© 2014, Scienceline Publication
www.science-line.com

ISSN: 2322-5114
Journal of World's Electrical Engineering and Technology
J. World. Elect. Eng. Tech. 3(1): 18-25, 2014

JWEET

Performance Evaluation of Three-Phase Induction Motor Fed by unbalanced voltage Combined with Over- or Under Voltage Using Finite Element Method

Ali Ebadi*, Mohammad Mirzaie, and Sayyed Asghar Gholamian

Department of Electrical and Computer Engineering, Babol University of Technology, Babol, Iran

*Corresponding's Email: ebadi.power@gmail.com

Abstract – *Unbalanced voltages can exist anywhere in a three-phase power distribution system. Thus, investigation of their effects on power system equipments, especially three-phase induction motors as most commonly used type of electric motors, is vital. This paper presents performance evaluation of a three-phase squirrel cage induction motor under unbalanced voltage combined with over- or undervoltage based on Finite Element Method (FEM) simulation. To achieve this purpose , number of unbalanced voltages with averages equal to 90, 100 and 110% of rated voltage is applied to FEM simulation model of the motor and its steady state operating performance has been analyzed and the resulted input/output power, losses, efficiency and torque have been discussed. The employed measure for voltage unbalance in the present work is complex voltage unbalance factor (CVUF) that consists of voltage magnitude and angle.*

Keywords: *CVUF, Efficiency, Induction Motor, Losses, Torque, Voltage Unbalance.*

ORIGINAL ARTICLE
Received 25 Dec. 2013
Accepted 07 March. 2014

INTRODUCTION

Voltage unbalance is an important index in evaluating power system quality. A balanced three-phase voltage source implies a situation in which the voltages are equal in magnitude with 120° difference in phase between any two-voltage phasors [l].

In three-phase power systems, the voltages are unbalanced commonly at the electric power distribution system (PDS) Due to the inevitable asymmetry of impedances of transmission lines and loads connected to the electrical network [2].

Based on a report of American National Standards Institute, the voltage unbalance of 66% of the PDSs in USA, is less than 1%, and that of 98% of the distribution systems is less than 3%, whilst for remaining 2% it is larger than 3% [3].

According to the above description, the Investigation on the performance of electrical equipments especially Induction Motors (IMs) as most popular type of electric motors under voltage unbalance has been always a major area of interest to researchers over the last century.

Among all electrical loads, induction motors have most importance in terms of the extent of use and amount of consumption of total produced electric energy in the world. Therefore, it is important to clarify the effects of quality of the PDS voltage on their operating performance. In fact, supplying a three-phase induction motor with unbalanced voltage supply has many negative effects on its performance. These effects include increased losses and, consequently, temperature rise, reduction in efficiency and insulation life of the motor. The Study of the influence of voltage unbalance on the performance of a three-phase induction motor goes back to 1936 [4], that It can show the long history of this issue.

However, the main challenge at the beginning a new work in this area is still choosing a suitable definition of voltage unbalance. In fact, there are three famous standard definitions that are given by the Institute of Electrical and Electronics Engineers (IEEE), National Electrical Manufacturers Associations (NEMA) and International Electrotechnical Commission (IEC) and the newest definition named Complex Voltage Unbalance Factor (CVUF) that is presented by Wang for first time [11].

IEEE defines voltage unbalance as the ratio of Maximum phase voltage deviation from average voltage to average phase voltage. NEMA has similar definition using line voltages [5]. Obviously, it is easier to use NEMA definition due to its easier access to line voltages in three-wire systems. IEC says voltage unbalance is the ratio of the amplitudes of positive- to negative-sequence voltages [7]. Finally, the CVUF is the ratio of positive- to negative-sequence voltages [11] that means it is an extended version of IEC definition of voltage unbalance (VUF).

According to the definitions, Both of the IEC and the NEMA definitions are considering only "magnitude" of

To cite this paper: Ebadi A, Mirzaie M, Gholamian SA. 2013. Performance Evaluation of Three-Phase Induction Motor Fed by unbalanced voltage Combined with Over- or Under Voltage Using Finite Element Method. *J World Elec. Eng. Tech.*, 3 (1): 18-25.
Journal homepages: http://www.jweet.science-line.com/

voltage unbalance to indicate the degree of unbalanced voltage. However, the CVUF take into consideration the angle as well as magnitude to describe the voltage unbalance phenomenon better.

Despite the above descriptions, Faiz et al. [4] showed; an infinite number of voltages can give the same voltage unbalance based on all mentioned definitions although the VUF and Specially CVUF are more suitable to use. Thus, Additional constraints for terminal voltages as well as these definitions must be considered to decrease error of computations.

Furthermore, the authors in [5] uses eight special cases of unbalanced voltages with the same VUF as well as the unbalanced voltages with the same positive-voltage component and different VUF to study efficiency, power factor and temperature rise of a three-phase induction machine based on experimental test. Note that, their assumptions have been criticized seriously by Faiz et. Al [4].

