Investigation of the Effects of Unbalanced Voltages on the Performance of a Three-Phase Squirrel Cage Induction Motor Using Finite Element Method

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ABSTRACT:
Induction motors are widely used in industrial, commercial and residential applications. An induction motor may exposed to the unbalanced voltage in the various operating conditions. Therefore, it is vital to investigate influences of voltage unbalance on performance of induction motors. In this paper, the performance of a three-phase squirrel cage induction motor has been simulated using Finite Element Method(FEM) supplied by different unbalanced voltages with the same Voltage Unbalance Factor(VUF) as well as the same positive-sequence phase voltage components. In addition, input/output powers, losses and efficiency of the simulated motor under mentioned conditions have been studied.

KEYWORDS: Efficiency, FEM, Induction Motor, Loss, Voltage Unbalance,VUF

1. INTRODUCTION

Voltage unbalance combined with under- or over voltage is a power quality problem which is known as a common phenomenon in three-phase power systems. In fact, the generated voltages are sinusoidal and balanced at generation and transmission levels but they will be unbalanced mainly at the distribution end and the point of utilization for several reasons. Some sources of voltage unbalance are the uneven distribution of single-phase loads in three-phase power systems, asymmetrical transformer winding impedances, open-Y, open-Δ transformer banks, incomplete transposition of transmission lines, blown fuses on three-phase capacitor banks and etc [1].

According to the above mentioned facts, performance analysis of equipments in power systems under voltage unbalance condition is very important. Three-phase induction motor is one of the most widely used equipment in industrial, commercial and residential applications for energy conversion purposes. Based on U.S. Department of energy, industrial motors consume seventy percent of electricity, and induction motors consists eighty percent of the loads in a typical industry [2]. Because of various techno-economic benefits, the three phase induction motors are used more than ever before. Although an induction motor is designed and built to work in balanced condition, however, most of them are connected directly to the electric power distribution system and they are exposed to unbalanced voltages unfortunately.

In theoretical point of view, the unbalanced voltage induce negative sequence current and mentioned current produces a backward rotating field in addition to the forward rotating field produced by the positive sequence one [3]. The interaction of these fields produces pulsating electromagnetic torque and ripple in speed [4, 5]. Such condition has severe negative effects on the performance of an induction motor. The influence of unbalance on the efficiency [6], derating in the machine [7], increase of losses, the undesirable effects on the insulation life [8], and life reduction due to temperature rise [9,10], are some contributions in this area. Note that, all works that were performed until now used mainly experimental tests and/or simulation by employing equivalent electrical circuit to study performance of these motors under unbalanced voltages.

In this work, performance of a three-phase squirrel cage induction motor is studied under voltage unbalance using finite element method. For this purpose a 2.2 kW, 380V induction motor has been simulated in Maxwell 12.1 and it is supplied by eight types of unbalanced voltages with the same voltage unbalance factor as well as seven numbers of unbalanced voltages with the same positive-sequence phase voltage component and its performance analyzed under mentioned conditions. In addition, power, losses and efficiency of the simulated machine under mentioned conditions have been studied. Experimental tests have been performed in no-load status and the input currents have been compared to verify the simulation model.

2. DEFINITIONS OF VOLTAGE UNBALANCE

Three general definitions for measuring the voltage unbalance have been founded in standards. The first definition is Line Voltage Unbalance Rate (LVUR) as defined by the National Electrical Manufactures Association (NEMA), the ratio of maximum voltage deviation from average line voltage magnitude to the average line voltage magnitude [11]. The second definition for voltage unbalance has been given by the IEEE is Phase Voltage Unbalance Rate or PVUR[6], this definition is similar to NEMA definition with a difference, the phase voltages has been used in IEEE definition instead of line voltages. Note that, in practical aspect, measuring of line voltage is easier in industry and in voltage unbalance condition, the phase voltages can have any phase angle, however, the phase voltages are used by IEEE definition and the phase angles are ignored in this definition, thus it seems NEMA definition is more appropriate to use, but LVUR is not enough comprehensive as it has been used with different assumptions in someworks. For example, in [12] it was assumes the average terminal voltage of the machine is equal to rated voltage.

