iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 7 **Issue:** VII **Month of publication:** July 2019

DOI:

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.177
Volume 7 Issue VII, July 2019- Available at www.ijraset.com

Voltage Unbalance and Its Impact on the Performance of Three Phase Induction Motor: A Review

Sunil Singh[1], Ajay Srivastava[2]
[1]Associate Professor, [2]Professor, Department of Electrical Engineering, College of Technology, GB Pant University of Ag & Tech Pantnagar, India

Abstract: Voltages are well balanced at the generator and the transmission levels but are not balanced at the utilisation or distribution levels due to unequal system impedances and unequal distribution of single-phase loads. An excessive level of voltage unbalance can poses serious problems to the induction motors connected to unbalanced voltage supply. Study of power quality impact of induction motor is of paramount importance as induction motors consume significant amount of energy of the total power generation. A comprehensive review of voltage unbalance factor by NEMA, IEEE, IEC and other researchers has been summarised. The method used for steady state analysis has been explained precisely. Definitions of voltage unbalance factor are analysed and compared given by different sources. Classification of unbalance is also summarised. Voltage unbalance impacts on the motor and mitigation techniques are also presented. Recommendation regarding precise derating factor has been given.
Keywords: Voltage unbalance, voltage unbalance factor, derating, Three Phase Induction Motors, complex voltage unbalance factor, mitigation

I. 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. Voltage unbalance, harmonics and sag are the most occurring and vulnerable power quality disturbances in India. Voltage unbalance is the long term power quality problem which exists in the power system permanently.

Excess level of voltage unbalance is very harmful to the various electrical devices especially induction motors. 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. Voltage unbalance is a common phenomenon which is observed almost everywhere in a three phase system across the world.

Although three phase voltage supply is quite balanced in both magnitude and displacement 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 can not be removed permanently.

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. Three phase induction motors are designed and manufactured such that all three phase windings are carefully balanced with respect to number of turns, placement of winding and resistance to operate with balanced supply.

Voltage unbalance can pose serious problems to the induction motors. Excess power loss, torque reduction, and torque vibrations are the major consequences of the unbalance voltage. Excess power loss results excess temperature rise which leads to shorten the life of induction motor. Torque vibration can also damage the rotor bearings and shaft. The influence of unbalanced voltages on the performance of induction motor was first studied by Reed and Koppman (1936) further Williams (1954) proved that an induction motor operation under unbalanced voltage would lead to efficiency reduction. Gafford (1959) pointed out that unbalanced voltage can cause extra temperature rise in an induction motor, which is likely to shorten the machine's life. Berndt *et al.* (1963) presented a method for derating of an induction motor operating with unbalance supply. R. F. Woll (1975) provided a simple and brief method in order to study the impact of unbalanced voltages on the losses and its negative effects on the insulating material of induction motor. Very few paper is reported the literature review on this topic. This paper has been divided in three parts, first parts is dedicated to understanding the term voltage unbalance and voltage unbalance factors given by different sources. In the second part, methods of study of voltage unbalance have been presented and lastly impacts of voltage unbalance on the performance of induction motor have been reviewed.

II. VOLTAGE UNBALANCE

In a balanced sinusoidal supply system, the three phases to neutral 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 degrees 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. 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 Electrotechnical 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 by[21]

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

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

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

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 (Fig 5); above 5 % unbalance motor operation is not recommended.

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

$$VUF\ or\ PVUR = \frac{maximum\ voltage\ deviation\ from\ average\ phase\ voltage\ magnitude}{average\ phase\ voltage\ magnitude} \times 100$$

$$= \frac{Max\left[\left|V_{a}-V_{avg}\right|,\left|V_{b}-V_{avg}\right|,\left|V_{c}-V_{avg}\right|\right]}{V_{avg}} \times 100\ \%$$

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.

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. The CVUF is a complex quantity having the magnitude and angle. Appropriately, complex voltage unbalance factor (CVUF) can be written as

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

Whereas $\mathbf{V_1}$ is positive sequence voltage phasor and $\mathbf{V_2}$ is negative sequence voltage phasor.

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) [11]. 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. 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) [22], 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.