In [6], the authors employ IEC definition to study motor life estimation using thermal model when it is supplied with a combination of over- or under voltages with unbalanced voltages. To do this, they calculated unbalanced voltages with averages equal to 90% and 110% of rated voltage of machine.

Gnacinski in [8, 9] uses the CVUF definition to deal with the effects of simultaneous voltage unbalance and over- or undervoltage on windings temperature, operational life and load carrying capacity of two different induction machines using the experiment and thermal modeling. It should be noted that he assumes the torque and the positive-sequence component of voltage are constant to achieve the objectives of Articles.

Anwari et. Al in [11] evaluate influences of under- and overvoltage unbalance on the losses, efficiency, power factor and derating factor of an induction machine based on the CVUF definition and by using MATLAB simulations. It is noteworthy that they assume constant load torque for the studied machine.

In [12], the negative effect of unbalanced voltage upon the losses and efficiency of a three-phase squirrel cage induction motor is investigated using analytical method and experiments. Nevertheless, effect of overvoltage unbalance is not considered and output power is assumed to be constant. as well, the effects of overvoltage unbalance on output power are not investigated.

In the present work, the CVUF definition of voltage unbalance has been used for better evaluation of performance of the IM under voltage unbalance combined with under- or overvoltage. For this purpose, the operating performance of a 3 HP, 380V induction motor has been simulated using Finite Element Method (FEM) supplied by some unbalanced voltages with the same CVUF and different averages. In addition, power, losses, efficiency and torque of the simulated machine have been analyzed and studied. Meanwhile, In order to realize the variations of the load, a linear load torque has been considered as the load.

Note that, in this work all FEM simulations have been performed in Maxwell V 12.1 environment and results have been processed using MATLAB/Simulink tools.

UNBALANCED VOLTAGES

The Fortescue's method of symmetrical components has been used widely for the analysis of unbalanced supply voltages. In accordance with Fortescue, three-phase line voltages (V_{ab}, V_{bc} and V_{ca}) can be resolved into the zero-, positive-, and negative-sequence line voltage components (U_0, U_1, and U_2) as follow [1]:

$$\begin{bmatrix} U_0 \\ U_1 \\ U_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} \tag{1}$$

Where $a = e^{(j2\pi/3)}$.

In three-phase induction motors without neutral path, line currents have no zero-sequence component. Thus, the positive- and negative-sequence phase voltage components (V_1 and V_2) can be expressed in terms of U_1 and U_2 by the following equations:

$$V_1 = \frac{U_1}{\sqrt{3}\angle 30} \tag{2}$$

$$V_2 = \frac{U_2}{\sqrt{3}\angle -30} \tag{3}$$

The Voltage Unbalance Factor (VUF) defined by IEC is:

$$VUF = \left|\frac{V_2}{V_1}\right| \times 100 = K_v \tag{4}$$

As was previously stated, the contribution of phase angle to the voltage unbalance has not been considered in this definition. However, more complete description of the voltage unbalance including the angle is obtainable using CVUF according to (5). In fact, it can be seen that the CVUF is an extension of the VUF.

$$CVUF = \frac{V_2}{V_1} \times 100 = K_v \angle \theta_v \tag{5}$$

Based on above description, the CVUF definition of voltage unbalance has been used in this paper as a better definition.

Using pervious equations, the eligible unbalanced voltages for purposes of this article have been calculated. So that, they include supply voltages with averages equal to 90, 100 and 110% of rated voltage and K_v=0,1,…,6 and also Θ_v=120°. These unbalanced voltages can be applied on the FE model of the IM to analyze effects of different unbalanced conditions on its performance.

SIMULATION USING FINITE ELEMENT METHOD

In this research, a 3 HP, 380 V three-phase squirrel cage induction motor has been employed to study [2]. Fig. 1 Shows the cross section of the simulated model of this motor has been meshed by 38896 triangles. As a general way, time-stepping FEM is used for the analysis of magnetic field. For the time-stepping FEM, time step should be fixed and the input voltage should be defined at each time step. It should be noted that to improve the shape of sinusoidal wave, smaller time steps are required. Therefore, in this work the time step equal to 0.1 ms has been used that is enough small regarding to electrical frequency and rated mechanical speed of the motor.

The governing equation for two-dimensional (2-D) FE analysis is given by [13]

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial A}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial A}{\partial y}\right)=\sigma\frac{dA}{dt}-J_0 \quad (6)$$

Where, μ is the permeability, A is the component of magnetic vector potential, σ is the conductivity of the materials, and J_0 is the exciting current density of the stator winding.

The voltage equation per each phase is [13]:

$$V_a=I_aR_a+L_e\frac{dI_a}{dt}+\frac{d\varphi_a}{dt} \quad (7)$$

Where V_a, I_a, R_a, Φ_a and L_e are the input voltage, the current, the resistance, the flux linkage of each phase and the end-coil inductance, respectively.

In order to realize the variations of the load, a linear load torque has been considered as the load so that is equal to rated output torque of machine at rated speed.

