Volume 8, Issue 6
December 2019

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

Investigation of Torque Performance of Three Phase Induction Motor under Unbalanced and Non-Sinusoidal Voltage Conditions

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ABSTRACT

Voltages are well balanced at the generator and the transmission levels but are not balanced at the utilization or distribution levels due to unequal system impedances and unequal distribution of single-phase loads. The power supply waveform also gets distorted due to increased use of electronic equipment. Distortion in supply waveform can be resolved into multiple frequency sinusoidal waveforms known as harmonics. An excessive level of voltage unbalance and harmonics can result excess power loss, torque reduction, and torque pulsation in the induction motors. Excess level of torque pulsation may damage the bearings and other mechanical parts of the induction motor. Impact of unbalanced and non- sinusoidal voltage on steady state value of torque and torque pulsation has been investigated on three phase induction motor using MATLAB/Simulink software. Torque pulsation is translated into the speed pulsation and the same has been investigated. Impacts of undervoltage unbalance, overvoltage unbalance, positive sequence harmonics and negative sequence harmonics are compared. Estimation for torque ripple factor (TRF) in terms of voltage unbalance factor and total harmonic distortion (THD) is devised.
Keywords: *Power quality, voltage unbalance, voltage unbalance factor, torque ripple factor, Three Phase Induction Motors, torque pulsation*

1. INTRODUCTION

The world is moving with a very fast pace towards the use of electronic and digital devices. Due to recent developments of electronics and computer based automatic and smart devices in every field, e.g. medical, bank, industry, homes etc., quality of power is increasingly becoming more and more important. Power supply waveform also gets distorted due to increased applications of electronic equipments. Distortion in supply waveform can be resolved into multiple frequency sinusoidal waveforms known as harmonics. Although three phase voltage supply is quite balanced at the generation and transmission levels, unbalance exits at utilization end due to unequal load distribution, incomplete transportation of transmission lines, defective transformers, blown fuses of three phase capacitor bank etc. Strictly speaking voltage unbalance can be considered as an irregularity of power supply system which cannot be removed completely. Voltage unbalance can be defined as a voltage variation in a power system in which the voltage magnitudes or the phase angle differences between them are not equal.

Voltage unbalance, harmonics and sags are the most occurring and vulnerable power quality disturbances in the world. Voltage unbalance and harmonic distortion are the long term power quality problems [1], which exists in the power system permanently. Excess level of voltage unbalance and/or harmonics shows various ill effects on induction motors e.g. excess power loss, torque reduction, and torque vibrations and excess power loss results excess temperature rise which leads to shorten the life of induction motor [3]-[12]. Torque vibration can damage the rotor bearings and shaft [9]. Induction motors are very popular in industrial uses due to their simple, rugged, inexpensive construction, reduced maintenance, and excellent operating characteristics. As rough estimate nearly 80% of world industrial motors are three phase induction motors and out of which more than 90% are squirrel cage induction motors. Therefore, it is very important to study the impact of power quality on the performance of the induction motor.

The influence of unbalanced voltages on the performance of induction motor was first studied by Reed and Koppman in 1936 [2]. Further, Williams in 1954, proved that an induction motor operation under unbalanced voltage would lead to efficiency reduction [3]. It was proved by various authors that unbalanced voltage can cause extra power loss which leads to excess temperature rise in an induction motor, consequently, shorten the machine's life [3]-[8]. Effect of temperature rise can be mitigated either by using the mitigating devices [21] or by derating of induction motor [5],[18],[19]. Attention has been paid to estimate the power loss, efficiency reduction, temperature rise caused by unbalanced and non-sinusoidal supply voltage. But less attention has been paid to investigate the torque performance of induction motor on unbalanced and non-sinusoidal voltage quantitatively. Most of the authors observed that unbalanced and harmonic distorted supply produces torque pulsation, but quantitative analysis has not been given due attention [9]-[11]. Prediction of torque pulsation due to unbalanced and non-sinusoidal supply voltage is of prime important as excess level of torsional vibration may affect the output product as well as affect the bearings and mechanical parts of the motor badly. Souto et al. In 1998, observed the impact of unbalance and harmonics on the torque and efficiency using SABER simulator [9]. They observed vibrations due to voltage unbalance and harmonic distortion supply. They also noticed that, the torque vibrations due to unbalance are more as compared to the harmonic distortion levels [9]. Youb analyzed the impacts of unbalance on the performance of torque vibrations and used the Torque ripple factor (TRF) to quantify the ripple in torque [12]. It was observed that small unbalance of 2% may create very significant torque vibrations approximately 22% [12] but impact of harmonic distortion is not included in the study. In this paper comprehensive analysis of impact of unbalance