III. STEADY STATE PERFORMANCE ANALYSIS OF IMPACT OF UNBALANCE ON INDUCTION MOTOR:

Unbalance supply voltage induces negative-sequence current which produces a backward rotating field in addition to the forward rotating field produced by the positive sequence voltage. The interaction of these fields produces pulsating electromagnetic torque and vibration disturbances resulting in increasing losses, stresses, 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, vibrations, acoustic noise, shortening of the life, and decreased rotating torque. Steady state analysis of an induction motor operating with unbalanced voltage supply is possible using symmetrical component approach. This requires the development of positive and negative sequence approximate equivalent circuit representation as shown in Fig 1. and Fig 2.Under normal operating conditions, core loss is constant. In view of this fact, core loss resistance R_c, representing the motor core loss, can be omitted from the equivalent circuit. But, for determining the shaft power or shaft torque, the constant core loss must be taken into consideration, along with the friction, windage and stray load losses.

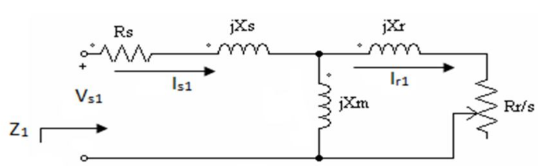


Fig 1 : Approximate positive sequence equivalent circuit

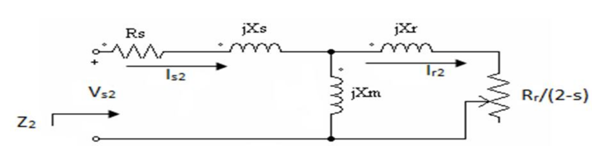


Fig 2 : Approximate negative sequence equivalent circuit

Let V_a, V_b, and V_c be the phase voltages of a motor. The corresponding zero- , positive and negative-sequence components (V_{a0}, V_{a1}, V_{a2}) of the voltages are given by:

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

Where $a = 1\angle 120^0$

Analysis of equivalent circuit gives;

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.177
Volume 7 Issue VII, July 2019- Available at www.ijraset.com

$$Z_i = R_s + jX_s + \frac{(jX_m)\left(\frac{R_r}{s_i} + jX_r\right)}{\frac{R_r}{s_i} + j(X_m + X_r)}$$

for positive-sequence impedance, $i = 1, (s_1 = s)$
for negative-sequence impedance, $i = 2, (s_2 = 2 - s)$.
The positive– and negative-sequence stator and rotor are;

$$I_{s1} = \frac{V_{s1}}{Z_1}, \quad I_{r1} = I_{s1} \times \frac{(jX_m)}{\frac{R_r}{s} + j(X_m + X_r)}, \quad I_{s2} = \frac{V_{s2}}{Z_2}$$

$$I_{r2} = I_{s2} \times \frac{(jX_m)}{\frac{R_r}{(2-s)} + j(X_m + X_r)}$$

Assuming that the machine in delta or ungrounded wye connected;

$$I_a = I_{s1} + I_{s2}$$
$$I_b = a^2 I_{s1} + a I_{s2}$$
$$I_c = a I_{s1} + a^2 I_{s2}$$

The motor input power and power factor can be expressed in terms of symmetrical components of the voltage and currents as:

Input active power $(P_{in}) = Re[3(V_{s1}.I_{s1}^{*} + V_{s2}.I_{s2}^{*})]$

Input reactive power $(Q_{in}) = Im[3(V_{s1}.I_{s1}^{*} + V_{s2}.I_{s2}^{*})]$

Input power factor $(p.f.) = cos\left[tan^{-1}\left(\frac{Q_{in}}{P_{in}}\right)\right]$

(*) indicates the conjugate value.

In case rotor core loss and mechanical losses are negligible, output power due to positive- and negative-sequence component may be defined as;

$$P_{m1} = 3I_{r1}^{2}\left(\frac{1-s}{s}\right) R_r \quad (3.24)$$

$$P_{m2} = 3I_{r2}^{2}\left(\frac{s-1}{2-s}\right) R_r \quad (3.25)$$

Whereas net output is; $P_m = P_{m1} + P_{m2}$

Where, P_{m2} is negative at normal slip because rotor rotates in opposite direction of the magnetic field produced by negative-sequence component. Torques produced by positive and negative-sequence component is;

$$T_{e1} = \frac{P_{m1}}{\omega_r} = \frac{P_{m1}}{\omega_s(1-s)} = \frac{3I_{r1}^{2} R_r}{s\omega_s} \quad (3.26)$$

$$T_{e2} = \frac{P_{m2}}{\omega_r} = \frac{P_{m2}}{\omega_s(1-s)} = \frac{3I_{r2}^{2} R_r}{(2-s)\omega_s} \quad (3.27)$$

Where, ω_m is angular speed of the rotor and ω_s is Synchronous speed. Therefore motor net output torque is given as:

$$T_e = T_{e1} - T_{e2} = \frac{3R_r}{\omega_s}\left(\frac{I_{r1}^{2}}{s} - \frac{3I_{r2}^{2}}{2-s}\right) \quad (3.28)$$