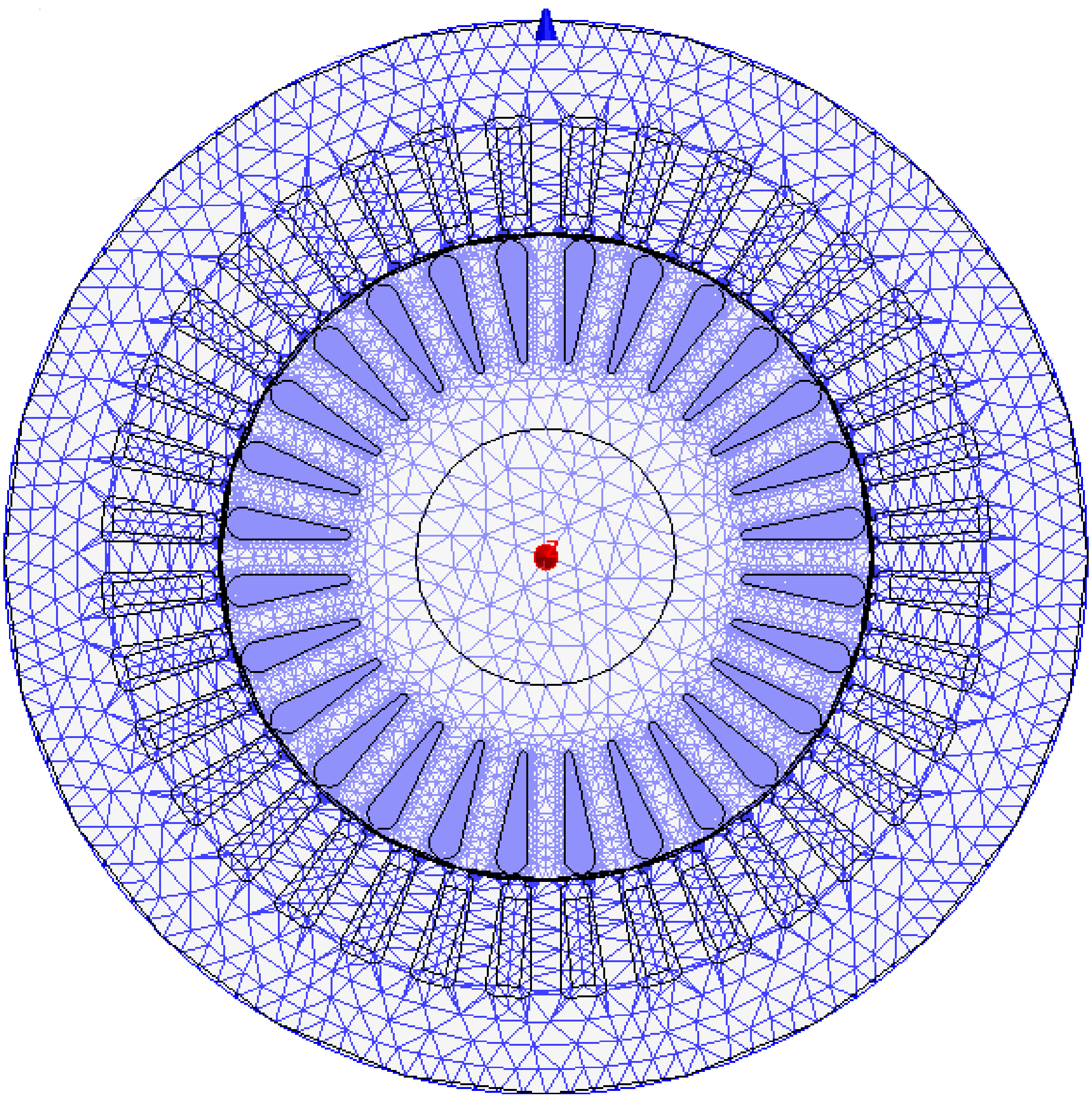

Fig. 1 - FE geometry and Mesh

RESULTS AND DISCUSSION

Simulating with Finite element method directs to more appropriate and detailed results. For instance, figs. 2 and 3 show magnetic flux density distribution and machine's stator currents in steady state and unbalanced voltages condition (VUF=6% and 10% overvoltage). It should be mentioned that the magnitude of unbalanced currents of induction motor can be more than unbalanced supply voltages (its providing factor) results in damages to the machine.

In this section, the calculated unbalanced voltages have been applied to the simulation model and the outcome data has been processed in Matlab/Simulink and the results have been discussed and analyzed.