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

voltage and non- sinusoidal supply on the torque and speed pulsation has been done using MATLAB/Simulink. Torque pulsation has been quantified by an index factor, torque ripple factor which is defined as the ratio of peak to peak torque to the average torque and is expressed in percentage. Torque ripple factor (TRF) is estimated from Voltage unbalance factor (VUF) and Total Harmonic distortion (THD). This paper enables to predict the torque ripple factor caused by VUF and THD.

2. VOLTAGE UNBALANCE AND HARMONIC DISTORTION

In a balanced sinusoidal supply system, all three phases voltages are equal in magnitude and are phase displaced from each other by 120 degrees. Any differences that exist in the three voltage magnitudes and/or a shift in the phase separation from 120^0 are said to be unbalanced supply. Causes of voltage unbalance include unequal impedances of three-phase transmission and distribution system lines, large and/or unequal distribution of single-phase loads, phase to phase loads and unbalanced three-phase loads. When a balanced three-phase load is connected to an unbalanced supply system the currents drawn by the load also become unbalanced [8]. The level of voltage unbalance is calculated using unbalance index term known as voltage unbalance factor (VUF), which is generally expressed in percentage.

A. Voltage Unbalance Factor:

Voltage unbalance factor is a measure of level of voltage unbalance in the system. There are various definitions of voltage unbalance factors but, out of these, National Electrical Manufacturer Association (NEMA) and International Electro technical Commission (IEC) definitions are well accepted and widely used definitions. All the definitions given by different sources are being given below:

1) NEMA Definition:

The voltage unbalance factor in percentage (VUF) at the terminal of a machine as given by the National Electrical Manufacturer Association (NEMA) Motor and Generator Standard (NEMA MGI) used in most studies is given as follows [14]

Voltage unbalance factor (VUF) or Line voltage unbalance rate (LVUR) is given by:

$$VUF\ or\ LVUR = \frac{\begin{array}{c} maximum\ voltage\ deviation\ from\ average \\ line\ voltage\ magnitude \end{array}}{average\ line\ voltage\ magnitude} \times 100$$

$$= \frac{Max\left[|V_{ab} - V_{avg}|, |V_{bc} - V_{avg}|, |V_{ca} - V_{avg}|\right]}{V_{avg}} \times 100$$

Where $V_{avg} = \frac{V_{ab}+V_{bc}+V_{ca}}{3}$

NEMA recommends that motors can be used safely up to one percent of VUF. If VUF exceeds one percent then, one should derate the motor as per NEMA derating curve; above 5 % unbalance motor operation is not recommended [14].

2) IEEE Definition:

As per IEEE standard 141, VUF is defined as the same way as NEEMA, only differences is that the phase voltages have been taken instead of line voltages and it is also called Phase unbalance voltage rate (PVUR).So as per IEEE definition VUF or PVUR[8]

$$= \frac{\begin{array}{c} maximum\ voltage\ deviation\ from\ average \\ phase\ voltage\ magnitude \end{array}}{average\ phase\ voltage\ magnitude} \times 100$$

$$= \frac{Max\left[|V_a - V_{avg}|, |V_b - V_{avg}|, |V_c - V_{avg}|\right]}{V_{avg}} \times 100\ \%$$

Where $V_{avg} = \frac{V_a+V_b+V_c}{3}$

IEEE definition cannot be used for angle unbalanced; therefore this definition is seldom used by researcher and field engineers.

