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Simulation and Mathematical Analysis of Three Phase Induction Motor Operating Under Unbalanced Voltages

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ABSTRACT

This paper investigates the performance of three phase induction motor having different unbalance voltage conditions with the different voltage unbalance factor (VUF). Under three different voltages unbalance conditions the performance of three phase induction motor is analyzed with mathematical calculations and MATLAB Simulink. The efficiency, power factor, and temperature rise of the machine has been calculated. Transient behavior of torque is also analyzed through Simulink Model. According to calculations and analysis the importance of positive sequence voltage on motor's performance has been pointed out. Comparison of efficiency and power factor is analyzed with positive sequence voltage under different VUF.

Keywords: *Three-phase Induction Motor, Unbalanced Voltages, VUF, Efficiency, Power factor, Positive sequence voltage.*

1. INTRODUCTION

A three phase induction motors is the most vital part of an assembly line in industry. Due to their various inconstant properties like no additional device required to start, simple in design, toughened composition, simple maintenance, cheap and precise accuracy it is commonly employed in electrical system. Its role in industry improved after the development of adjustable speed drives and its integration in energy conversion. There are many types of power quality disturbances occur in electrical system like voltage unbalance, harmonics, and sag etc. Because of all these disturbances study of voltage unbalance is more important in induction motor because of its extensive use. Abnormal supply conditions can be Over Voltage, Under Voltage, and Single Phasing and distributed levels of THD between the phases. Other factors also lead to unbalance voltage in power system including unbalanced loads, incomplete transposition of transmission lines, unsymmetrical transformer connections like open-Y, open delta transformer connections, blown fuses on three phase capacitor banks, etc. Most of the faults in induction motor are displayed in Figure 1.

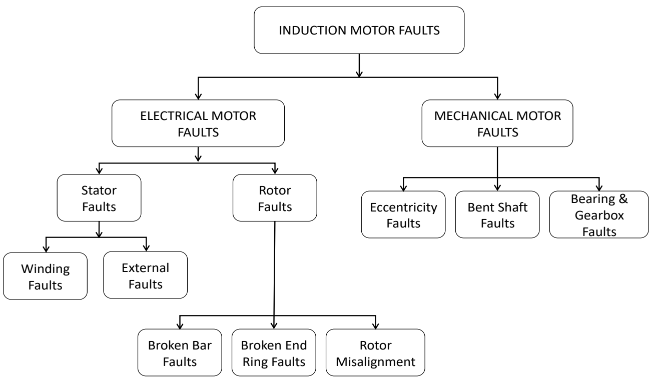

Figure 1: Types of faults found in induction motor

Voltage unbalance is defined as the variation of voltage magnitude in three phases or the deviation in angle, i.e., they are not 120° apart or both the situations can occur. The proposed paper introduces the different causes of abnormal voltage supply conditions in system & it's bad results on IM performance. The set-up of a squirrel cage IM has been carried out on established MATLAB Simulink software. The results are calculated for different feasible samples of abnormal supply condition.

1.1 Interpretations of Voltage Unbalance:

The two main interpretations useful for calculation of abnormal voltage are discussed below.

The *first interpretation* is defined by the NEMA and Generator standards (NEMA MGI), is as follows:

Percentage Voltage Unbalance (PVU)

$$= \frac{\text{Maximum voltage deviation from average voltage}}{\text{Average voltage}} * 100$$

The *second interpretation* for voltage unbalance has been given by the International Technical Commission, is as follows:

Voltage Unbalance factor (VUF) (in %) = (V_2/V_1) *100

where V_1 is the magnitude of positive sequence voltages and V_2 is the magnitude of negative sequence voltages.

Both the two general indexes Percentage Voltage Unbalance and Voltage Unbalance factor are positive real numbers used to evaluate the abnormal voltage values that affects the performance of induction motors.