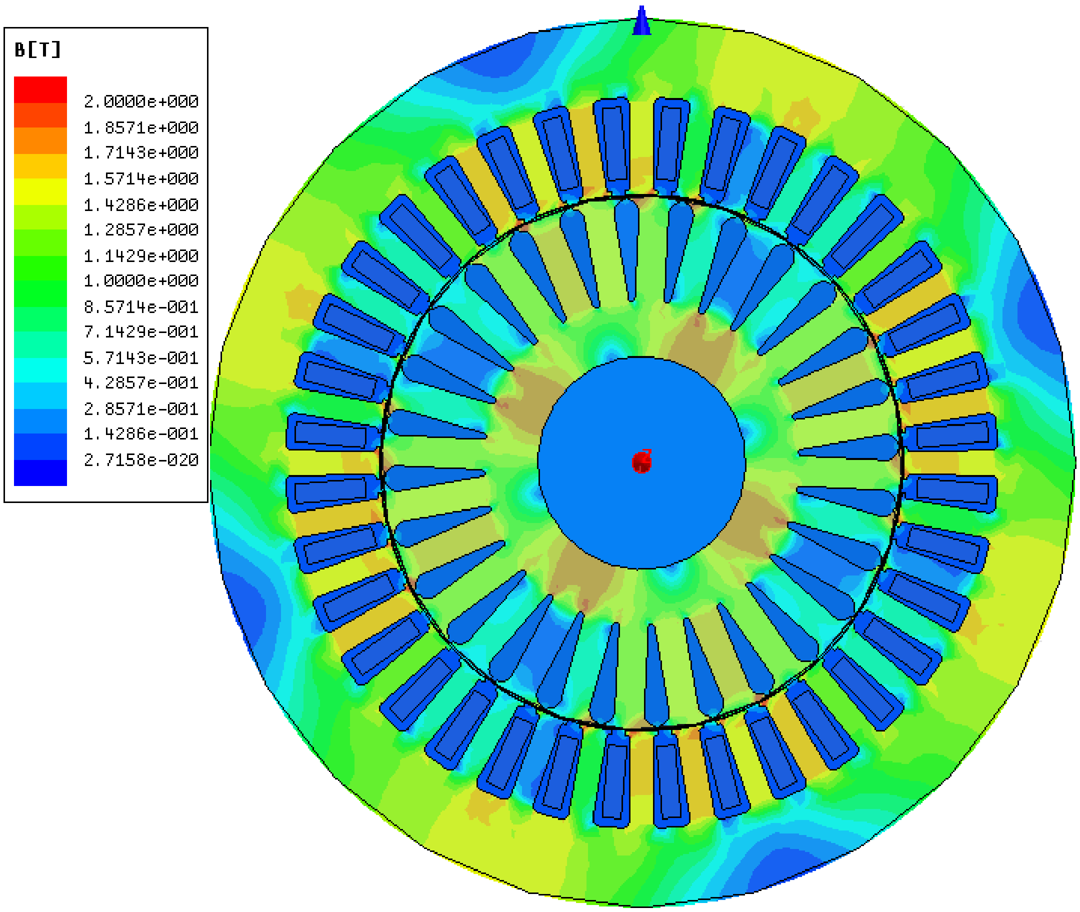

Fig. 2 - Distribution of Magnetic Flux Density Under Unbalanced Voltage

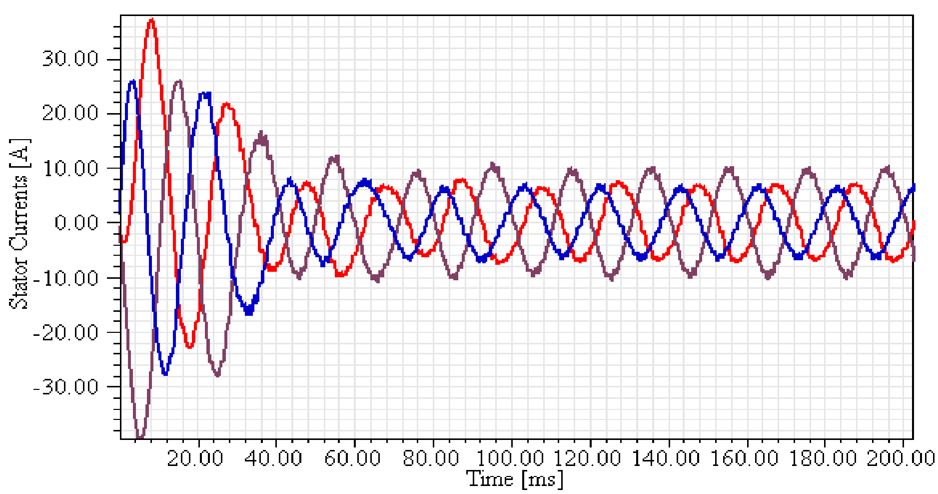

Fig. 3 - Stator Currents Under Unbalanced Voltage

A. Power, Losses and Efficiency

In this section, to have a better comparison, the output, input and loss powers are normalized with respect to their corresponding rated values. The output and input powers of the machine at different conditions of voltage unbalance are shown in Figs. 4 and 5, respectively. As shown in Fig.4, when unbalanced voltages with equal means are applied to the motor, with an increase in VUF (at constant θv), the output power has a very small and negligible drop. This behavior can be explained by the dependency of the output power of the machine to the positive sequence component of supply voltage and the close values of this parameter for unbalanced voltages with equal means [15]. Therefore, as can be seen in Fig. 4, the machine has the lowest and highest output power during under voltage unbalance and over voltage unbalance, respectively So that, the output power can get even bigger than its rated value under unbalanced combined with over voltage. However, this increase is not of interest and has negative consequences as follows.