Third definition is Voltage Unbalance Factor, given by International Electrotechnical Commission (IEC) as follows [1]:

$$VUF = \left|\frac{V_2}{V_1}\right| \times 100 \tag{1}$$

Where, V_2 and V_1 are the voltages of the negative- and positive-sequence components respectively, that they can be calculated by the method of symmetrical components developed by Fortes cue. This definition provides a more accurate view of the voltage unbalance, due to calculation of negative-sequence voltage.

3. DIFFERENT TYPES OF VOLTAGE UNBALANCE

In this paper, The IEC definition of voltage unbalance has been used. But this is clear that there are many unbalanced voltages with the same VUF. Therefore, here are considered the following eight special cases of unbalanced voltage with the same VUF[6]: (1) Single phase under-voltage unbalance (1Φ-UV), (2) Two phase under-voltage unbalance (2Φ-UV), (3) Three phase under-voltage unbalance (3Φ-UV), (4) unequal single phase angle displacement (1Φ-A), (5) unequal two-phase-angle displacement (2Φ-A), (6) Single phase over-voltage unbalance (1Φ-OV), (7) Two phase over-voltage unbalance (2Φ-OV), (8) Three phase over-voltage unbalance (3Φ-OV). The mentioned types of unbalanced voltages with VUF = 6% are calculated and tabulated in Table 1. The effects of voltage unbalance cases with the same VUF on performance of a three-phase squirrel cage induction motor can be investigated with these voltages. In order to distinguish contributions of the negative-sequence voltage component to the effects of unbalance on the motor's performance, the positive-sequence voltage was fixed at V_1= 219.39 V and the negative-sequence voltage was adjusted so that the VUF varied from 1% to 7%, the achieved voltages are shown in Table 2.

4. SIMULATION OF INDUCTION MOTOR USING 2D FEM

In this section, simulation procedure of induction motor using FEM has been introduced briefly.

4.1. Analysis Model

Figure 1 shows the meshed quarter cross section of the analyzed 2.2 kW, 380 V and 50 Hz motor [13, 14].

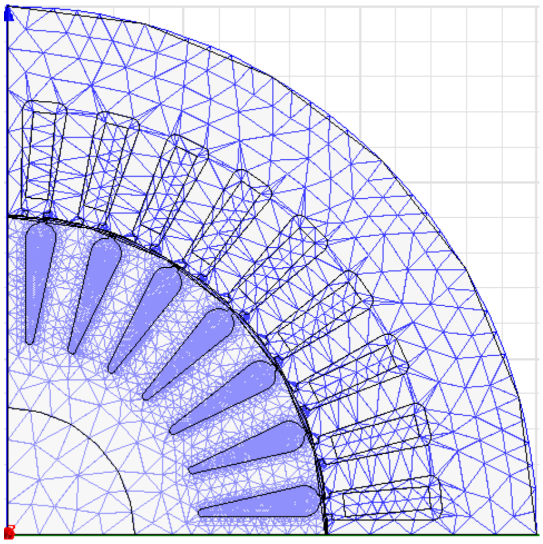

Fig. 1. Meshed model of the IM

4.2. Time Stepping 2D FEM

In this work, time-stepping FEM has been used for the analysis of the magnetic field. In the time-stepping FEM, the input voltage should be defined at each time step. The governing equation for two-dimensional FEM analysis is given by [15]:

Table 1. Eight types of unbalanced voltages with the same VUF

Type	3Φ-UV	2Φ-UV	1Φ-UV	2Φ -A	1Φ -A	1Φ-OV	2Φ-OV	3Φ-OV
V_a (V)	178.27∠0	181.38∠0	182.07∠0	219.39∠0	219.39∠0	261.37∠0	270.35∠0	274.67∠0
V_b (V)	185.18∠0	187.60∠0	219.39∠240	219.39∠227.7	219.39∠240	219.39∠240	249.96∠240	252.56∠240
V_c (V)	215.93∠120	219.39∠120	219.39∠120	219.39∠109.7	219.39∠109	219.39∠120	219.39∠120	224.84∠120
V_1 (V)	193.105	196.142	206.974	218.555	218.607	233.396	246.542	250.001
V_2 (V)	11.586	11.769	12.419	13.113	13.116	14.003	14.792	14.999
VUF (%)	6	6	6	6	6	6	6	6