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The Induction - Machine Model

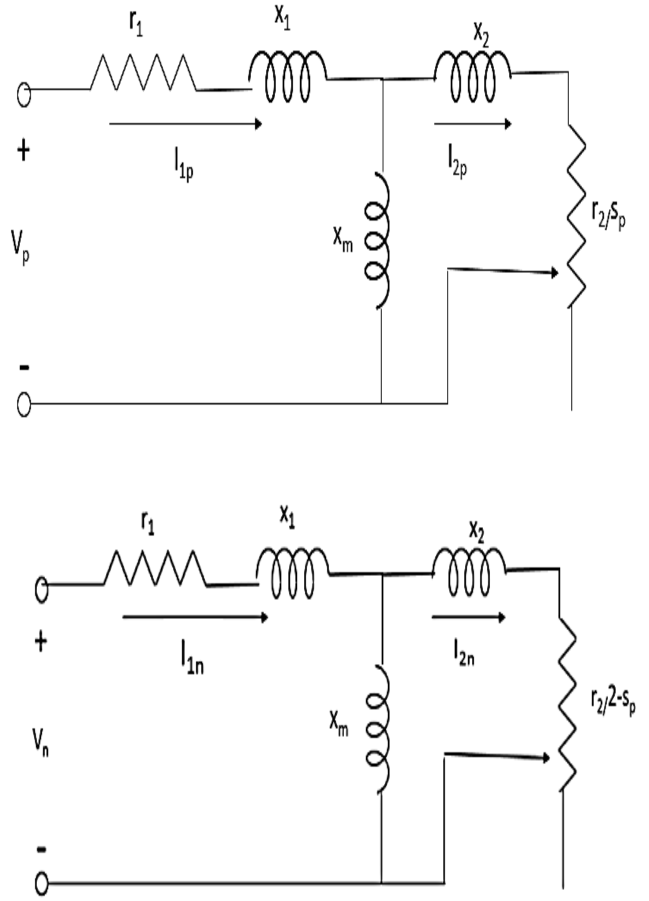

Figure 2: The sequence line-to neutral equivalent circuit of three phase induction machine

This circuit shown in Figure 2 is applicable for both the networks i.e., for positive sequence as well as for negative sequence networks.

The per phase values are defined as below.

V_p-positive sequence voltage
V_n-negative sequence voltage
R_s-stator resistance
X_s-stator reactance
R_r-rotor resistance referred to stator
X_r-rotor reactance referred to stator
X_m-magnetizing reactance
Z_p-positive- sequence impedance of motor
Z_n -negative- sequence impedance of motor
I_{ps} -stator positive- sequence current phasor
I_{pr} -rotor positive- sequence current phasor
I_{ns} -stator negative- sequence current phasor
I_{nr} -rotor negative- sequence current phasor
s -operating slip of motor.

When the system is balanced, i.e., all the three voltages applied to induction machine are same.

$$V_{ab} = 127\angle 0^\circ$$
$$V_{bc} = 127\angle 240^\circ$$
$$V_{ca} = 127\angle 120^\circ$$

By calculating from the below formulas

$$V_p = \frac{V_{ab} + aV_{bc} + a^2V_{ca}}{3} \quad (1)$$

$$V_n = \frac{V_{ab} + a^2V_{bc} + aV_{ca}}{3} \quad (2)$$

$$V_a = 127\left[\cos(0) + j\sin(0)\right]$$
$$= 127V$$

$$aV_b = 127\left[\cos(240) + j\sin(240)\right]$$
$$= 127V$$

$$a^2V_c = 127.0\left[\cos(120) + j\sin(120)\right]$$
$$= 127V$$

By putting the values in equation (1) V_p comes out to be 127 Volts and V_n is 0 as there is no unbalance condition.

$$Slip(s) = \left(\frac{\omega_{ms} - \omega_m}{\omega_{ms}}\right) \quad (3)$$

$$= \frac{1500 - 1440}{1500} = 0.04$$

$$Z_s = \frac{R_s + jX_s + (jX_m) + \left(\frac{R_r}{s} + jX_r\right)}{R_r / s + j\left(X_m + X_r\right)}$$
(4)

$$I_{ps} = \frac{V_p}{Z_1} \quad (5)$$

$$= \frac{127\angle 0^\circ}{17.53\angle -150.49^\circ}$$
$$= -6.29 + j3.56$$

$$I_{pr} = I_{ps} * \frac{jX_m}{R_r / s + j\left(X_m + X_r\right)} \quad (6)$$

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$$I_{pr} = (-6.29 + j3.56) * \frac{j38.9872}{18.55 + j39.94}$$
$$= 6.39\angle -4.59°$$