Efficiency of the motor is defined as: $\eta = \frac{P_{out}}{P_{in}} \times 100\%$

IV. IMPACT OF VOLTAGE UNBALANCE ON INDUCTION MOTOR:

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 makes difficult problems in induction motor applications, such as a heating problem, increased losses, and vibrations, acoustic noises, shortening of the life, and decreased rotating torque. So this section can be classified as follows:

A. Impact on Losses, Efficiency, Heat Generation and Life Expectancy

As the voltage unbalance increases, the losses increases identically, this will result to increase in the temperature. Temperature increment curve is somewhat above the motor loss curve because; heated resistance has more value than the less heated resistance

(Fig 3). Due to excess loss, the efficiency will decreases as value of unbalance increases [2], [11]. If the positive sequence voltage is kept constant, efficiency diereses on increase value of VUF [11]. Approximate formula to find temperature rise based upon experiments has been given as:

Percentage increase in temperature rise will be two times the square of the VUF. It has been well established fact that every increase of 10 degree will result half of the insulation life [21].

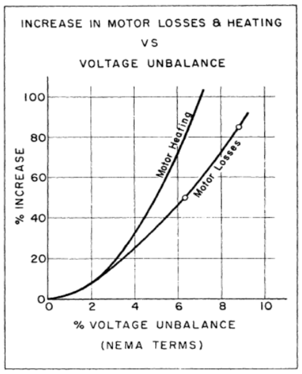


Fig 3:Increament of loss and heat

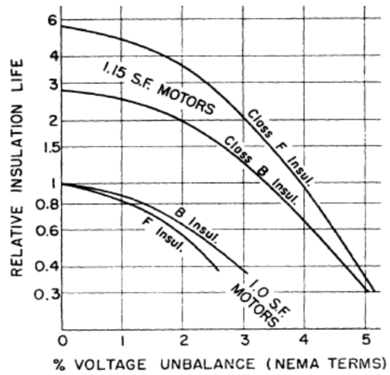


Fig 4: Life expectancy

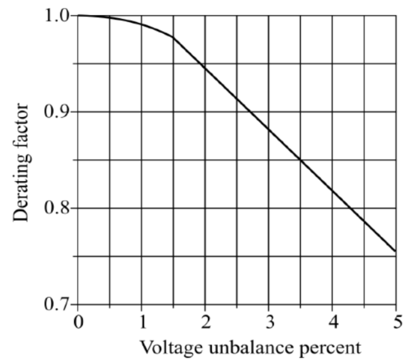


Fig 5: NEEMA derating curve

B. Impacts on Torque, Vibrations and Noise:

The value of steady state torque is reduced due to negative torque produced by negative sequence current. Unbalanced supply creates the rotating field elliptical instead of circular [3], magnitude of torque pulsation become increased that may result mechanical damage of bearings. Due to torque pulsation, vibrations and noise is increased which is proportional to the voltage unbalance factor.

C. Impact on Power Factor

With increment of VUF, power factor may increases or decreases. The power factor mainly depends upon the value of positive sequence voltage. Power factor increases at UVU case and decreases in the OVU case. Negative sequence voltage has little impact on the power factor [6].

V. MITIGATION TECHNIQUES OF UNBALANCED VOLTAGE

Establishment of zero voltage unbalance on a distribution system is clearly impossible due to uneven distribution of single-phase loads on the three phases. However, utility system level and plant level mitigation techniques can be used to improve the voltage unbalance and its effects.

A. Redistribution of single-phase loads equally to all phases.
B. Reduction of the system unbalance that arise due to system impedances such as those due to transformers and lines.
C. Use of modern power electronics devices e.g. D.STATECOM, DVR,UPQC
D. To protect induction motors relays that trip the motor on negative sequence voltage and current can be employed. It has been stated that the negative sequence current detecting relays have a better sensitivity compared to negative sequence voltage detecting relays.