Table 2. Unbalanced voltages with the same positive-sequence phase voltage component

VUF (%)	1	2	3	4	5	6	7
V_a (V)	223.19∠0	226.99∠0	230.79∠0	234.59∠0	238.39∠0	242.19∠0	245.99∠0
V_b (V)	219.39∠240	219.39∠240	219.39∠240	219.39∠240	219.39∠240	219.39∠240	219.39∠240
V_c (V)	215.59∠120	211.79∠120	207.99∠120	204.19∠120	200.39∠120	196.59∠120	192.78∠120
V_1 (V)	219.39	219.39	219.39	219.39	219.39	219.39	219.39
V_2 (V)	2.193	4.387	6.581	8.775	10.969	13.163	15.374

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial A}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial A}{\partial y}\right)=\sigma\frac{dA}{dt}-J_0 \qquad (2)$$

In above equation, 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:

$$V_a = I_a R_a + L_e\frac{dI_a}{dt}+\frac{d\varphi_a}{dt} \qquad (3)$$

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. Note that, Le is calculated by RMxprt toolbox in Maxwell 12.1.

4.3. Calculation of Copper Loss

The stator winding and the conductor bar losses are calculated using FEM. The conductor bar loss (W_R) can be Calculated as follows [15]:

$$W_R = I^2R = \sigma\vec{E}^2.\Delta s.L \qquad (4)$$

$$\nabla\times\vec{A}=\vec{B} \qquad (5)$$

$$\nabla\times\vec{E}=\frac{\partial\vec{B}}{\partial t}=-\nabla\times\frac{\partial\vec{A}}{\partial t} \qquad (6)$$

In which, B, E, σ and $\Delta s.L$ are magnetic flux density, Electric field intensity, the rotor bar conductivity and an element volume in the conductor bars.

4.4. Calculation of Core Loss

According to traditional ac machine theory, iron loss in watts per kilogram can be calculated in each element with equation (7), therefore total iron loss is obtained from the summation of iron losses in the all elements.

$$P_c = P_h + P_e = K_h f B_m{}^{\alpha} + K_e f^2 B_m{}^2 \qquad (7)$$

In above equation, P_h and P_c are respectively, hysteresis loss component and eddy current component, both in watts per kilogram. B_m and f are the peak value of the flux density and the frequency, respectively. K_h, K_e and α are constants provided by the manufacture for M530-50A lamination.

4.5. Simulation Setting

In order to realize the variations of the load, a linear load torque with the following equation has been considered as the load:

$$T_{LOAD}=\left(\frac{T_{FL}}{\omega_{rated}}\right)\times\omega \qquad (8)$$

In eq. (8), T_{FL} is full load torque, ω_{rated} and ω are rated speed and speed of the machine.

Transient solver with step time of 10^{-4}s has been used in simulations and quarter cross section of motor is meshed with 9688 triangles. Simulation of each cycle (0.02s) consumed 236.3 seconds of time using 3GHz core 2 Duo CPU and 2 Giga Byte of DDR2 Ram.

5. RESULT AND DISCUSSION

In this section, the unbalanced voltages that shown in Tables 1 and 2 are applied to the model and the results have been discussed.

5.1. Performance Analysis of the IM under Unbalanced Voltages with the Same VUF

The distribution of the magnetic flux density and the stator currents under unbalanced voltage(1Φ-UV) are shown in figures 2 and 3, respectively. It can be observed, the flowed currents in the stator are unbalanced obviously and this condition can have undesirable effects on the operation of the machine.

The input and output powers, the copper losses and the core loss under the eight unbalance conditions with the same VUF are shown in figures 4-6, respectively. It should be noted that the mentioned values in the unbalanced condition have been normalized with the corresponding values for the balanced condition. Based on figure 4, the input and output powers increases with increasing positive-sequence voltage component. This increase is such that when induction motor supplied by unbalanced voltages combined with over voltage in one or more phases, the output power have exceeded from equal value in balanced situation.

