voltages [1].

Induction motors, which require a completely sinusoidal voltage source though under standard operations conditions, generate a fairly small amount of current harmonic because of the winding structure and nonlinear iron core performance. The behaviour of the induction motor is greatly influenced in the condition of a significantly distorted voltage source, so derating must be supposed to apply. The aforementioned derating in motor features is highly related to the harmonic output of the voltage waveforms, in both degree and amplitude, and its analysis is primarily related to the iron losses included [2]. The non-sinusoidal voltage supplied to electrical motors could even lead to
overheating, torque pulsing, and noise. During applications around the line, inverters feed variable speed drive motors which can generate large voltage distortion [3].

In the past induction motors were used essentially for constant speed applications as there was the unavailability of the variable frequency voltage supply. The output voltage of the inverter can be adjusted by controlling the inverter by the PWM method [4]. Sürgevil T, 2011 aimed to analyze the behavior of the inverter through the simulation model in the variable-speed operation of induction motors. The Simulink results were found from a mathematical model induction motor drive system driven with a three phase boost DC/AC inverter [5]. Rahman T. et. al, 2016 concluded the simulation test reveals the overall inverter loss value comparing with the single phase inverter of the micro-grid system. As their expectation states, the three phase inverter is suitable for applications where the AC voltage as the output should be greater than DC as input and economically possible [6]. Uma D. and K. Vijayarekha, 2017 developed the Adjusted Speed Drive Mathematical Model (ASD), considering synchronous induction motor reference frame equation, the VSI switching device model, and the diode-bridge-rectifying model, and validated simulated results for the suggested mathematical model [7]. Al-Badran H et. al, 2018 presented a SiC inverter with an output filter for feeding an induction machine. The work aims to obtain sinusoidal voltages on the terminals of the machine in a way that the terminal voltages can be easily measured and used for feeding the voltage [8]. Nurhaida A S et al., 2019 designed and implementation of three-phase voltage source inverter (VSI) for variable frequency drive. The emphasis was to produce variable frequency output appropriate to be supplied to the induction motor for the drive of variable speed control [9].

This work represents the MATLAB/SIMULINK of a DC to AC inverter supply three phase induction motor squirrel-cage (3PIM) with a PWM adjusting both the voltage output value and frequency. The procedure of comparing sinusoidal control voltage with a triangular waveform at a chosen switching frequency was used for generating PWM pulses. Then this study examines and demonstrates the effects of imbalanced supply voltages and its effect on the operation and performance of a three-phase induction motor. The motor rated at 10 HP and the inverter is designed to use the "Universal Bridge" block and the "Asynchronous Machine" block motor.

This paper analyzes the performance of three phase induction motor under the effects of balanced and imbalanced non-sinusoidal voltages. The remainder of this paper is organized as follows. Section two describes the modeling of variable frequency drive, pulse width modulation technique (PWM), and objective of total harmonic distortion (THD). Section three presents the unbalanced voltage identifications. Section four present simulation used in the tests and discuss the obtained results. Finally, conclusions are given in section five.

2. Modeling of Variable Frequency Drive

2.1. Modeling of Induction Motor

By the standard operating of induction motor, the steady-state equivalent circuit is resulting. Depending on the equivalent circuit, the steady-state result of the variable speed induction motor is measured. Dynamic simulation is among the essential processes to validate the development of the motor drives coordination. Thus the dynamic model is essential for the induction motors [10]. The dynamic models of the induction motors are got from the principles. The d-q models produce of two windings for the rotor and stator of the induction motors.

Conversion of (a-b-c) to (d-q) axes retained for developing the dynamic model is depending on simple trigonometric relationships. The derivative is used a different dynamic model and dependent on easy trigonometric expression. Induction motor mathematical equations include differential equations that are changing concerning the time that assisted to select synchronous reference frames. The suppositions which are prepared to develop the dynamic models of induction motors are as follows:

1) The air gap is uniform
2) Stator and rotor windings are balanced, with the MMF being distributed sinusoidally
3) Inductance versus rotor position is sinusoidal; and
4) Saturation and changes in the parameter are neglected.
The model’s equations derived from the d-q circuit of three phase induction motor Squirrel cage shown in figure 1.

