

# 1 Three-Phase Induction Motor's Torque under Voltage Unbalance

2 sobhan ghanbari<sup>1</sup>, Dr. Sobhan Ghanbari<sup>2</sup> and Pezhvak Sheikhzadeh-Baboli<sup>3</sup>

3 <sup>1</sup> K. N. Toosi University of Technology

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## 6 Abstract

7 Considering widely use of three-phase induction motors in industry, commercial and residential  
8 applications and the probability that they may exposed to the unbalanced voltages, it is very  
9 important to clarify the effects of voltage unbalance on the performance of them. In this paper,  
10 authors simulated a three phase squirrel cage induction motor under six types of unbalanced  
11 voltages with same VUF combined with under voltage or over voltage in one or more phases  
12 using two-dimensional finite element method. Electromagnetic torque of the mentioned motor  
13 analyzed and effects of voltage unbalance on its average torque and torque ripple investigated  
14 and also, emphasized to detect unbalance condition, torque frequency analysis can be used.

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16 *Index terms*— finite element method, induction motor, torque analysis, unbalanced voltages, VUF, ripples.

## 17 1 Introduction

18 oltage unbalance combined with under-or over voltage is a voltage quality problem. The mentioned phenomenon  
19 can be found in a threephase power system commonly. Different factors cause unbalanced voltage in power  
20 system including unbalanced loads, incomplete transposition of transmission lines, open-Y, open- $\Delta$  transformer  
21 connections, blown fuses on three-phase capacitor banks and etc. The induction motors are widely used in  
22 industrial, commercial and residential applications and most of them are connected directly to electric power  
23 distribution system (PDS). Therefore it is very important to clarify the effect of voltage unbalance on the  
24 performance of IM (Hirotosuka et al., 2006).

25 The unbalanced voltages induces negative sequence current and mentioned current produces a backward  
26 rotating field in addition to the forward rotating field produced by the positive sequence one. The interaction of  
27 these fields produces pulsating electromagnetic torque and ripple in velocity (Alwash and Ikhwan, 1995; ??mith  
28 and Dorrell, 1996) Such condition has severe impacts on the performance of an induction motor.

29 The influence of unbalance on the efficiency (Lee, 1999), increase of losses, and the negative effects on the  
30 insulation life (Gnaciński, 2008), temperature rise, and life reduction (Pillay and Manyage, 2006), derating in  
31 the machine (Anwari and Hiendro, 2010) are some contributions in this area.

## 32 2 II.

## 33 3 Different Definitions of Voltage Unbalance in Standards

34 There are three general definitions for measuring the voltage unbalance in standards. The first definition is LV  
35 UR, given by NEMA, is as follow (NEMA ??G 1, 2003):
$$\left[ \frac{\max(V_{ab}, V_{bc}, V_{ca})}{\text{avg}(V_{ab}, V_{bc}, V_{ca})} - 1 \right] \times 100\%$$

36 
$$\frac{\max(V_{ab}, V_{bc}, V_{ca})}{\text{avg}(V_{ab}, V_{bc}, V_{ca})} - 1 = \times(1)$$

37 In (1)  $V_{ab}$ ,  $V_{bc}$  and  $V_{ca}$  are line-to-line voltages.
$$\frac{\max(V_{ab}, V_{bc}, V_{ca})}{\text{avg}(V_{ab}, V_{bc}, V_{ca})} - 1 = \times(2)$$

38 The second definition for voltage unbalance has been given by the IEEE Std 141 is PVUR as follow:
$$\frac{\max(V_{a}, V_{b}, V_{c})}{\text{avg}(V_{a}, V_{b}, V_{c})} - 1 = \times(3)$$

39 Where  $V_{a}$ ,  $V_{b}$  and  $V_{c}$  are phase voltages.
$$\frac{\max(V_{a}, V_{b}, V_{c})}{\text{avg}(V_{a}, V_{b}, V_{c})} - 1 = \times(4)$$

40 In (3)  $V_{a}$ ,  $V_{b}$  and  $V_{c}$  are phase voltages.

41 And The third definition is Voltage unbalance factor (VUF) has been given by IEC (Lee, 1999; Anwari and  
42 Hiendro, 2010):
$$\frac{\max(V_{a}, V_{b}, V_{c})}{\text{avg}(V_{a}, V_{b}, V_{c})} - 1 = \times(5)$$

44 Where,  $V_1$  and  $V_2$  represent the positive and negative sequence phase voltage components that they can be  
 45 calculated with the application of the Fortescue transformation in the complex plane, as follow:  
 46  $V_a = \frac{1}{3}(V_1 + V_2 + V_0)$   
 47  $V_b = \frac{1}{3}(V_1 + a^2 V_2 + V_0)$   
 48  $V_c = \frac{1}{3}(V_1 + a V_2 + V_0)$   
 49 is the Fortescue operator. The VUF then calculated as in (5).