Having paid attention to figure 5, with increasing positive-sequence voltage, the stator copper loss decreases in voltage unbalance conditions due to under voltage in one or more phases, and increases considerably in other conditions. However, the rotor copper loss increase with the increasing positive-sequence voltage in all conditions. All in all, total copper loss has smaller amounts when positive-sequence voltage has closer values to rated voltage. Note that, the unbalance conditions due to over voltage in one or more phases led to most copper loss, this is because of the increase of output power in these conditions.

Considering figure 6, Core loss in unbalance conditions combined with over voltage is more than other conditions including balanced and unbalanced voltages due to under voltage. Note that, amount of core loss is much lower than total copper loss and it can be ignored in performance analysis of the induction motor without any problem.

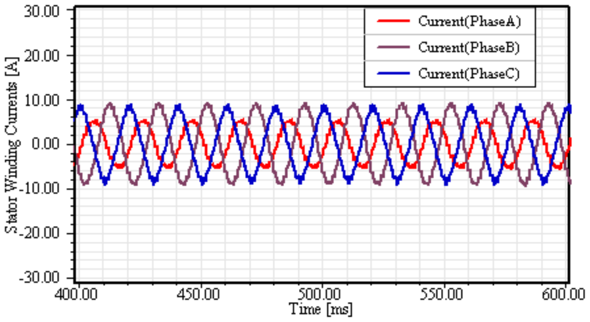

Fig. 2. The stator currents under unbalanced voltage (1Φ-UV)

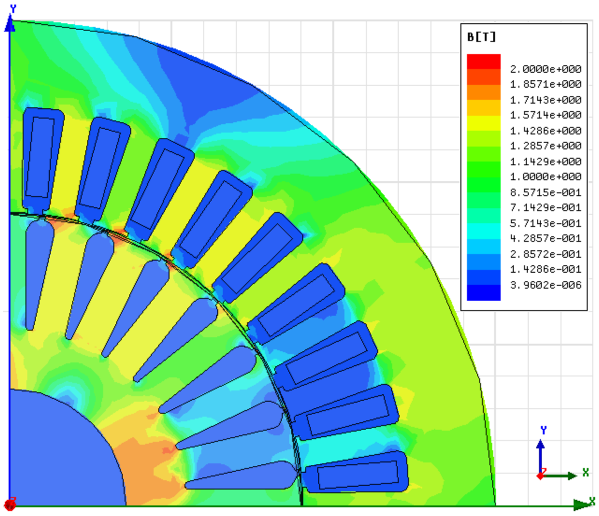

Fig. 3. The distribution of the magnetic flux density under unbalanced voltage (1Φ-UV)