![Figure1. d-q equivalent circuit of three-phase induction motor.](image)

2.2. Voltage Source Inverter Modeling
The Universal Bridge configuration uses a three phase universal power inverter which consisting of a bridge configuration with six power switches. As from the context menu, it can select the type of power switch and converter settings. The Universal Bridge configuration permits converter simulation to use both natural power devices (diodes or thyristors) and the IGBT-like forced commutation device. Construct two-stage voltage source converters (VSC), the Universal Bridge configuration is the fundamental block. Bridge arms Number Set to 3, to be transformed into three phases (six switching devices).

2.2.1 Pulse Width Modulation Technique (PWM). The inverter consists of six switches that are attached to the center of each inverter arm for each phase output as shown in figure 2. Within the easiest form, the inverter's output AC voltages are controlled by three reference signals compared with a high-frequency carrier waveform. The product of the comparison is used for turning switches ON or OFF in each arm. For the induction motors regulation with steady voltage/frequency (V/F), control of the output voltage of the inverter is always needed. The inverter-based PWM (Pulse Width Modulation) gives the better steady V/F controlling of the induction motors. The sinusoidal PWM is good enough and the most common among the different PWM techniques, providing smooth V/F changeover. Modulation of the pulse width is a procedure wherein the inverter receives a set input voltage dc and a regulated ac output voltage is gotten by changing the inverter component for on and off times. That's the most common procedure of regulating the voltage output and this procedure is called the technique of modulation of the pulse width. PWM is an internal control procedure that results better than an external control procedure. There have been various PWM techniques for inverters that are a source of variable frequency voltage. To get the needed output voltage in the line side of the inverter, an appropriate PWM technique is applied. Within that technique, the switching moment is determined by a high-frequency triangular carrier wave to compare with the sinusoidal reference wave. If the modulating signal is a sinusoidal amplitude Am and the amplitude of the triangular carrier wave is Ac, so the modulation index is defined as the proportion m = Am / Ac. Note that it can control the amplitude of the supplied output voltage by regulating the modulation index[11].

So, The average DC supply voltage is 653 V., therefore, the fundamental component of the 50 Hz inverter voltage is 400 V [12].

2.2.2 Fourier Transform of a Distorted Waveform. The Fourier transform is multiple methods that can be treated as a mathematical technique in several scientific fields to convert a difficulty to one that can be overcome rather simply. The Fourier transform's major feature is in the ability to convert the signal from the time domain to the frequency domain, which typically provides further details related to the signal being studied. Another type of Fourier transformation is the "Discrete Fourier Transform (DFT)", which represents sinusoidal components of an input function by specifying the amplitude and phase of each component. Such features allow the DFT suitable for the analysis of computer-saved data. In general, the DFT is commonly used in the signal analysis to evaluate the frequencies used in a mathematical sampled signal procedure. Given that power system troubles are dependent on transient, a detailed signal analysis cannot be given by the DFT itself. A greatly faster algorithm has been
developing the Fast Fourier Transform (FFT). Such makes calculation speed quicker for analyzing a Fourier signal [13].

\[ X_k = \sum_{n=0}^{N-1} x_n e^{\frac{2\pi i}{N}kn}, k = 0, ..., N - 1 \]  
\[ (1) \]

where \( e \) is the base of the natural logarithm and is \( i \) the imaginary part \( (i^2 = -1) \).

Figure 2. Three-phase VSI by using IGBT.

2.2.3 Total Harmonic Distortion (THD). Nonsinusoidal input current contains two pulses every half period. The present waveform is undergoing a strong degree of harmonic distortion. Therefore, the load was considered as non-linear load since the current isn’t proportional to the supplied voltages. When this current passes across the impedance it generates harmonics of the voltage. The total sum of such harmonics of voltage then generates a distorted voltage, which mixes with the fundamental voltage. The "Total Harmonic Distortion (THD)" is the best generally recognized and frequently used indicator of distortion. It is computed by comparing the harmonic content RMS to the fundamental RMS. Because the harmonics of various orders are orthogonal, the RMS of the distorted voltage part can be measured [14].

\[ v_h = \sqrt{V_2^2 + V_3^2 + ... + V_n^2} = \sqrt{\sum_{n=2}^{\infty} V_n^2} \]  
\[ (2) \]

Where \( V_2, V_3, ..., V_n \) are the harmonics of the value of the voltage. If \( V_1 \) is the fundamental component voltage of RMS.