## 4 III.

### 5 Different Types of Voltage Unbalance

52 For this article, VUF selected to use. But this is significant they are many unbalanced voltages possible with the  
 53 same voltage unbalance factor. In the present work following six different unbalanced cases are considered (Lee,  
 54 1999):

55 (1) Single phase over-voltage unbalance (1?-OV) (2) Two phase over-voltage unbalance (2?-OV) (3) Three  
 56 phase over-voltage unbalance (3?-OV) (4) Single phase under-voltage unbalance (1?-UV) (5) Two phase under-  
 57 voltage unbalance (2?UV) (6) Three phase under-voltage unbalance (3?UV) A wide variety of research has been  
 58 done on modeling of unbalanced condition in study of induction machines. In the unbalanced voltage operating  
 59 condition the torque can be written as follow (Xu and Wang, 2007):  
 60  $T = T_0 + T_2 \sin(2\omega t)$  (7)

61 Where,  $T_0$  is the DC torque and  $T_2$  is the torque component which frequency is twice the supply frequency.  
 62 In a simpler way assuming induction motor as a RL load the torque can be written as:  
 63  $T = \frac{VI}{\omega} \sin(2\omega t)$  (8)

64 In which  $V$  and  $I$  are input voltage and current of each phase respectively. Assuming sinusoidal waveforms for  
 65 voltage and current this equation can be rewritten as follow:  
 66  $T = \frac{VI}{\omega} \cos(2\omega t)$  (9) So,  $T = \frac{VI}{\omega} \cos(4\omega t)$  (10)

67 Based on equation (10) the resulting torque would include a DC term and a term which frequency is twice  
 68 the fundamental frequency of the applied voltage. In order to detect the unbalanced supply voltage this extra  
 69 torque component can be used.

## 6 V.

### 7 Using FEM

70 In this section authors introduced briefly about procedure of induction motor simulation using finite element  
 71 method.

72 a) Analysis Model Table I and Fig. ?? show the technical data of the analyzed motor and also, its meshed  
 73 quarter cross section, respectively. b) Time-Stepping 2D FEM At the present study, time-stepping FEM is used  
 74 for the analysis performance of mentioned induction machine. The dynamic equations of the induction machine  
 75 can be written as follow (Krause, 1986):  
 76  $\frac{d\psi}{dt} = V - Ri$  (11)

77 In (11),  $I$  and  $V$  are current and voltages of the three phase stator windings, respectively.  $\psi$  and  $R$  are the  
 78 matrices of the phase flux linkage and stator winding resistances.

79 The dynamic equation of mechanical system of machine is (Krause, 1986):  
 80  $J \frac{d\omega}{dt} = T - T_L$  (12)

## 8 Theoretical Aspects of the Electromagnetic Torque under Unbalanced Condition

82 In order to realize the variations of the load for simulated motor, a linear load torque with the following equation  
 83 is considered as the load:  
 84  $T_L = T_{rated} \frac{\omega}{\omega_r}$  (13)

85 In (13),  $T_{FL}$  is full load torque,  $\omega_r$ ,  $\omega$  rated are speed and rated speed, respectively.

86 The used voltages (and their positive and negative sequence components) in performance simulation of motor  
 87 under unbalanced voltage condition are listed in Table II. These voltages are selected so that their VUF is similar  
 88 and equal to 6%. Transient solver with step time equal to 0.1 ms is used in simulations. Quarter cross section of  
 89 motor meshed with 9688 triangles. Simulation of each cycle (20ms) using 3GHz core 2do CPU and 2 Giga Byte  
 of DDR2 Ram, consumed 236.3 seconds of time.