As shown in Fig. 5, the machine power consumption for all three types of voltage unbalance increases with the increase of VUF significantly, So that the biggest input powers corresponds to voltage unbalance accompanied by over voltage. The reason behind this bigger power consumption is the increase of output power in these conditions. Similarly, the lowest power consumption occurs when unbalanced voltage with under voltage is applied.

Considering the aforementioned explanations and Fig. 6, the efficiency of the machine for all the cases decreases with the increase of VUF. The best conditions in terms of efficiency are related to unbalanced voltages with mean value equal to rated voltage of the machine and the worse efficiencies are resulted when the machine supplied by over voltage unbalance, which is due to increase in the output power. It should be noted that in practical, in order to increase efficiency and decrease the negative effects of voltage unbalance, the load of machine should be reduced [16].

The copper losses of stator and rotor have been shown in figs. 7 and 8. Paying attention to these figs., the losses under unbalanced voltages with same average, increase by raising the VUF. Anyway, machine experiences most copper losses of stator and rotor in overvoltage and undervoltage conditions, respectively. All in all, as it is obvious in fig. 9, for all cases the more VUF leads to the more total copper losses. Also, for the unbalanced voltages with the same VUF, least and most copper losses is relevant to the unbalanced voltages with the average of equal to nominal voltage and 110% of nominal voltage, respectively. It is worth noting that these observations are in contrast with [10]. This is due to the consideration of load variation under voltage unbalance condition in this work.

Eventually, fig. 10 shows the fact that core losses is a function of average values of machine supply voltages that increases with average raising. Besides, changes in voltage unbalance leads to small and irregular variations of it.