Thus the THD for voltage and current is given by respectively:

\[ THD_v = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \]  
\[ (3) \]

\[ THD_i = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \]  
\[ (4) \]

3. Unbalanced Voltage Identifications

There are three voltage imbalance definitions are described and identified as below.

3.1 NEMA Identification (National Equipment Manufacturer’s Association)

The NEMA expression for voltage imbalance is often referred to as the Line Voltage Unbalance Rate (LVUR) [15] and described by:

\[ \%LVUR = \frac{\text{max voltage deviation from the average line voltage}}{\text{average line voltage}} \times 100 \]  
\[ (5) \]
3.2 IEEE Identification

The IEEE identification of imbalance voltage, moreover called so the "Phase Voltage Unbalance Rate (PVUR)" [16], is given by:

\[
\% PUVR = \frac{\text{max voltage deviation from the average phase voltage}}{\text{average phase voltage}} \times 100
\]  

(6)

3.3 IEC Identification

The IEC identification of voltage unbalance moreover termed the exact identification of imbalance voltage is defined such as the percentage of "the negative sequence voltage component to the positive sequence voltage component"[17]. "The percentage voltage unbalance factor (% VUF)" , is given by:

\[
\% VUF = \frac{\text{negative sequence voltage component}}{\text{positive sequence voltage component}} \times 100\% = \frac{V_n}{V_p} \times 100
\]  

(7)

Where \( a = 1\angle 120^\circ \) , \( a^2 = 1\angle 240^\circ \)

The "complex voltage unbalance factor (CVUF)" was mostly referred to as the "proportion of negative sequence voltage phasor to positive sequence voltage phasor". This measurement of CVUF has an angle and value will be as follows:

\[
\text{CVUF} = \frac{V_n}{V_p} = K_v \angle \theta_v
\]  

(8)

Where \( K_v \) the magnitude and \( \theta_v \) the angle of the CVUF.

4. Simulation Results and Discussion

The total modeling of MATLAB/SIMULINK of the drive system is shown in figure 3. The parameters and rated specification for the motor are given in table 1.

![Image](image_url)

**Figure 3.** MATLAB/SIMULINK of variable frequency drive.
Table 1. Parameters and Rated specification for the induction motor [12].

| Specifications | Values | Parameters | Values |
|----------------|--------|------------|--------|
| Rated Power    | 10 HP  | Stator resistance $R_s$ | 0.7384 ohm |
| Rated Voltage  | 400/230 V | Rotor resistance $R_r$ | 0.7422 ohm |
| Poles          | 4      | Stator reactance $X_s$  | 0.9566 ohm |
| Rotor Speed    | 1440 rpm | Rotor reactance $X_r$  | 0.9566 ohm |
| Frequency      | 50 Hz  | Magnetizing $X_m$ | 38.9872 ohm |
| Connection     | Y      | Friction factor  | 0.0343 kg.m² |
| Phase          | 3      | Moment of Inertia  | 0.000503 |

Then induction motor driven by an inverter represents an AC drive system, then the terminal voltage is contaminated by many harmonics thus the influence of the harmonics is observed in the wave-forms in figures (4,5,6 and 7). The start-up of the induction motor fed from six pulses, voltage source inverter was simulated and the simulation results for speed, electromagnetic torque, stator currents, and rotor currents are tabulated in table 2. And FFT analysis is shown in figures 4 and 5.