## 9 VI.

91 Result and Discussion a) Balanced Condition Fig. 2 shows the electromagnetic torque of the simulated induction  
 92 motor in time domain when supply voltage is balanced. This torque in frequency domain is showed in Fig. ??.  
 93 The frequency analysis has been made using FFT. Ripple in torque waveform in time domain or in other words,  
 94 torque components except DC component in frequency domain are mainly due to teeth slot effect. Skew is applied  
 95 to electrical machines in order to reduce undesirable teeth slot effects such as cogging torques, higher-harmonic  
 96 air-gap fields, torque ripple, vibrations, and noise (De Gersem et Al., 2003). But applied skew will be ignored in  
 97 simulation using two dimensional finite element method therefore it can be expected that calculated ripple due  
 98 to teeth slot effect is higher than corresponding value in the real skewed machine. However, ignoring the skew

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99 has not any significant error in study of the performance of electrical machines and 2D FEM is widely used in  
100 this area

## 101 **10 b) Unbalanced Condition**

102 The electromagnetic torque of the motor under an unbalanced case (2?-OV) has been shown in Fig. ???. Fig. ??  
103 shows the mentioned torque in frequency domain. According to this figures, there is a 100 Hz component Where  
104 T, T LOAD , ?, J and B m are electromagnetic moving torque, load torque, velocity of the rotor, total moment  
105 of inertia of rotor and load, and damping, respectively.  
106 3?

## 107 **11 Conclusions**

108 In this paper, performance of a three phase induction motor under six types of unbalanced voltages with same  
109 VUF has been simulated using 2D FEM and also, studied electromagnetic torque of the motor in this condition.  
110 It is seen that both average torque and torque ripple increase with increasing positive sequence voltage component  
111 for considered types of unbalanced voltages. Even in case of unbalanced voltages combined with over voltage in  
112 one or more phases, average torque exceeded from equal value in balanced case. Authors emphasized to detect  
113 unbalance condition, torque frequency analysis can be used.

## 114 **12 XIII Issue IX Version I**

## 115 **13 ( )**

## 116 **14 Year**

## 117 **15 References Références Referencias**

118 Three-Phase Induction Motor's Torque under Voltage Unbalance with significant value in motor's torque as  
119 expected. Fig. ?? shows DC term and 2nd harmonic order of electromagnetic torque how change when induction  
120 motor supposed balanced and six various types of unbalanced voltages with same VUF equal to 6% as before  
121 mentioned. It can be seen in considered six types of unbalanced voltages, both average torque and 2nd harmonic  
122 order increase with increasing positive sequence voltage component. According to Fig. ??, the unbalanced  
123 voltages does not always lead to reduced average torque of motor, even in case of unbalanced voltages combined  
124 with over voltage in one or more phases, average torque exceeded from equal value in balanced case. But this  
125 increase is not desirable because it would be associated with increased power losses and reduced efficiency (Lee,  
126 1999). Note that when 2nd harmonic order of torque increases, ripple in velocity will increase. In other words,  
127 ripple in velocity increase with increasing positive sequence voltage component, also. The mentioned ripple in  
128 torque and velocity can be used to detect the unbalanced supply voltage for the induction motors that they may  
129 suppose unbalanced voltages. <sup>1 2</sup>