I_{ns}=0, V_n=0 and I_{nr}=0 as there is no unbalance in voltages

$$P_p = 3I_{pr}^{2}\left(\frac{1-s}{s}\right)R_r \quad (7)$$

$$P_p = 3\left[\left(6.39(\cos(-4.59 + j\sin(-4.59)\right]^2 * \frac{0.96}{0.04} * 0.7822$$
$$= 2179.2W$$

P_n=0

$P_{out}=P_p+P_n$ (8)

=2179.2W

Input Active Power is

$$P_{in} = \text{Re}\left[3\left(V_p I_{ps}^* + V_n I_{ns}^*\right)\right] \quad (9)$$

$$P_{in} = \text{Re}\left[3\left(127(-6.29 - j3.56\right)\right]$$
$$= \text{Re}\left[2396.49 - j1356.36\right]$$

2396.49W

Input Reactive power is

$$Q_{in} = \text{Im}\,g\left[3\left(V_p I_{ps}^* + V_n I_{ns}^*\right)\right] \quad (10)$$

1356.36W

$$pf = \cos\left[\tan^{-1}\left(\frac{Q_{in}}{P_{in}}\right)\right] \quad (11)$$

Efficiency of motor is defined as

$$\eta = \frac{P_{out}}{P_{in}} * 100 \quad (12)$$

=90.9%

For set of 3-Ø under voltages unbalanced voltages, $V_a V_b, V_c$, the positive and negative sequence voltages V_p and V_n are given by

$$V_a = 110\angle 0°, V_b = 112.7\angle 240°, V_c = 125\angle 120°$$

$$V_p = \frac{V_a + aV_b + a^2V_c}{3}$$

$$V_n = \frac{V_a + a^2V_b + aV_c}{3}$$

Where a= -0.5+j0.866 anda^2= -0.5-j0.866

$$V_a = 110\left[\cos(0) + j\sin(0)\right]$$
$$= 110V$$
$$aV_b = 112.7.0\left[\cos(240) + j\sin(240)\right]$$
$$= 112.605V$$
$$a^2V_c = 125.0\left[\cos(120) + j\sin(120)\right]$$
$$= 125V$$

By putting the values in equation (1) V_p comes out to be 115.86 Volts

For the value of V_n

$$V_a = 110V$$

$$a^2V_b = -56.26 + j97.5$$

$$aV_c = -62.49 - j108.25$$

By putting the values in equation (2) V_n comes out to be 4.66 Volts with an angle 51.43

$$\%VoltageUnbalance = \left(\frac{V_n}{V_p}\right) * 100$$

From the above definition, value of unbalance (VUF) comes out to be 4%.

Analysis of equivalent circuit gives

$$Z_s = \frac{R_s + jX_s + (jX_m) + \left(\frac{R_r}{s} + jX_r\right)}{R_r / s + j\left(X_m + X_r\right)}$$

$$Z_1 = (0.7384 + j0.9566) + \frac{j38.9872(18.55 + j0.9566)}{18.55 + j39.94}$$
$$= \frac{772.64\angle -85.41}{44.03\angle 65.08}$$
$$= 17.54\angle -150.49°$$

Positive sequence currents are

$$I_{ps} = V_p / Z_s$$

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$$I_{ps} = \frac{V_p}{Z_1} = \frac{115.86\angle 0°}{17.53\angle -150.86°}$$
$$= -5.76 + j3.211$$

$$I_{pr} = I_{ps} * \frac{jX_m}{R_r / s + j\left(X_m + X_r\right)}$$

$$I_{pr} = \left(-5.76 + j3.211\right) * \frac{j38.9872}{18.55 + j39.94}$$
$$= 5.83\angle -4.28°$$