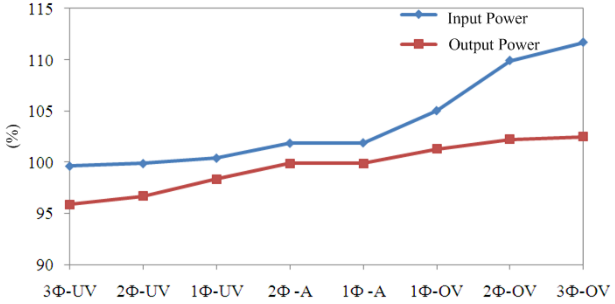

Fig. 4. Input and output powers under unbalance conditions with the same VUF

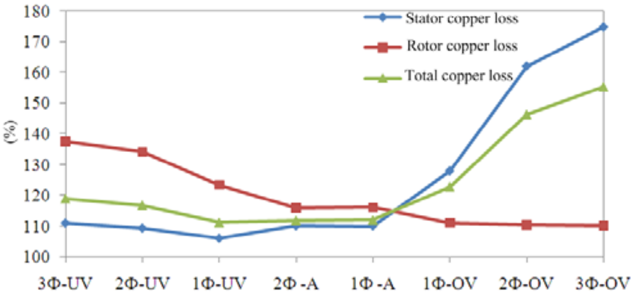

Fig. 5. Copper losses under unbalance conditions with the same VUF

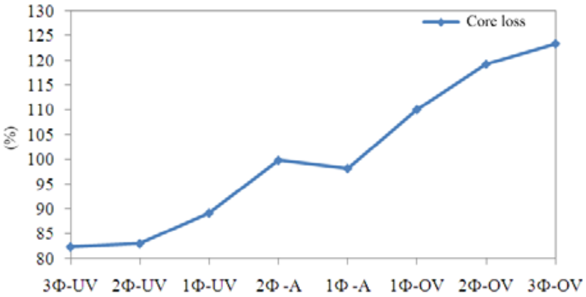

Fig. 6. Core loss under unbalance conditions with the same VUF

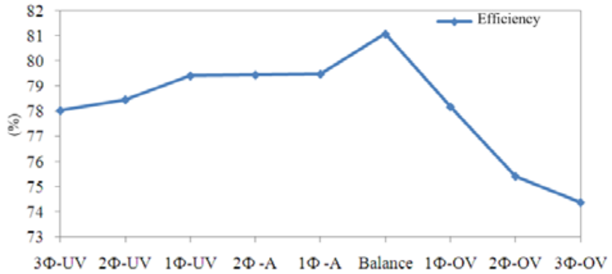

Fig. 7. Efficiency under balance condition and unbalance conditions with the same VUF

Figure 7 shows the efficiency of the induction motor at balanced and unbalance conditions. Observing this figure, the IM has better efficiency when positive-sequence voltage has closer value to rated voltage (unlike total copper loss). Note that, the efficiency at all unbalance conditions is lower than balance condition

5.2. Performance Analysis of the IM under Unbalanced Voltages with the Same Positive-Sequence Voltage

According to Figure 8, the output power under unbalance conditions experiences negligible reduction with the increasing VUF. However, the input power increases with increasing VUF.

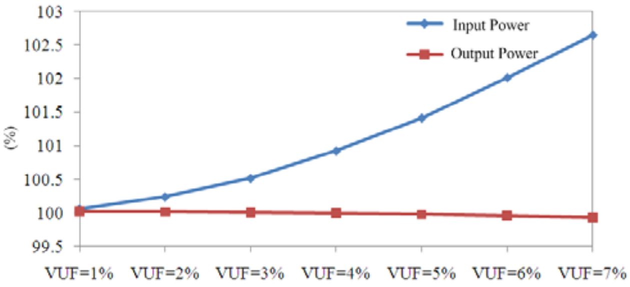

Fig. 8. Input and output powers under unbalance conditions with the positive-sequence voltage

Figure 9 shows that the stator and rotor copper losses increase with increasing VUF so that, increment of the rotor copper loss is more than increase of the stator copper loss. The reason is that the rotor equivalent circuit is more sensitive to the slip [16].

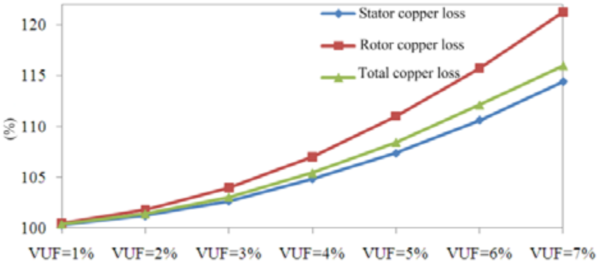

Fig. 9. Copper losses under unbalance conditions with the same positive-sequence voltage

According to Figure 10, variation of the core loss in voltage unbalance condition with the same positive-sequence voltage is negligible. Finally, regular reduction of efficiency with increasing VUF can be seen in Figure 11.

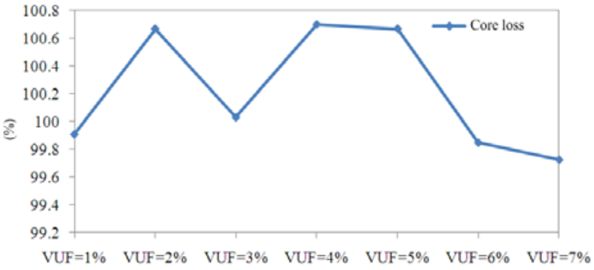

Fig. 10. Core loss under unbalance conditions with the same positive-sequence voltage

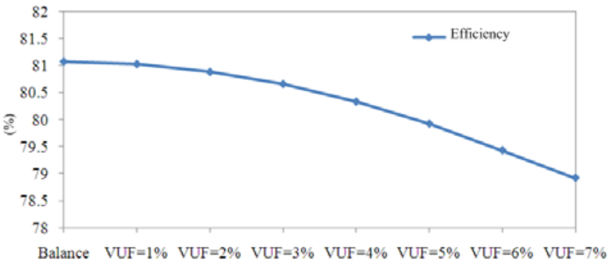

Fig. 11. Efficiency under balance condition and unbalance conditions with the same positive-sequence voltage

6. EXPRIMENTAL TEST

In order to investigate the accuracy of the FEM analysis model and because of lack of access to dynamometer, no-load tests have been done in laboratory and measured no-load currents have been compared with the corresponding simulation values in this section. The test plan and the test setup are shown in the figure 12 and figure 13, respectively. According to these figures, it can be seen that some types of unbalanced voltages are achievable by changing the autotransformer ratio in phase a. The applied voltages on the induction motor are gathered in table 3 and also, the corresponding results for the phase currents obtained from no-load tests and simulations are shown in table 4. Paying attention to these tables, High correlation between results obtained from the two methods can be seen. This comparison can prove the accuracy of employed 2D FEM model of machine at this project.

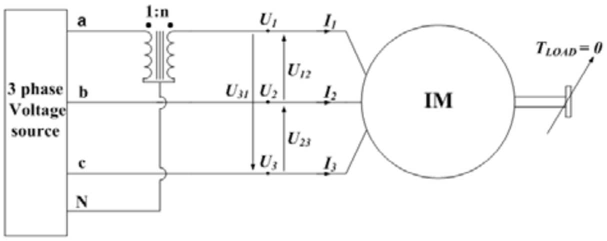

Fig. 12. Test Plan

Fig. 13. Test Setup

Table 3. The applied voltages on the machine.

Supply condition	Approx. balance	1Φ-UV	1Φ-OV
U_1 (V)	$217.1\angle 0$	$210.4\angle 0$	$230.8\angle 0$
U_2 (V)	$218.1\angle -121.06$	$221.4\angle -120.86$	$221.8\angle -120.87$
U_3 (V)	$218.5\angle -120.03$	$221.5\angle 120.70$	$222.6\angle -120.06$

Table 4. The experimental and simulation results for the no-load currents.

	I_1 (A)		I_2 (A)		I_3 (A)	
Method / Supply condition	FEM	Exp.	FEM	Exp.	FEM	Exp.
Approx. balance	3.531	3.5	3.546	3.53	3.361	3.47
1Φ-UV	3.194	3.01	3.706	3.84	3.459	3.35
1Φ-OV	3.891	3.81	3.737	3.44	4.165	3.97

7. CONCLUSION

|In this paper, performance of a three-phase squirrel cage induction motor have been simulated and analyzed using Finite Element Method supplied by eight types of unbalanced voltages with the same VUF and seven numbers of unbalanced voltages with the same positive-sequence phase voltage component and following conclusions can be drawn:

The simulated machine has different performances under unbalanced voltages with the same VUF, as the better conditions considering efficiency of the machine are resulted when positive- sequence component value is closed to rated voltage of the machine.

When the simulated machine supplied by unbalanced voltages with the same positive- sequence component, the efficiency of the machine decreases with increasing VUF, regularly.

Output power decreasing is not a certain result of voltage unbalance, however drop of efficiency is always its consequence.

The VUF is not accurate criterion to use for performance analysis of three-phase induction motor under unbalanced voltage supply and further investigation to create more complete definition is Inevitable.

Ignoring the quality of power supply can be due to harmful effects on performance of induction motors and protection methods must be applied to mitigate these effects.

Finite Element Method can be used as a powerful tool for studying performance of the induction motors under voltage unbalance conditions.

8. ACKNOWLEDGMENT

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