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Figure 1: (

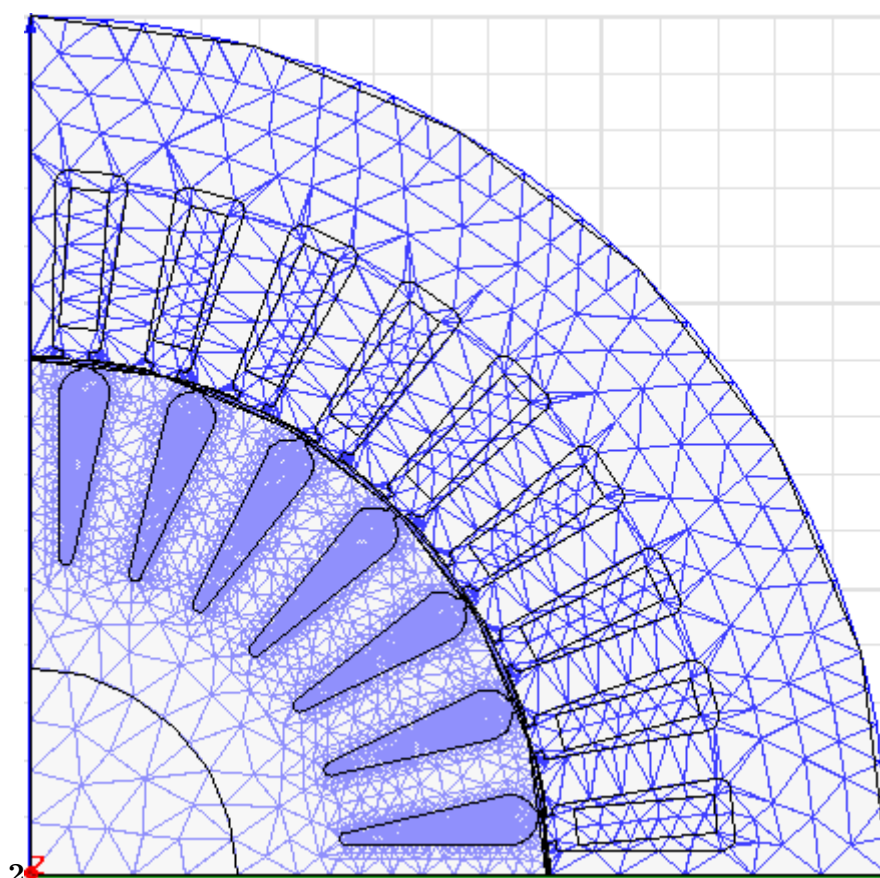
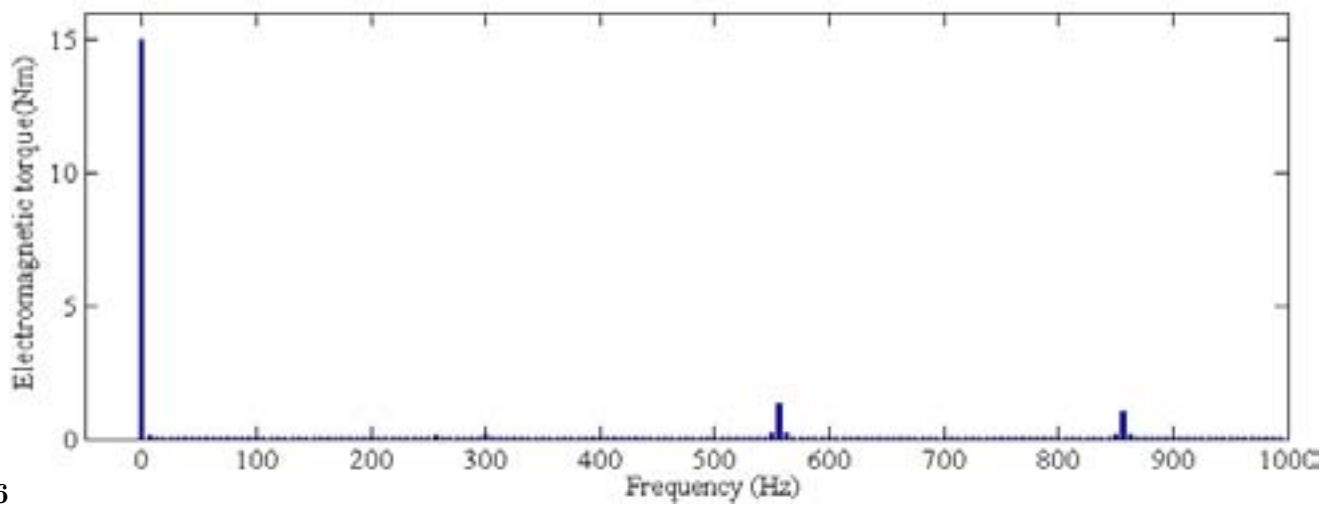


Figure 2: Figure 2 :



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Figure 3: Figure 3 :Figure 4 :Figure 5 :Figure 6 :

I

| Item             | Value | Item                      | Value    |
|------------------|-------|---------------------------|----------|
| Input Voltage(V) | 380   | Stator outer diameter(mm) | 150      |
| Output Power(kW) | 2.2   | Rotor outer diameter(mm)  | 90       |
| Frequency (Hz)   | 50    | Core length(mm)           | 90       |
| Rated current(A) | 5.3   | Air gap(mm)               | 0.3      |
| Pole number      | 4     | Stator lamination type    | M530-50A |
| Rated speed(rpm) | 1410  | Rotor lamination type     | M530-50A |
| Connection       | Y     | No. turns in stator coil  |          |

[Note: 44 Figure 1 : Mesh description of the model XIII Issue IX Version I 2 ( ) Year Three-Phase Induction Motor's Torque under Voltage Unbalance IV.]

Figure 4: Table I :

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Figure 5:



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