For negative sequence impedance slip s is 2-s

$$Z_n = \frac{R_s + jX_s + (jX_m) + \left(\frac{R_r}{(2-s)} + jX_r\right)}{R_r / (2-s) + j\left(X_m + X_r\right)} \quad (13)$$

$$Z_n = 0.7384 + j0.9566 + \frac{j38.9872\left(\frac{0.7422}{1.96} + j0.9566\right)}{\frac{0.7422}{1.96} + j\left(38.9872 + 0.9566\right)}$$
$$= 1.51\angle -120.12°$$

Negative sequence currents are

$$I_{nr} = I_{ps} * \frac{jX_m}{R_r / (2-s) + j\left(X_m + X_r\right)} \quad (14)$$

$$I_{nr} = \left(-2.08 + j0.31\right)\left[\frac{j38.9872}{0.378 + j39.94}\right]$$
$$= 2.94 - j0.418$$

$$I_{ns} = \frac{V_n}{Z_n}$$
$$= \frac{4.66\angle 51.43°}{1.51\angle -120.12°}$$
$$= 3.08\angle 171.55° \quad (15)$$

In case core losses and mechanical losses are negligible, output power due to positive and negative sequence may be obtained as [6]

$$P_p = 3I_{pr}^2\left(\frac{1-s}{s}\right)R_r$$

$$P_p = 3I_{pr}^2 * \frac{0.96}{0.04} * 0.7422$$
$$= 1786.37W$$

$$P_n = 3I_{nr}^2\left(\frac{s-1}{2-s}\right)R_r \quad (16)$$

$$P_n = 3(I_{nr}^2) * \frac{0.96}{0.04} * 0.7422$$
$$= 9.57W$$

Whereas net output is

$$P_{out} = P_p + P_n$$

$$P_{out} = 1795.94W$$

Input Active Power is

$$P_{in} = \mathrm{Re}\left[3\left(V_p I_{ps}* + V_n I_{ns}*\right)\right]$$

Input Reactive power is

$$Q_{in} = \mathrm{Im}\,g\left[3\left(V_p I_{ps}* + V_n I_{ns}*\right)\right]$$

Efficiency of motor is defined as

$$\eta = \frac{P_{out}}{P_{in}} * 100$$

$$\eta = 88.7\%$$

2. IMPACT OF VOLTAGE UNBALANCE ON MACHINES

Due to unequal voltages, there will be imbalance of currents which will increase the copper losses. Additional loss of power will occur in the electrical system if supply is unbalanced. Voltage unbalance is directly proportional to power dissipation that results in extra power bills. The resistance for positive sequence current is much larger than negative sequence current, context little disturbance in voltage waveform give rise to addition in current and similarly addition in losses, consequently, motor windings will heat up and there will be breakdown of winding insulation. The life of winding insulation is reduced due to more winding temperature and might finally the motor will fail. The negative-sequence voltage contributed by unequal supply voltages give rise to reverse torque and direct to motor oscillations and noise. Acute unbalance in voltage may even cause the complete damage of motor [3]. If motor is connected to unbalanced supply, there is not only positive sequence currents are produced but also negative sequence currents are present there. Losses will be more due to the presence of negative sequence currents; the efficiency will also decrease as value of unbalance increases. A VUF of 5% in motors give rise to reduction in capacity of motor by approx. 25 percent. With increase of VUF, power factor may increase or decreases. Power factor increases in under

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voltage case and decreases in the overvoltage case [2]. Very less effect has been noted on power factor due to reverse sequence voltage.

As supply system becomes unbalanced, uncharacteristic triplen harmonics are produced. Due to flow of excessive ac line currents on some phases give rise to additional heating effect on diodes. Due to the increment in undesirable harmonic currents also results in harmonic obstacles in the voltage supply.

3. SIMULATION AND RESULTS

The approached model is simulated in MATLAB to check the effects of unbalanced supply conditions. Table 1. shows the values of voltages and angles taken for each of the three-phase supply voltages under different seven unbalanced conditions.

- Balanced condition
- 3−ØUnder voltage
- 2−ØUnder voltage (UV)
- 1−ØUnder voltage (UV)

Table 1: Various unbalance conditions and comparison between different parameters

Condition	V_a	V_b	V_c	VUF (%)
Balanced	127.0∟0°	127.0∟240°	127∟120°	0
3-Ø-UV	110∟0°	112.7∟240°	125∟120°	4
2-Ø-UV	111.8∟0°	114.3∟240°	127.0∟120°	4
1-Ø-UV	112.4∟0°	127∟240°	127∟120°	4
3-Ø-UV	103.2∟0°	107.2∟240°	125∟120°	6
2-Ø-UV	105∟0°	108.6∟240°	127∟120°	6
1-Ø-UV	105.4∟0°	127.0∟240°	127∟120°	6

Condition	Positive voltage (V_p)	Negative Voltage (V_n)	Efficiency (%)	Power Factor (pf)
Balanced	127.0∟0°	0	90.9	0.871
3-Ø-UV	115.86∟0°	4.66∟51.43°	88.7	0.892
2-Ø-UV	117.69∟0°	4.69∟51.22°	89.14	0.885
1-Ø-UV	**122.13∟0°**	4.86∟0°	**89.16**	**0.877**
3-Ø-UV	111.79∟0°	6.69∟50.14°	87	0.894
2-Ø-UV	113.5∟0°	6.803∟51.34°	88.67	0.887
1-Ø-UV	**119.81∟0°**	7.19∟0°	**88.9**	**0.879**

Calculations has been done to study that the how the various unbalance conditions effect the three-phase induction motor when the voltage unbalance factor is same. In addition to different supply conditions and their sequence components, results obtained for efficiency and power factor of three phases IM. Table 1 shows that when the voltage unbalance factor is same there is 6.27V change in positive sequence voltage for 4% VUF and 8.02 V for 6% VUF and change in negative sequence voltage components is 0.2 V for 4% VUF and 0.5V for 6% VUF. Having the unchanged value of VUF, we are capable to understand the level of unbalanced voltage from the value of positive sequence component of voltage. Positive sequence component of voltage is very important to consider as it has a major role to understand the concept of voltage unbalance [7]. From the above table we can found that positive sequence voltage has a direct relation with efficiency and inverse relation with power factor. It is also noted that power factor of the motor is higher in unbalanced voltage condition as compared to balanced voltage condition.

3.1 Temperature Rise of the Machine:

NEMA states "Unbalanced currents in stator windings are produced, when the unbalanced voltages are applied to three phase induction motor. Even if there is small variation in voltage it results in large change in percentage of current unbalance [1]. Due to these current unbalances the change in temperature of the motor will be highly risen as compared to the motor operating with same particular load under balanced voltage conditions. As we know that

$$\text{Temperature rise}(\%) = 2*(\text{voltage imbalance})^2*100 \quad (3.1)$$

From above formulae we can calculate the percentage increment in temperature rise.

Table 2: Calculation of temperature rise with different percentage of Voltage Unbalance

Percentage Voltage Unbalance	Percentage temp rise
1	2
2	8
3	18
4	32
5	50

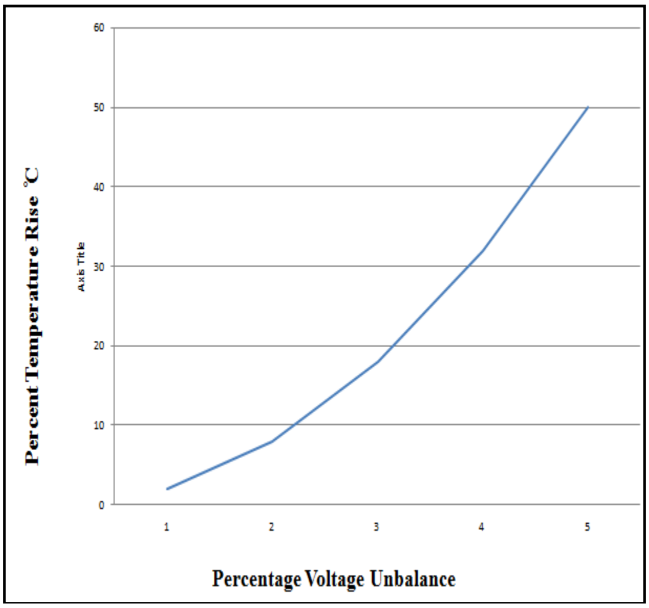

Figure 3. Calculation of temperature rise w.r.t Percentage Voltage Unbalance

Figure 3 demonstrates that there is exponential increase in winding temperature when the percentage of voltage unbalance increases. If the unbalance in voltage is more than 2% it would not be acceptable because the temperature rise of the motor will shoot up beyond the limits of motor specifications. Due to this shoot up in temperature, machine's life got worsened. NEMA states the limit of unbalanced voltages should not be greater than 5%. Various

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studies reveals that with every 10° increase in temperature average life of insulation becomes almost half[5].

3.2 Impact of Unbalanced Supply Conditions on Electromagnetic Torque with VUF 4%

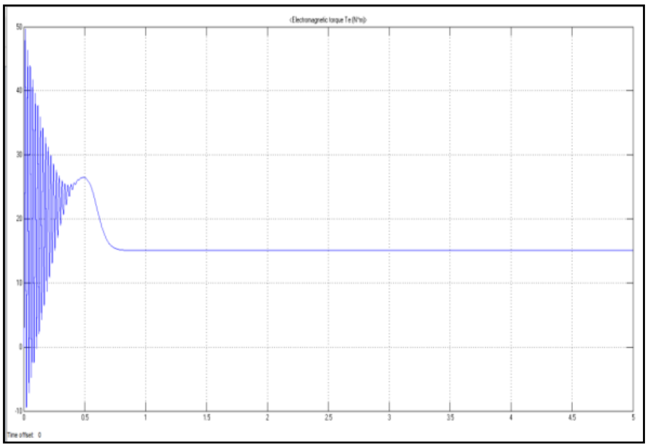

Figure 4(a) Electromagnetic torque for balanced voltage

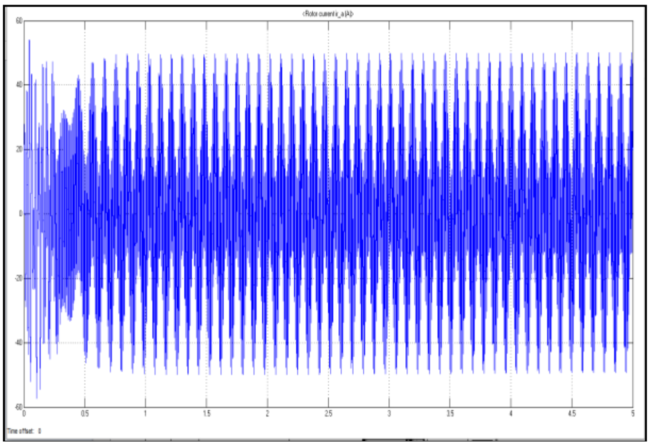

Figure 4(b)Electromagnetic torque for 3phase UV

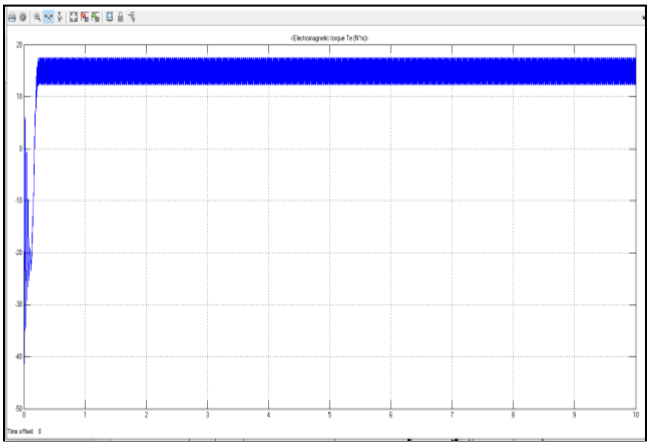

Figure 4(c)Torque for two phase undervoltage

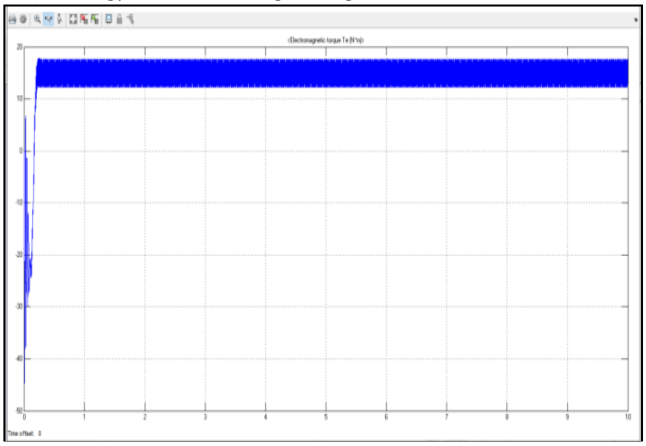

Figure 4(d) Electromagnetic Torque for single phase under voltage

Figure 4(a), (b), (c) and (d) shows the results for the electromagnetic torque considering different unbalanced conditions stated above. After an initial increased fluctuation, the torque comes to settling value little above than 15Nm when the voltage is balanced [8]. But, at steady state the oscillatory torque is obtained rather than constant value under balanced voltage condition. When voltage applied is not balanced, torque is not steady, but it remains oscillatory at around 15 Nm.

CONCLUSION

From the above analysis we can conclude that the value of positive sequence component and percentage of unbalance is necessary to understand the features of power system. Reduction in efficiency when supplied by unbalanced voltages will lead to higher electricity charges. Consequently, the total load will be raised and spinning reserve of the total generators will be lowered. Negative sequence currents are introduced due to unbalance supply conditions as compared to balanced conditions. These unbalance currents and oscillatory torques leads to more vibrations and noise which will damage the motor. As the unbalance in voltage increases consequently temperature of the motor will increase which will permanently damage the motor. To avoid this situation motor should be derated [4]. Various PWM techniques should be applied to decrease the torque pulsations of an Induction Motor [9].

REFERENCES

[1] Cummings et al., "Protection of induction motors against unbalanced voltage operation," IEEE Trans. Ind.Applicat.,vol1A-21,pp778-792,May/June 1985.

[2] A. Wallace, A.R von Jouanne, E.J. Wiedenbrug, and P.S Andrews, "The measured effects of under-voltage, over-voltage and unbalanced voltages on the efficiency and power factor of induction motors over wide range of load," in PEVD Conf.Proc.,1997.

[3] C.Y Lee, "Effect of unbalanced voltages on the operation performance of a three phase induction

ITEE Journal
Information Technology & Electrical Engineering
ISSN: - 2306-708X

motor," IEEE Trans Energy Conversion, vol14, pp.202-208, June 1999.

[4] Pillay P, Hofmann P, ManyageM, " Derating of induction motors operating with a Combination of unbalanced voltages and over or under voltages.," IEEE Transactions on Energy Conversion. 17(4), pp.485-491,2002.

[5] Etamaly, A.M, "A modified harmonics reduction technique for a three phase controlledconverter," IEEE Transaction on Industrial Electronics, 55(3) pp.1190-1197,2008.

[6] Ansari AA, Deshpande DM,"Mathematical Model of Asynchronous Machine inMatlab/ Simulink", International Journal of Engineering Science and Technology, 1260-1267,2010.

[7] Anwari M, Hiendro A., "New unbalance factor for estimating performance of a three-phase induction motor with under-and overvoltage unbalance."IEEE Transactions on Energy Conversion, 25(3), pp.619-625,2010.

[8] Donolo P, Bossio G, De Angelo C, Garcia G, DonoloM. "Voltage unbalance and harmonic distortion effects on induction motor power, torque and vibrations.", Electric PowerSystems Research. 140. pp. 866-873, 2016.

[9] D.Piazza, M.C and Pucci, M, "Techniques for efficiency improvement in PWMmotor drives, "Electric Power System Research 136,pp.270-280,2016.

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