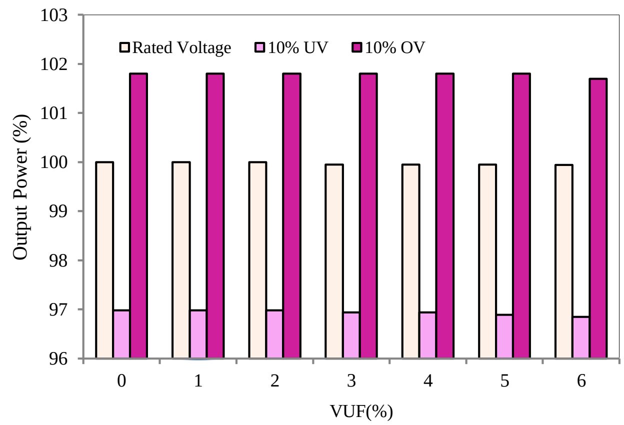

Fig. 4 - Output Power Under Different Voltage Conditions with Θ_v=120°

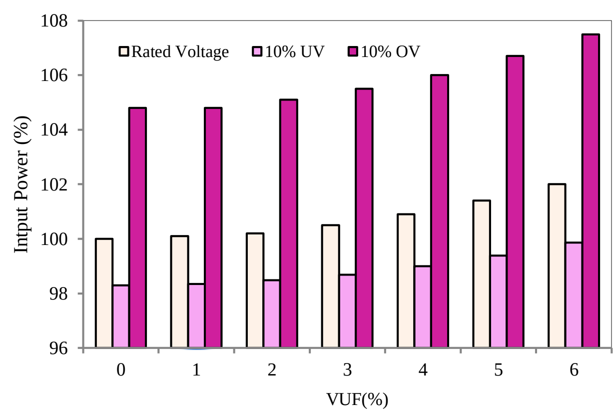

Fig. 5 - Input Power Under Different Voltage Conditions with Θ_v=120°

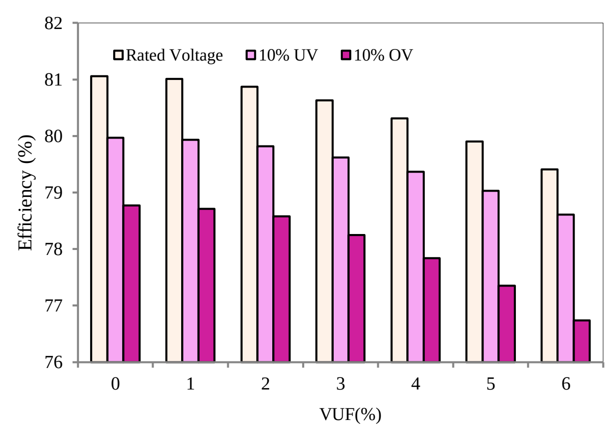

Fig. 6 - Efficiency Under Different Voltage Conditions with Θ_v=120°

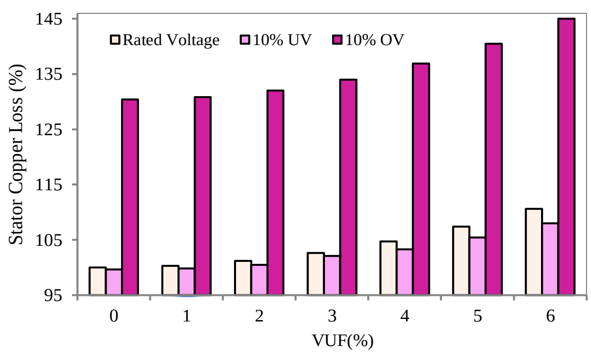

Fig. 7 – Stator Copper Loss Under Different Voltage Conditions with Θ_v=120°

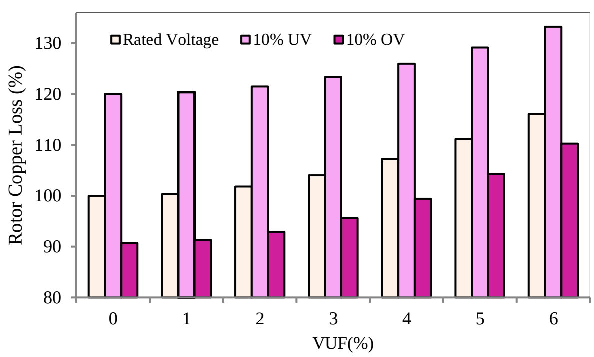

Fig. 8 – Rotor Copper Loss Under Different Voltage Conditions with Θ_v=120°

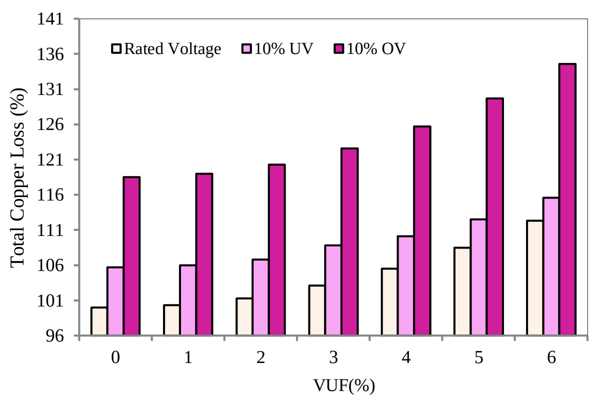

Fig. 9 – Total Copper Loss Under Different Voltage Conditions with Θ_v=120°

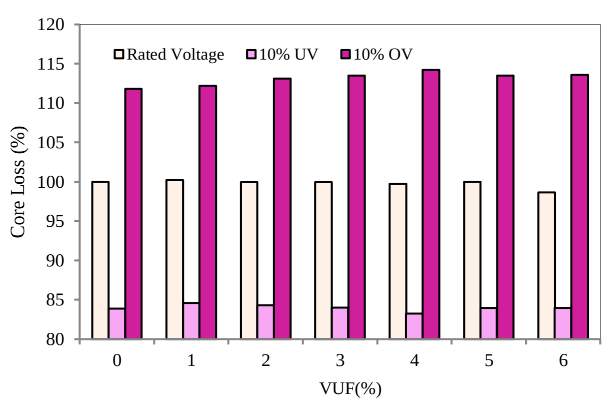

Fig. 10 –Core Loss Under Different Voltage Conditions with Θ_v=120°

B. Torque Analysis

From electrical circuit theory point of view, whenever a balanced three-phase load is supplied with balanced voltages, instantaneous input power of load will be constant, and if the voltages are unbalanced, the consumed power includes alternative component with twice of supply frequency as well as DC or constant value. This fact would be true for three-phase induction motors as the input power and the output power which has a ratio of input power are constant in balanced voltage conditions, but they have ripple with twice of supply frequency in unbalanced conditions. Thereupon, according to equation (12), electromagnetic torque of machine under the balanced voltage will be constant, but it would have a ripple with twice frequency as well as its constant value under unbalanced conditions. Note that in (12), Tem, Po and ωm are respectively electromagnetic torque, output power and mechanical angular velocity of machine.

$$T_{em} = {P_o}/{\omega_m} \tag{12}$$

Furthermore, simulated steady state electromagnetic torque of machine has been shown based on time and frequency domain in figs. 11 and 12, respectively. These figs. are for conditions that the Finite Element model of machine is under unbalanced voltage with VUF=6% and has overvoltage. In these figs., a notable ripple of machine torque in frequency of 100Hz is observable (the supply voltage frequency is 50Hz). It should be mentioned that there are some components other than DC component and 100 Hz ripple of torque FFT transformation shown in fig. 12 Cause of presence of these high frequency components is the teeth slot effect in machine. For practical works, the machine rotor is built like skewed to reduce the teeth slot effect, but in simulation with 2D finite element method, the rotor is supposed to be cylindrical and non-skewed, so the calculated high frequency components of this method are higher than actual values[17,18].