Table 2. The Results of imbalanced non-sinusoidal supply

| conditions | Balanced sinusoidal | Balanced nonsinusoidal | Overvoltage nonsinusoidal | Under voltage nonsinusoidal |
|------------|---------------------|------------------------|---------------------------|-----------------------------|
| (RMS)$V_a$ | 230°.00             | 230°.00                | 234.5°.00                 | 224.7°.00                   |
| (RMS)$V_b$ | 230°.00 – 120°      | 230°.00 – 120°         | 235.5°.00 – 120°          | 224.5°.00 – 120°            |
| (RMS)$V_c$ | 230°.00 – 240°      | 230°.00 – 240°         | 237.7°.00 – 240°          | 220°.00 – 240°              |
| $I_{as}$(peak) | 18.82°.00 – 27.5°  | 19.08°.00 – 29°       | 19.1°.00 – 32.4°         | 19.8°.00 – 19.5°           |
| $I_{bs}$(peak) | 18.82°.00 – 147.5° | 19.08°.00 – 149°      | 17.95°.00 – 146°         | 21.3°.00 – 148°            |
| $P_{in}$(W)  | 8157                | 8296                   | 8291                      | 8377                        |
| $P_{out}$(W) | 7440                | 7439                   | 7460                      | 7405                        |
| T(N.m)       | 717.4               | 857                    | 831                       | 972                         |
| N(r.p.m.)    | 49.4                | 49.4                   | 49.4                      | 49.4                        |
| Efficiency   | 91.21               | 89.67%                 | 89.9%                     | 88.4%                       |
| p.f.         | 0.888               | 0.749                  | 0.717                     | 0.845                       |
| Pos. seq. $(V_p')$ | 230                   | 230                   | 235.9                     | 223                         |
| Neg. seq. $(V_n)$ | 0                     | 0                     | 0.945°.00 – 137.78°      | 1.53°.57.84°               |
| %CVUF        | 0                   | 0.4°.00 – 137.78°     | 0.68°.57.84°              |                             |
Figure 4. Phase current and its spectrum FFT balanced sinusoidal and non-sinusoidal supply.

Figure 5. Phase current and its spectrum FFT for over and under voltage unbalanced non-sinusoidal.

Figure 6. Speed and torque responses for unbalanced overvoltage inverter supply.
Figure 7. Stator and rotor currents responses for unbalanced overvoltage inverter supply.

Figure 8. Speed and torque responses for unbalanced under-voltage inverter supply.
In the non-sinusoidal supply (six-step inverter) in figure 6 and figure 8 for balance condition, the rotor rotates at the rated speed of 1438 rpm which reaches a steady state at 0.15 seconds. The increased in the voltage magnitude in non-sinusoidal supply raises the rotor speed, that is almost arrived at 0.2 seconds steady-state to be 1442 rpm as shown in figure 6, while the magnitude of the voltage decreases, the rotor speed falls to 1431 rpm which reaches steady-state slightly more lowest at nearly 0.3 seconds as shown in figure 6 as stated in table 2. Furthermore, in non-sinusoidal supply for balance condition, the torque presents high-frequency components and the torque also oscillates at around 50 Nm. Likewise, for over and under unbalance conditions produce irregular torque pulsations, not the same any other unbalanced voltage situations as shown in figures 6 and 8. The rotor current in non-sinusoidal supply in figures (7 and 9), for balance condition, introduces high-frequency components, and the rotor current is affected by a high frequency and the figure displays approximately 0.1 seconds to set up to the rating of rotor current after initially enlarged pulsations of
the current. Moreover, over and under the unbalance condition of these figures show that the rotor current introduces high-frequency components and a steady-state is achieved lowest at nearly 0.2 seconds. On the other hand, in non-sinusoidal supply in figures (7 and 9), for balance conditions, the stator current will be 19.08A in table 2 and when voltage unbalanced occur for over-voltage, the stator current will be swing between 18A and 20A, while for under unbalanced voltage, the stator current will be increased slightly to become 19.8A which more than balanced condition. Additionally, there are unsafe harmonic in stator currents in case of non-sinusoidal supply either in balance or over and under unbalance conditions leads to the generation of harmful harmonics which is satisfied with paper in reference [3] this affect the performance of the motor, introducing a pulsating torque and noise. By using FFT analysis in comparison with sinusoidal supply, that the total harmonic distortion (THD) is 0.02% while for non-sinusoidal balance supply the THD is increased to become 16.43% as stated in table 3 and shown in figure 4. Also, there is an increase in THD for over and under voltages about 17.91% and 16.68% as shown in figure 5 respectively.

**Table 3. THD for balanced and imbalanced non-sinusoidal supply.**

| condition                                      | Balanced sinusoidal supply | Balanced non-sinusoidal supply (inverter) | Over-voltage non-sinusoidal supply (inverter) | Under-voltage non-sinusoidal supply (inverter) |
|------------------------------------------------|---------------------------|------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| THD                                            | 0.02%                     | 16.43%                                   | 17.91%                                        | 16.68%                                        |
| fundamental                                   | 18.82                     | 19.01                                    | 18.41                                         | 19.73                                         |

Note that the currents of the rotor and stator are very noisy. The noise introduced by the PWM inverter is also observed in the electromagnetic torque waveform $T_e$. However, the motor’s inertia prevents this noise from appearing in the motor's speed waveform. Also, all the plots in previous figures for balanced and unbalanced non-sinusoidal supply are summarized in table 4 to simplify a study of the impact on the motor parameters of various imbalanced voltage situations. The overvoltage shown has low stator current, highest ripple, and over Rated average speed with improved efficiency. In overvoltage, there is an enhancement in efficiency as compared to the under imbalanced condition reach about 89.9% with losses 831watt and for a balanced non-sinusoidal supply of about 89.6% with losses 856.6 watts. While the under-voltage has shown has high stator current, highest ripple, and underrated average speed with a decreased efficiency of about 88.4%. Also, there are increased in total losses in balanced non-sinusoidal voltage by nearly 19.4% as compared with balanced sinusoidal voltage. Also, by applying the IEC definition and depend on the positive and negative sequence component we can evaluate the voltage unbalance factor (VUF) as clear in table 2 which shows increasing in this factor for over and under conditions. As compared with the balance conditions.

**Table 4. Comparison of the motor performance between the balanced and unbalanced non-sinusoidal supply.**

| conditions                              | Stator Current Magnitude | Rotor Current Ripples | Average Speed | Steady State Torque (Nm) (Settling time) |
|-----------------------------------------|--------------------------|----------------------|---------------|----------------------------------------|
| Balance sinusoidal                      | Rated                    | No ripple            | Rated         | (0.1 s)                                |
| Balance non sinusoidal                  | Over Rated               | High Ripple          | Rated         | (0.15 s)                               |
| OV                                      | under Rated              | High Ripple          | over Rated    | (0.2 s)                                |
| UV                                      | Over Rated               | High Ripple          | Below Rated   | (0.3 s)                                |
5. Conclusion
In this paper new comprehensive and generalized procedure is presented to predict the negative impacts of unbalanced voltages on the performance of three phase squirrel-cage induction motor. The pulse-width modulated switching can be employed in the control of the inverter supplied the motor. These aspects were investigated through simulation models developed in MATLAB/Simulink and their validity was verified by simulation results. Focusing on the parameters like speed, torque, power factor, line currents, and efficiency in case of unbalanced non-sinusoidal voltages. The major findings of the analysis in this case, the efficiency of the motor in balanced non-sinusoidal voltages is less than the efficiency at full loads of balanced sinusoidal voltages by 1.54%. Likewise, is less than the efficiency at balanced sinusoidal voltages by 1.31% and 2.81% for over and under conditions respectively. Also, the results show that the current pulled by the motor in an unbalanced non-sinusoidal voltage situation is higher than the current in balanced sinusoidal voltage condition at full load by 1.013% and for over and under by 1.015% and 1.05% respectively. Moreover, for non-sinusoidal voltage supplied motors may cause overheating, pulsation torque, and noise. To have access to applications through the line, changeable speed drives motor is supplied from an inverter which can cause extreme voltages distortion. As well, a less in Power factor is produced through balanced non-sinusoidal voltages at full load by 13.9% as compared with balanced sinusoidal voltages while there is decreased by 17.1% and 4.3% for over and under conditions respectively. A PWM controller-based switching phenomenon is used to overcome the losses in the inverter which increases the overall system efficiency. In general, in the case of unbalance voltages, the efficiency of the motor would be decreased and the ripple would be decreased significantly destructing the motor application.

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