3) IEC Definition:

The voltage unbalance factor (VUF) is defined by International Electrotechnical Commission (IEC) as the ratio of negative-sequence voltage component to the positive-sequence voltage component.

VUF in percentage $= \frac{V_2}{V_1} \times 100$, Where V_2 is negative sequence voltage component magnitude and V_1 is positive sequence voltage component magnitude. This definition is popular among researchers [22].

4) Complex Voltage Unbalance Factor (CVUF):

An extension of VUF is the complex voltage unbalance factor (CVUF) that is defined as the ratio of negative-sequence voltage phasor to positive sequence voltage phasor [16]-[17]. The CVUF is a complex quantity having the magnitude and angle. Appropriately, complex voltage unbalance factor (CVUF) can be written as

CVUF in percentage $= \frac{\mathbf{V_2}}{\mathbf{V_1}} \times 100$

Whereas $\mathbf{V_1}$ is positive sequence voltage phasor and $\mathbf{V_2}$ is negative sequence voltage phasor. We have used IEC definition as it gives accurate result and can be used in phase voltage or line voltage.

B. Classification of Unbalancing

There may be different types of unbalance in a supply system with a possibility of voltage variations above and below the rated value. Thus voltage unbalance can be classified into overvoltage unbalance (OVU), under-voltage unbalance (UVU) and angle unbalance (AU) [8]. OVU is a condition when the three phase voltages are not equal to each other, in addition positive sequence component is greater than the rated value while UVU is a condition where the three phase voltages are not equal to each other and in addition the positive-sequence component is lesser than the rated value.

Volume 8, Issue 6
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ITEE Journal
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Angle voltage unbalancing is the condition when magnitudes of all voltages are not equal to 120 degree. OVU, UVU, and phase angle unbalance are further classified as single phase, two phases and three phase unbalance. Some other authors have used the term balanced over voltage (BOV) and balanced under voltage (BUB) [20], but these term falls under the definition over voltage and under voltage, so these terms are not required as these are not unbalance, these are simply under voltage and over voltage. One more term should be used i.e. rated voltage unbalance (RVU), at this condition positive sequence voltage becomes one. So including this new term (RVU), unbalance may be classified as OVU, UVU, RVU and AU. For the same voltage unbalance, OVU, UVU, RVU and AU will have different amount of losses, that's why these term has special significance [22]. We have investigated the result using Undervoltage unbalance and Overvoltage unbalance.

C. Harmonics:

Harmonics are sinusoidal voltages or currents having frequencies that are integer multiples of the frequency at which the supply system is designed to operate. Harmonics combine with the fundamental voltage or current, produces waveform distortion. Harmonic distortion exists due to the nonlinear characteristics of devices and loads on the power system.

Harmonic indices:

Two most commonly used indices for measuring the harmonic content of a waveform is the total harmonic distortion (THD). THD is a measure of effective value of harmonic distortion and may be applied to either voltage or current. It is given by the formula [1]:

$$THD = \frac{\sqrt{\sum_{h=2}^{h_{max}} M_h^2}}{M_1}$$

Where M_h is the rms value of harmonic component h of the quantity M. If only one harmonic present then it is known as Individual harmonic distortion (IHD).

Current distortion levels can be characterized by a total harmonic distortion, as described above, but this can often be misleading. For instance, many adjustable speed drives will exhibit high total harmonic distortion values for the input current when they are operating at very light loads. This is not a significant concern because the magnitude of harmonic current is low, even though its relative distortion is high.