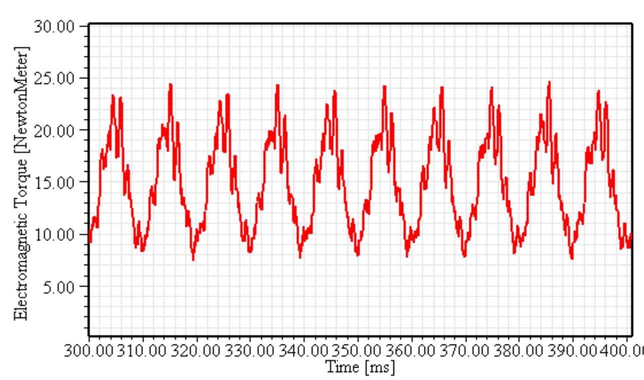

Fig. 11 – Electromagnetic Torque in Time Domain for Unbalanced Condition

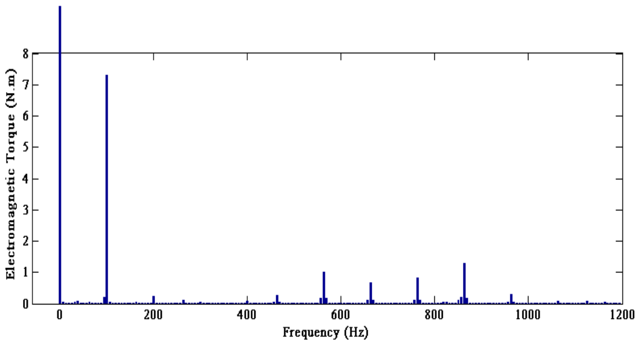

Fig. 12 – Electromagnetic Torque in Frequency Domain for Unbalanced Condition

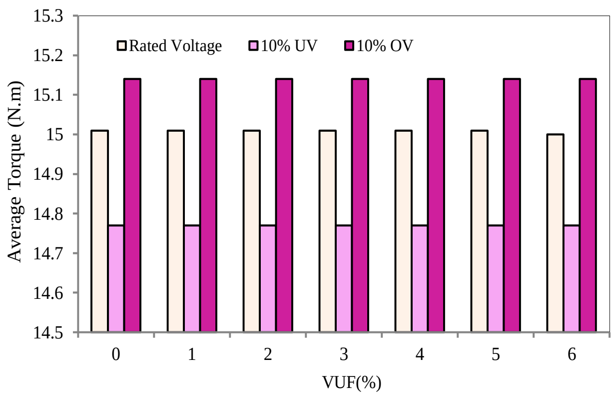

Fig. 13 – Torque Average Under Different Voltage Conditions with Θv=120^o

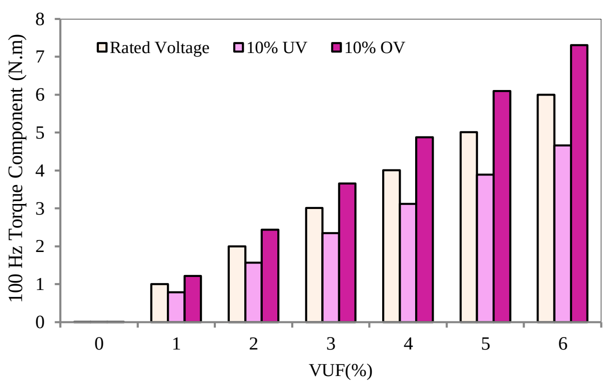

Fig. 14 – 100 Hz Torque Component Under Different Voltage Conditions with Θv=120^o

Regarding the above mentioned explanations, analyzing DC and ripple values of machine torque under unbalanced voltage conditions is a matter of importance. Figs. 13 and 14 show the average torque of simulated motor and the second order component value (100Hz) under mentioned various unbalanced voltage conditions, respectively. as shown in these figs., output torque of machine like its output power is mainly a function of value of voltages positive sequence component or, average value of voltages magnitudes as increases with their raising and its changes for voltages with same average and different VUF are negligible. Nonetheless, the torque ripple increases rapidly with increasing of voltage unbalance. Indeed, the torque ripple under same VUF condition increases with increasing of voltages averages which is mainly because of increasing of negative sequence component. Note that, in unbalanced voltage conditions, the torque ripple is a function of value of voltage negative sequence component [15].

CONCLUSION

This paper presents the employment of Finite Element Method to simulate and study the performance of a three-phase squirrel cage induction motor when supplied by unbalanced voltages, in combination with over- and undervoltages. Based on the achieved results, it is seen that the induction motor under voltage unbalance experiences has increased losses, consumed electric power and torque ripple and decreased efficiency. It has been confirmed that the CVUF is not a compelete measure for estimating machine performance under unbalanced voltage, however considering the voltages averages magnitudes as well as CVUF is a good criterion for proper estimation of machine situation. With regard to this issue, the worst condition of machine considering total losses and efficiency for the same CVUF is when supplied by unbalanced voltages combined with overvoltage and best condition happened under unbalanced voltages with averages equal to rated voltage of machine. Thus, it can be said despite the fact that CVUF is the most complete criteria to describe the degree of voltage imbalance, but not yet complete. On the other hand, operating performance of the induction motor under unbalanced voltages depended to balanced performance with same voltage average, so it can be concluded that to create a more complete definition to measure voltage unbalance; authors must replace “degree of voltage imbalance” with “degree of deviation from closest balanced voltages” as a major issue in future works.

Acknowledgements

The authors would like to thank Mr. Rahmani and Mr. Setareh (R&D management office of Motogen Corporation, Tabriz, Iran) for providing data of the studied three-phase induction motor.

REFERENCES

[1] S.Y. Huang and Y.H. Wang, “Analysis of a Three-phase Induction Motor under Voltage Unbalance Using the Circle Diagram Method,” International Conference on Power System Technology, pp. 165-170, 2004.

[2] A. Ebadi, M. Mirzaie and S. A. Gholamian, “Torque Analysis of Three-Phase Induction Motor Under Voltage Unbalance Using 2D Fem,” International Journal of Engineering Science and Technology, vol. 3, no. 2, pp. 871- 876, 2011.

[3] "Electric Power Systems and Equipment-Voltage Rating (60 Hertz)", ANSI Standard, Publication No. ANSI C84.1-1995.

[4] J. Faiz, H. Ebrahimpour and P. Pillay, "Influence of Unbalanced Voltage on the Steady-State Performance of a Three-Phase Squirrel-Cage Induction Motor," IEEE Transactions on Energy Conversion, vol. 19, no. 4, pp. 657- 662, 2004.

[5] C.Y. Lee, "Effects of Unbalanced Voltage on the Operation Performance of a Three-phase Induction Motor," IEEE Transactions on Energy Conversion, vol. 14, no. 2, pp. 202-208, 1999.

[6] P. Pillay and M. Manyage, "Loss of Life in Induction Machines Operating With Unbalanced Supplies," IEEE Transactions on Energy Conversion, vol. 21, no. 4, pp. 813 – 822, 2006.

[7] A. Ebadi, M. Mirzaie and S. A. Gholamian, "A Comparison Between Electrical Circuit and Finite Element Modeling Methods for Performance Analysis of a Three-Phase Induction Motor under Voltage Unbalance," Iranian Journal of Electrical & Electronic Engineering, vol. 8, no. 2, pp.188-194, 2012.

[8] P. Gnaci´nski, "Windings Temperature and Loss of Life of an Induction Machine Under Voltage Unbalance Combined With Over- or Undervoltages," IEEE Transactions on Energy Conversion, vol. 23, no. 2, pp. 363-371, 2008.

[9] P. Gnaci'nski, "Effect of unbalanced voltage on windings temperature, operational life and load carrying capacity of induction machine," Energy Conversion and Management, vol. 49, no. 4, pp. 761 – 770, 2008.

[10] M. Anwari and A. Hiendro, "New Unbalance Factor for Estimating Performance of a Three-Phase Induction Motor With Under- and Overvoltage Unbalance," IEEE Transactions on Energy Conversion, vol. 25, no. 3, pp. 619-625, 2010.

[11] Y. J. Wang, "Analysis of effects of three-phase voltage unbalance on induction motors with emphasis on the angle of the complex voltage unbalance factor", IEEE Transaction on Energy Conversion, vol. 16, no. 3, pp. 270– 275, 2001.

[12] J. Faiz, H. Ebrahimpour and P.Pillay, "Influence of unbalanced voltage supply on efficiency of threephase squirrel cage induction motor and economic analysis," Energy Conversion and Management, vol. 47, no. 3, pp. 289-302, 2006.

[13] A. Ebadi, M. Mirzaie and S. A. Gholamian, "Employing Finite Element Method to Analyze Performance of Three-Phase Squirrel Cage Induction Motor under Voltage Harmonics," Research Journal of Applied Sciences, Engineering and Technology, vol. 3, no. 10, pp. 1209- 1213, 2011.

[14] J. J. Lee, Y. K. Kim, H. Nam, K. H. Ha, J. P. Hong and D. H. Hwang, "Loss Distribution of Three-Phase Induction Motor Fed by Pulsewidth-Modulated Inverter," IEEE Transactions on Magnetics, vol. 40, no. 2, pp. 762– 765, 2004.

[15] G. R. Bossio, C. H. De Angelo, P. D. Donolo, A. M. Castellino and G. O. Garcia, "Effects of Voltage Unbalance on IM Power, Torque and Vibrations," IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives, pp. 1– 6, 2009.

[16] P. Pillay, P. Hofmann, M. Manyage, "Derating of Induction Motors Operating With a Combination of Unbalanced Voltages and Over or Undervoltages," IEEE Transactions on Energy Conversion, vol. 17, no. 4, pp. 485– 491, 2002.

[17] H. De Gersem, K. Hameyer and T. Weiland, "Skew Interface Conditions in 2-D Finite-Element Machine Models," IEEE Transaction on Magnetics, vol. 39, no. 3, pp. 1452-1455, 2003.

[18] A. Ebadi, M. Mirzaie and S. A. Gholamian, "Investigation of the Effects of Unbalanced Voltages on the performance of a Three-Phase Squirrel Cage Induction Motor Using Finite Element Method," Majlesi Journal of Electrical Engineering, vol. 7, no. 2, pp. 140-145, 2013.