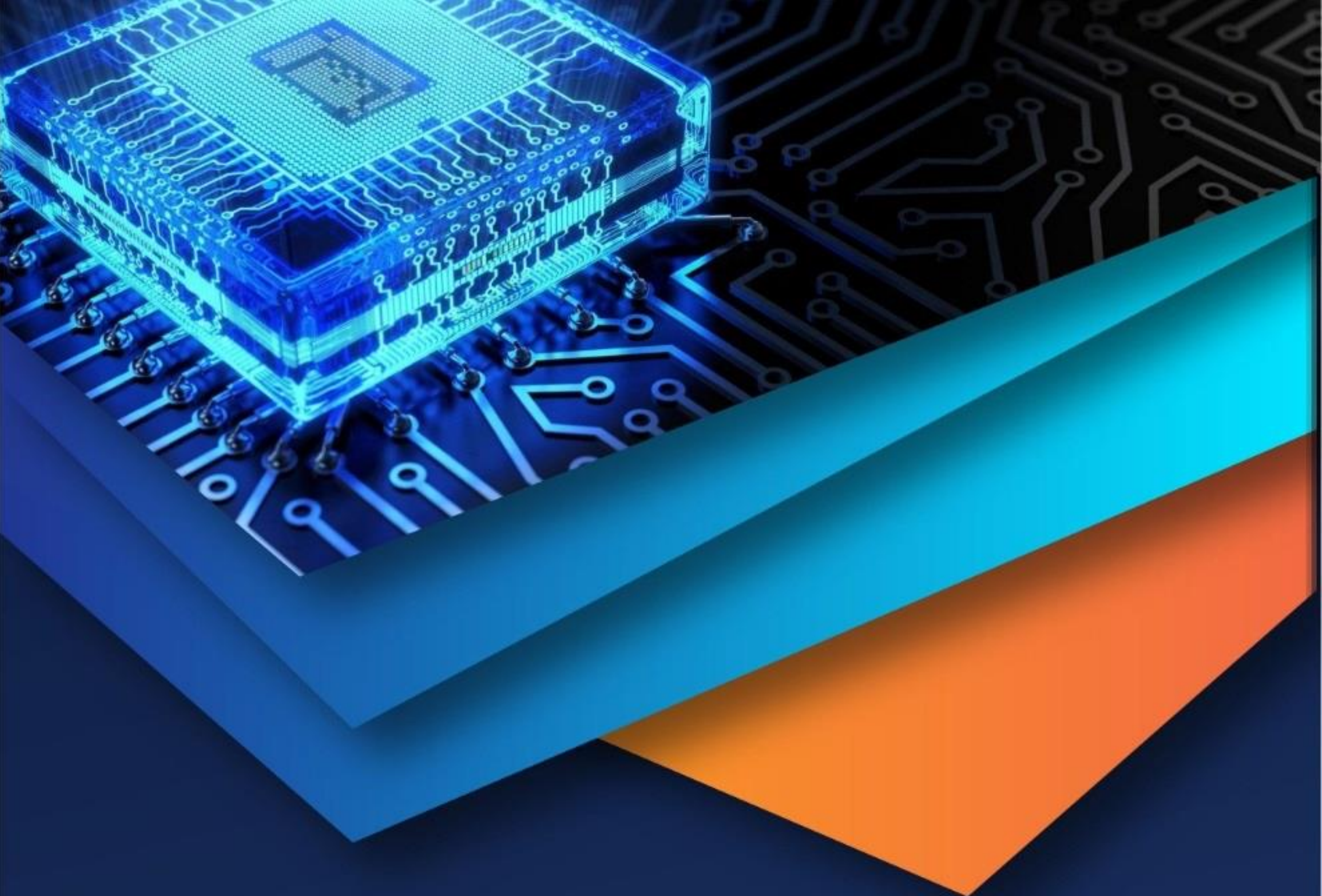
One more simple way to cope up with this problem is derating, means existing motor should be derated by multiplying the derating factor as given by NEMA (Fig 3). New motor should be purchased after multiply inverse of derating factor so that generation of excess heat can be avoided. Various derating methods has been given by the researcher [3], [10],[14],[17]. Derating based on complex voltage unbalance factor is more accurate then NEMA [14]. One should also take care of positive sequence voltage for accurate derating of the induction motor [6].

VI. CONCLUSION

A comprehensive review of voltage unbalance factor by NEEMA, IEEE, IEC and other researchers has been summarised in a precise manner. The methods used for steady state analysis has been explained in details. Any voltage unbalance factor will not reflect exact unbalance condition as VUF is calculated at a particular average voltage or positive sequence voltage. Same VUF may be there for different value of positive sequence voltage. Since losses also depend on positive sequence voltage, therefore derating of the motor not only depends upon VUF but also depends upon positive sequence voltage. Therefore in the classification of unbalance, one more term is recommended for addition i.e. terminal unbalance voltage. Terminal voltage should also be taken into consideration only then precise derating can be evaluated. Mitigation of voltage unbalance can be done either by derating of motor or by using advance electronic devices.