Therefore other term is used to describe the current harmonic distortion i.e. Total Demand Distortion (TDD) which is defined as [1]:

$$TDD = \frac{\sqrt{\sum_{h=2}^{h_{max}} I_h^2}}{I_L}$$

Where I_L is the peak or maximum demand load current at fundamental frequency component, measured at the point of common coupling (PCC). Limiting value of THD in distribution network as per IEEE 519-1992 is 5% and of Individual harmonic distortion (IHD) is 3% [13].

3. IMPACT OF VOLTAGE UNBALANCE ON INDUCTION MOTOR TORQUE

It is well established that unbalanced supply voltage produces the negative-sequence current and it results a backward rotating field in addition to the forward rotating field produced by the positive sequence voltage. The interaction of these fields reduces the steady state torque and produces pulsating electromagnetic torque that results the increased vibrations and noise in the machine. Even though the unbalanced voltage applied to the motor is small, large unbalanced motor current can flow because of relatively low negative sequence impedance. The large unbalanced current creates significant problems in induction motor applications, such as a heating problem, increased losses, low efficiency and shortening the motor life.

To measure the torque pulsation, an index term torque ripple factor (TRF) is used which is given by [12]:

Torque ripple factor (TRF) in percentage

$$= \frac{Peak\ to\ peak\ magnitude\ of\ torque}{Average\ torque\ or\ dc\ value\ of\ torque} \times 100$$

A MATLAB/Simulink model has been designed and 4kw, 400V, 50Hz squirrel cage induction motor is chosen for the study. Two cases of voltage unbalance have been taken i.e. over voltage unbalance and under voltage unbalance. Readings of torque ripples were taken at different values of voltage unbalance factor. Two different graphs are plotted, one for overvoltage case and other for under voltage case. It was observed that the torque ripple factor has linear relationship with the voltage unbalance factor. Relationship between both the variables have been found using curve fitting. TRF for overvoltage unbalance is more than TRF for undervoltage unbalance. In overvoltage condition, torque ripple magnitude is increased much higher than that of increment in steady state value of torque. TRF for over voltage comes out approximately 12.8 times (Fig1) whereas for under voltage case it is approximately 11.5 times (Fig2) greater than the VUF. Difference in ripple can also be verified by torque curve w.r.t time (Fig 3 & Fig 4).

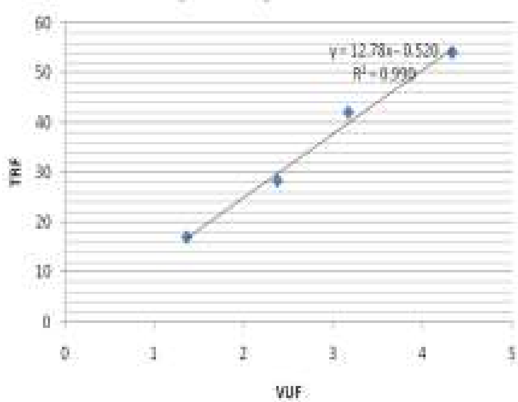

Fig 1: Variation of TRF with VUF in over voltage case

ITEE Journal
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ISSN: - 2306-708X

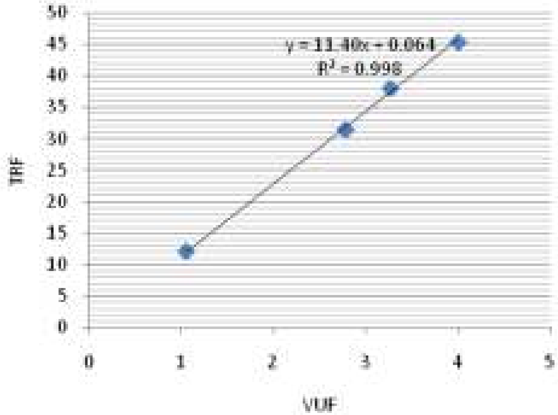

Fig 2: Variation of TRF with VUF in under voltage case

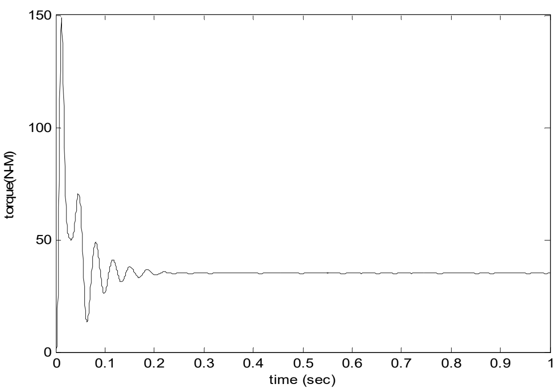

Fig 3 Torque variation at balanced supply voltage

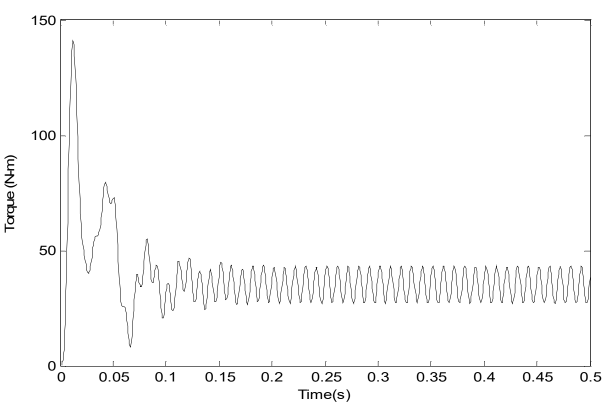

Fig 4: Torque variation at unbalanced supply (with VUF 4%)

4. IMPACT OF NON-SINUSOIDAL VOLTAGE ON INDUCTION MOTOR TORQUE:

It can be shown that the harmonic voltages and currents of the order $h = 3k + 1$ (where k is an integer) are of positive sequence and harmonic voltages of the order $h = 3k - 1$ are of negative sequence. Similarly it can be shown that harmonics of the order $h = 3k$ are of zero sequence. A positive sequence harmonic h will produce a rotating field, which moves in the same direction as the fundamental at a speed h times that of the fundamental field. Similarly rotating field produced by a negative sequences harmonic will move in the direction opposite to the fundamental at h times its speed. Zero sequence components do not produce a rotating field. Since the waveform is symmetrical, hence odd harmonics is not present, only even harmonics will be present. Positive sequence components (i.e., 7th, 13th, 19th…) will assist torque production, whereas the negative sequence components (5th, 11th, 17th…) will act against the direction of rotation resulting in torque pulsations. Zero sequence components (i.e., triplen harmonics) are stationary and do not rotate, therefore, any harmonic energy associated with them is dissipated as heat. The magnitude of torque pulsations generated due to these harmonic sequence components can be significant and cause shaft torsional vibration problems [22] .

To estimate the impact of non sinusoidal waveform, we classified the problem into three sections (i) applied the voltage consisting positive sequence harmonic (7^{th}) (ii) applied the voltage consisting negative sequence harmonic (5^{th}) (iii) applied the voltage consisting both positive and negative sequence harmonic in ratio 2:1. TRF is calculated for all above three conditions and plotted w.r.t. THD (Fig 5- Fig 7).

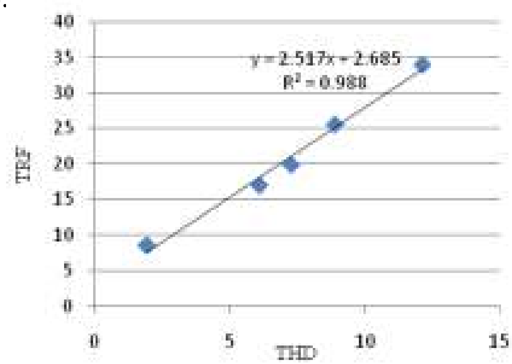

Fig 5: Effect of fifth harmonic on TRF

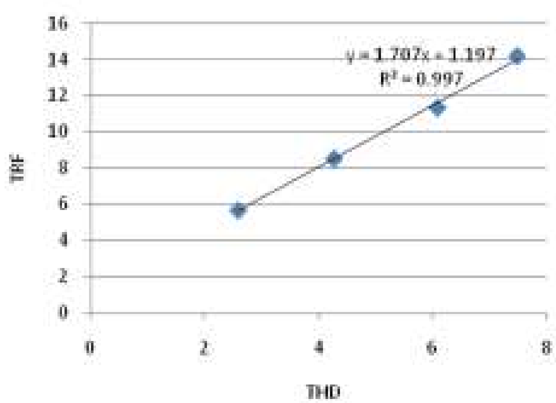

Fig 6: Effect of seventh harmonic on TRF

Volume 8, Issue 6
December 2019

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

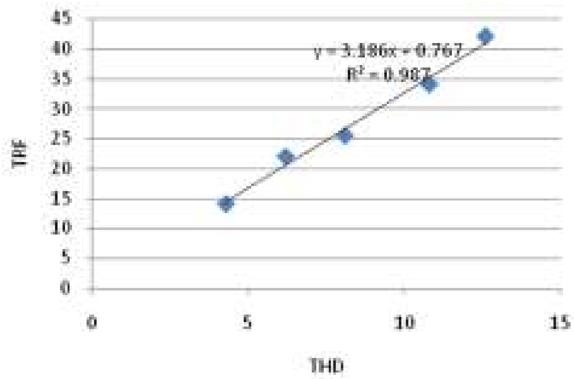

Fig 7: Effect of combined harmonic (5th&7th)

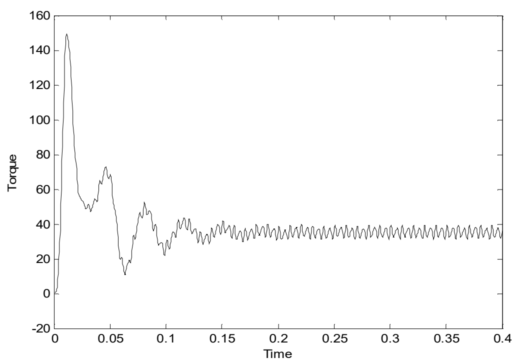

Fig 8: Torque pulsation due to harmonics (THD=7)

It was observed that impact of negative sequence harmonic is more severe than the positive sequence harmonic.TRF is found 2.5 times of THD for negative sequence, 1.7 times for positive sequence and 3.2 times for combined case. When unbalanced and harmonic supply is applied with THD 7.85 and VUF 3.915, the torque ripple factor is found 48.5 which is just greater than that in the case of VUF. Therefore it can be concluded that TRF is much affected by unbalance then the non-sinusoidal voltage supply. For one percent increase of VUF, TRF increases approximately 12 % whereas, one percent increase in THD results 3% increase of TRF. Impact on speed was also investigated and it was found that torque pulsation is translated into speed pulsation but with less magnitude due to inertia of the motor. Torque pulsation is also plotted with time (Fig 8).

5. CONCLUSION

Induction motor torque performance is severely affected by unbalanced supply voltage. Torque ripple factor is very much dependent on the voltage unbalance factor and it linearly varies with voltage unbalance factor. One percent increase in voltage unbalance factor produces approximately 12% torque pulsation i.e. torque ripple factor. Harmonic contents also affect the torque performance, one percent increase in THD results 3% increase in TRF. It was observed that impact of negative sequence harmonic is more severe than the positive sequence harmonic. TRF is found 2.5 times of THD for negative sequence, 1.7 times for positive sequence and 3.2 times for combined case. Overvoltage unbalance is more harmful than the undervoltage unbalance. Derating is not the effective solution of torque vibrations, only mitigation of unbalance in voltage supply is best solution for reduction of torque vibration. Torque pulsation is translated into speed pulsation but with less magnitude due to inertia of the motor.

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