REFERENCES

[1] J. E.Willams.1954. Operation of three phase induction motor on unbalance voltages. AIEE Trans, Vol-73, pp.125-133, April 1954.
[2] Gafford, W. C. Duester hoef, and C. C. Mosher, “Heating of induction motors on unbalanced voltages,” AIEE Trans., Pt. III-A, Power App.Syst., vol. PAS-78, pp. 282–297, June 1959.
[3] Berndt and N. L. Schmitz, “Derating of polyphase induction motors operated with unbalanced line voltage,” AIEE Trans., Pt.III-A, Power App. Syst., vol. PAS-84, pp. 471–479, Feb. 1964.
[4] R. F Woll, “Effect of unbalanced voltage on the operation of poly-phase induction motor”, IEEE Trans on IA, IA-11,No.1 pp. 38-42, Jan / Feb 1975.
[5] Cummings, P.G., "Estimating Effect of System Harmonics on Losses and Temperature Rise of Squirrel-Cage Motors" IEEE Transactions on Industry Applications, Vol. IA22, No. 6, pp. 1121-1126, Nov./Dec. 1986.
[6] Lee, C.Y. 1999. Effects of unbalanced voltage on the operation performance of a three-phase induction motor. IEEE Trans. Energy Conversion **14(2),** 202–208.
[7] Y.J. Wang, “Analytical study of study state performance three phase induction motor connected to unbalanced three phase voltage” IEEE Power Engineering Society, winter meeting, Singapore, pp. 23-27, January 2000.
[8] Annette von Jouanne, Basudeb (Ben) Banerjee, “Assessment of voltage unbalance”, IEEE Transactions on power delivery, VOL. 16, NO. 4, pp. 782-790, October 2001.
[9] Pillay, P. and Manyage, M. 2001. Definitions of voltage unbalance. IEEE Power Engineering Review **21(5),** 50-51.
[10] 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 Trans. On EC, vol.16, No.3,pp.270-275,2001.
[11] Gosbell, V.J., Technical Note No. 6 - VOLTAGE UNBALANCE.2002, Integral Energy Power Quality Centre, School of Electrical,Computer & Telecommunications ngineering, University of Wollongong.
[12] P. Pillay, P. Hoftman, and M. Manyage,“Derating of induction motors operating with the combination of unbalanced voltages and over orunder voltages,’’ IEEE Trans. EC, vol. 17, pp. 485-491, Dec. 2002.
[13] Faiz, J., Ebrahimpour, H. and Pillay, P. 2004. Influence of unbalanced voltage on the steady state performance of a three-phase squirrel cage induction motor, IEEE Trans.Energy Conversion **19**(**4),** 657–662.
[14] J. Faiz and H. Ebrahimpour, “Precise derating of three phase induction motors with unbalancedvoltages,” IEEE Trans IAS, Vol.6, No.5, pp.485-491, 2005.
[15] J. Faiz, H. Ebrahimpour and P. Pillay,“Influence of unbalanced voltage on efficiency ofthree phase squirrel cage induction motor andeconomic analysis” IEEE Trans EC, Vol.47, pp.289-302, 2006.
[16] K. S. Sandhu, and V. Chaudhary, "Steady State Modelling of Induction Motor Operating With Unbalanced Supply System" WSEAS Transactions on IRCUITS and SYSTEMS, issue 2, volume 8, pp 197-206, Feb. 2009.
[17] A.A.Ansari, D.M.Deshpande,NIT Bhopal,”Investigation of performance of 3 phase Asynchronous Machine under Voltage Unbalance’ in JATIT vol 1 pp 21,2009.
[18] Lamia Youb,“Effects of Unbalanced Voltage on the Steady State of the Induction Motors”, Vol. 2, No. 1, pp. 1583-1589, March 2014.
[19] Rajashree U Patil and Guide Prof. H. B. Chaudhari, “Behaviour of Induction Motor at Voltage Unbalanced”, International Journal of Engineering Research & Technology (IJERT), Vol. 4 Issue 05, May-2015.
[20] R.C. Dugan, M.F. Mc Granaghan, H.W. BEATY, Electrical Power Systems Quality. New York: McGraw-Hill, 1996.Bollen, M.H.J. 2000. Understanding Power Quality Problems. IEEE Press, New York, USA.
[21] NEMA Std. Publication MG1-1993.
[22] P Giridhar Kini, R C Bansal and R S Aithal “Impact of voltage unbalance on the performance of three-phase induction motor” The south pacific journal and applied sciences,24, pp 45-50,2006.



10.22214/IJRASET

45.98

IMPACT FACTOR: 7.129

IMPACT FACTOR: 7.429

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY