# Performance Analysis of Induction Motor Operating at Unbalanced Under and Overvoltage supply-A comparative approach

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**Abstract: When an induction motor is operated at unbalanced voltage supply the performance characteristics like efficiency, power factor, input power, output power and losses are affected. In this paper performance of 3-phase squirrel cage induction motor operating at balanced and unbalanced voltage supply has been analyzed. In order to follow the comparative approach, the machine is first analyzed at the balanced condition followed by the analysis at under-voltage and over voltage unbalance condition. The analysis is carried out considering the definition of voltage unbalance given by International Electrotechnical Commission (IEC). MATLAB/Simulink has been used to simulate a 2hp induction motor operated at balance and unbalance voltage with a fixed load and with different percentages of unbalance**.

**Keywords:** *Induction motor, unbalanced voltage, performance characters, VUF, IEC.*

## 1. Introduction

Three phase squirrel-cage induction motor is known as work horse of industries and considered to be an important class of electrical machines. Induction motor is preferred in industrial, residential and commercial systems due to its high torque to volume ratio, lower maintenance, and simple construction, robust and reliable operation. When induction motor is operated at unbalanced voltage supply then voltage breaks up into two components positive sequence component and negative sequence component. The negative sequence component produces a magnetic field in addition to the magnetic field of positive sequence component. The unwanted component i.e negative sequence component causes serious ill effects like reduction in torque, efficiency, and over-heating. As the voltage unbalance increases the negative sequence component increases and positive sequence component decreases[1].The NEMA (National Electrical Manufactures Association) recommends that the motor should not be operated if the voltage unbalance is more than 5% for any length of time[2].

If an induction machine is connected to a large power system then it's found that voltage unbalance exists at the machine terminals even though it is supplied with a balanced source. This is because although voltages are equal in magnitude, with the individual phases 120$^o$ apart at the generation and transmission levels but the voltages at distribution stage and utilization side can be unbalanced [2], [3]. The causes of voltage unbalance in power system can be unbalanced loads, incomplete transposition of transmission lines, blown fuses on three phase capacitor banks, open delta transformer connections and many more [2]–[10] Unbalanced voltage can be either higher or lower than nominal balanced voltage (over or under voltage unbalance.

In over voltage unbalance the positive sequence component will be higher than the balanced rated voltage, and in under-voltage case positive sequence component will be lower than rated voltage. There's a lot in literature about the unbalanced operation of the machine[2], [8], [3]–[6], [11] but this paper presents a comparative approach about the performance of induction motor operated at both voltage unbalance cases with consideration of different percentages of voltage unbalance. There exist numerous voltage unbalance definitions by international standards like NEMA, IEC, IEEE but in most of the papers either the line voltage unbalance rate (LVUR) defined by NEMA(National Electrical Manufactures association) or the voltage unbalance factor (VUF) defined by IEC(International Electro Technical Commission) has been considered. [11], [12]. This paper considers the definition by IEC.

## 2. System Model

### *2.1 Different definitions of voltage unbalance*

In order to choose which voltage unbalance definition to be incorporated, different voltage unbalance definitions have been described below. And it follows that IEC definition has been incorporated which makes use of symmetrical components-A method under which an unbalanced phasor is resolved into a set of balanced phasors.

**National Electrical Manufacture's Association (NEMA)**

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The NEMA voltage unbalance definition is based on line voltage unbalance rate (LVUR) given in equation[11].

$$LVUR(\%)=\frac{\text{Max voltage deviation from avg line voltage}}{\text{average line voltage}} \quad (1)$$

$$=\frac{Max[|V_{ry}-V_{av}|,|V_{yb}-V_{av}|,|V_{br}-V_{av}|]}{V_{av}}\times 100$$

Where;

$$V_{av}=\frac{V_{ry}+V_{yb}+V_{br}}{3}$$

Note that magnitude of line voltages has been considered under this definition[11].

### 2.2 IEEE definition for voltage unbalance:

The IEEE voltage unbalance definition is based on Phase voltage unbalance rate (PVUR) given in equation-2.

$$PVUR(\%)=\frac{\text{Max voltage deviation from avg phase voltage}}{\text{Average phase voltage}} \quad (2)$$

$$=\frac{[|V_r-V_{av}|,|V_y-V_{av}|,|V_b-V_{av}|]}{V_{av}}$$

Where,

$$V_{av}=\frac{V_{ry}+V_{yb}+V_{br}}{3}$$

It could be conceived from the equations-1 and 2 that the difference between two definitions mentioned above is of phase and line voltage considerations[11].

### 2.3 International Electrotechnical Commission (IEC):

The equation-3 mentioned below gives the IEC definition of voltage unbalance as the ratio between the negative and positive sequence component. Note that under balanced conditions $K_v$=0.

$$VUF(\%)=\frac{|V_n|}{|V_p|}\times 100=Kv \quad (3)$$

Where $V_p$ denotes the positive sequence component and $V_n$ denotes the negative sequence component.

**Other *Definitions*:**

Definitions given by NEMA, IEEE and IEC only consider magnitude of unbalance. Complex unbalance factor defines the unbalance voltage by considering unbalance in voltage as well in angle and is defined by

$$CVUF=\frac{V_n}{V_p}=K_v\angle\theta_v \quad (4)$$

### 2.4 Induction Motor Model

Here the analysis of induction motor is done by using symmetrical component method. For analysis of an induction motor under unbalanced conditions positive sequence component and negative sequence components are required

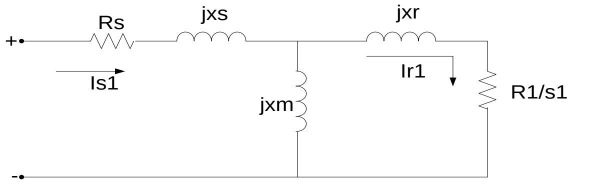


Fig.1 (a) Equivalent circuits of motor with positive sequence circuit

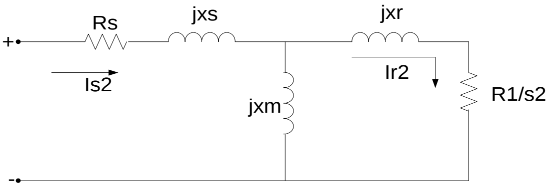


Fig.1 (b) Equivalent circuits of motor with negative sequence circuit.

Fig.1 shows the equivalent circuit of an induction motor. Both circuits are defined to be same but difference between two circuits is of slip, for positive sequence slip $s_1=s$ and for negative component $s_2=2-s$.

$$Z_i=\frac{R_s+jXs+(jXm)(\frac{R_r}{S_i}+jXr)}{(\frac{Rr}{S_i})+j(Xm+Xr)} \quad (5)$$

Here i=1 for positive sequence and i=2 for negative sequence. Below are given some important equations developed from the equivalent circuits mentioned above:

Input power to machine is:

$$P_i=R_e[3(V_{s1}I_{s1})^*+(V_{s2}I_{s2})^*] \quad (6)$$

Power factor of the machine:

$$p.f=\cos[\tan^{-1}(\frac{Q_{in}}{P_{in}})] \quad (7)$$

Output power of the machine:

$$P_{out}=P_1+P_2 \quad (8)$$

Where:

$$P_1=3[(I_{r1})^2(\frac{1-s_1}{s_1})Rr] \quad (9)$$

$$P_2=3[(I_{r2})^2(\frac{1-s_2}{s_2})Rr] \quad (10)$$

Motor output torque:

$$T_{out}=T_1+T_2 \quad (11)$$

$$T_1 = \frac{P_1}{\omega_m} = \frac{3I_{r1}^{\ 2}R_r}{s_1\omega_s} \qquad (12)$$

$$T_2 = \frac{P_2}{\omega_m} = \frac{3I_{r2}^{\ 2}R_r}{s_2\omega_s} \qquad (13)$$

Where; $w_m = w_s(1-s)$

Efficiency of the motor is given as;

$$\eta = \frac{P_{out}}{P_{in}} \qquad (14)$$

## 3. Simulation results and discussions

For analyzing the performance characteristics i.e. efficiency, power factor, input power, output power and losses, the machine has been simulated in Matlab/Simulink. The developed model is shown appendix A .The parameters of the machine are: Line to line voltage 400V, rated power 1.5kW, frequency 50Hz, 2-pole pairs, Δ connected. The motor has resistance and mutual inductance of equivalent circuit of motor in ohms per phase belonging to the stator and rotor are: Rs=4.023Ω, Rr = 4.023Ω, Lm=0.3046 H, J=0.1$kg\ m^2$.

For balanced voltage simulation is run at voltages $V_a = 230\angle 0^o$, $V_b = 230\angle +240^o$ $V_c = 230\angle +120^o$ here $V_a$ ,$V_b$ and $V_c$ are phase voltages. The cases of voltage unbalance (over and under voltage) used in this paper are given in the table I mentioned below.

Table .1.Supply voltage at different unbalance factor

| $K_v$ | Unbalance condition | $V_a$ | $V_b$ | $V_c$ |
|---|---|---|---|---|
| 5% | Under voltage | 220.47<0.08 | 205.21<242.58 | 204.67<122.49 |
| | Over voltage | 262.48<0.08 | 244.33<242.58 | 243.65<122.49 |
| 3% | Under voltage | 216.27<0.05 | 207.11<241.53 | 206.71<121.48 |
| | Over voltage | 257.50<0.05 | 246.55<241.53 | 246.11<121.48 |
| 1% | Under voltage | 212.03<0.0 | 212.03<240.50 | 208.79<120.48 |
| | Over voltage | 252.52<0.01 | 248.85<240.50 | 208.79<120.48 |

### *3.1 Operation of motor at balanced voltage*

When motor is operated at balanced condition, obviously it does not cause any ill effects and operation of motor will be reliable. The results obtained from simulation at balanced voltage are given in Table.2.

Table.2. Machine is operated at balanced supply

| Condition | Efficiency (%) | P.F | Input | Output | Losses |
|---|---|---|---|---|---|
| Balanced | 75.88 | 0.8267 | 2709 | 2056 | 653.5 |

### *3.2 Operation of motor at under & over unbalance voltage*

When motor is operated at unbalanced supply, it's noted that the performance characteristics are affected. And the affect depends upon the percentage voltage unbalance.

### *3.3 Efficiency*

Fig.1 shows the graph of efficiency vs. VUF, and it is clear from the graph that with the increase in VUF (voltage unbalance factor), efficiency of the induction motor is decreasing. For the same VUF, the efficiency of the motor is higher in overvoltage unbalance than if it is operated at under-voltage unbalance.

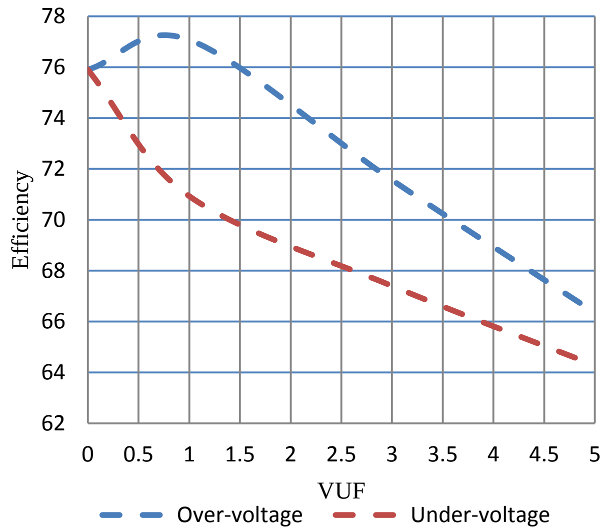


Figure .1 Efficiency vs VUF

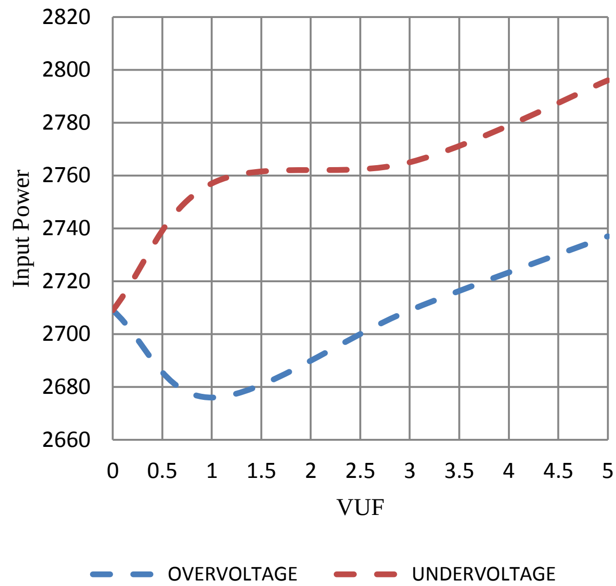


Figure.2. Input power Vs VUF

### *3.4 Input power and Power factor*

Operation of induction motor with under-voltage supply causes higher electric power consumption as shown in fig-2. Whereas it is found that the power factor is poor in case of overvoltage unbalance as compared to under-voltage unbalance. It can be observed from the graph in

Fig.3 that power factor is decreasing as degree of unbalance is increasing.

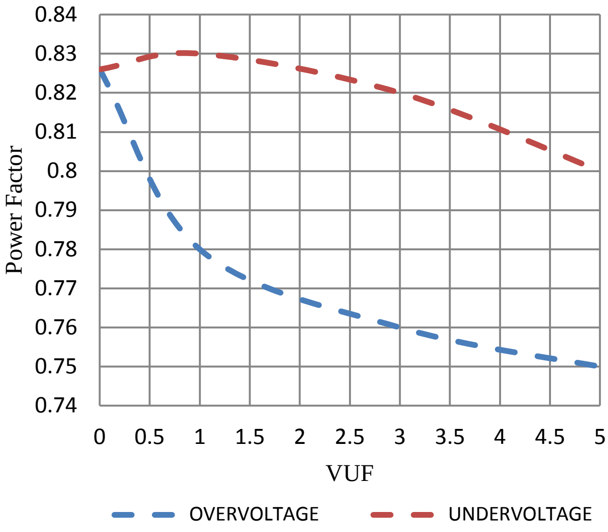


Figure.3. Power factor vs VUF

### *3.5 Output Power*

Fig .4 shows the variation of output power of motor with the unbalance voltage. It is clear from the graph that the output power is high in the situation of over-voltage case having higher efficiency than under-voltage case. As the voltage unbalance factor increases the output power of the motor is decreasing.

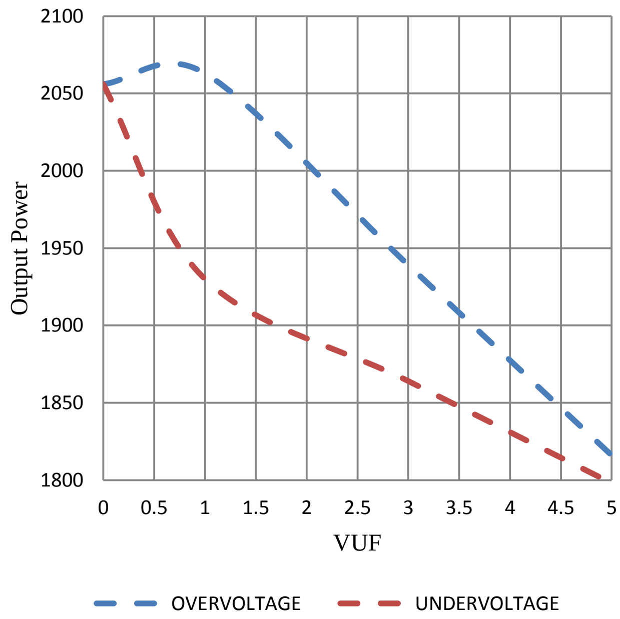


Figure.4. Output power vs VUF

### *3.6 Total Losses and derating factor*

Due to voltage unbalance motor consumes high electric power causing lower efficiency and higher losses. Actually, the same VUF can have many voltage unbalance cases. The curve provided by NEMA given in fig-5 is roughly estimated and is only concerned with VUF.

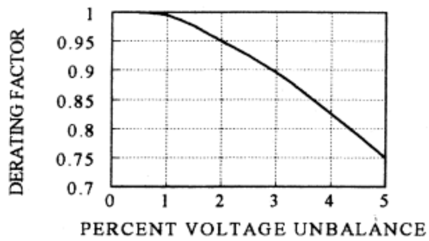


Figure .5. Curve of derating factor provided by NEMA


Figure.6. Total Losses vs VUF

As in case of over voltage unbalance, the efficiency of motor is higher as compared to under-voltage unbalance and thus losses are high in under-voltage as depicted in graph given in Fig.6.

Losses cause rise in temperature in the winding of induction motor. Due to rise in temperature in the winding of motor, life of the motor will be reduced. To protect the motor from damage, a derating factor must be used to reduce the losses as well temperature of the motor as shown in Table.3.

Table.3. Machine is operated at various voltages

| S.No | Efficiency | P.F | I/P | Output | Losses | Slip |
|---|---|---|---|---|---|---|
| Balanced | 76.0 | 0.826 | 2709 | 2056 | 653.5 | 0.0808 |
| 1%(UV) | 70.03 | 0.838 | 2757 | 1930 | 826.2 | 0.1019 |
| 3%(UV) | 67.4 | 0.822 | 2765 | 1864 | 901.4 | 0.1018 |
| 5%(UV) | 64.28 | 0.807 | 2796 | 1798 | 998.8 | 0.1018 |
| 1%(OV) | 77.07 | 0.786 | 2676 | 2063 | 613.7 | 0.0659 |
| 3%(OV) | 71.56 | 0.761 | 2709 | 1939 | 770.5 | 0.0658 |
| 5%(OV) | 66.35 | 0.758 | 2737 | 1816 | 921.1 | 0.0657 |

## 4. Conclusion

This paper analyzes and compares the performance of three phase squirrel cage induction motor operated at unbalance voltage(over-voltage or under-voltage), considering mainly efficiency, power factor, input power, output power, total losses and derating factor. It is concluded from the simulated results that

- At unbalance supply the efficiency of the motor decreases steeply as voltage unbalance increases.
- Motor consumes high power in under-voltage case however power factor is poor in case of over-voltage as compared to under-voltage.
- Output power is higher in over-voltage case due to high efficiency of motor.
- Due to lower efficiency of motor in under-voltage case losses are higher in this case.
- Losses causes heating in the winding of the motor causing damage to winding and reducing life of motor, so it is asserted that motor should be de-rated.

Voltage unbalance does not causes loses in the motor only but it causes more electricity charges due to poor power factor and reduced efficiency, motor consumes more power .

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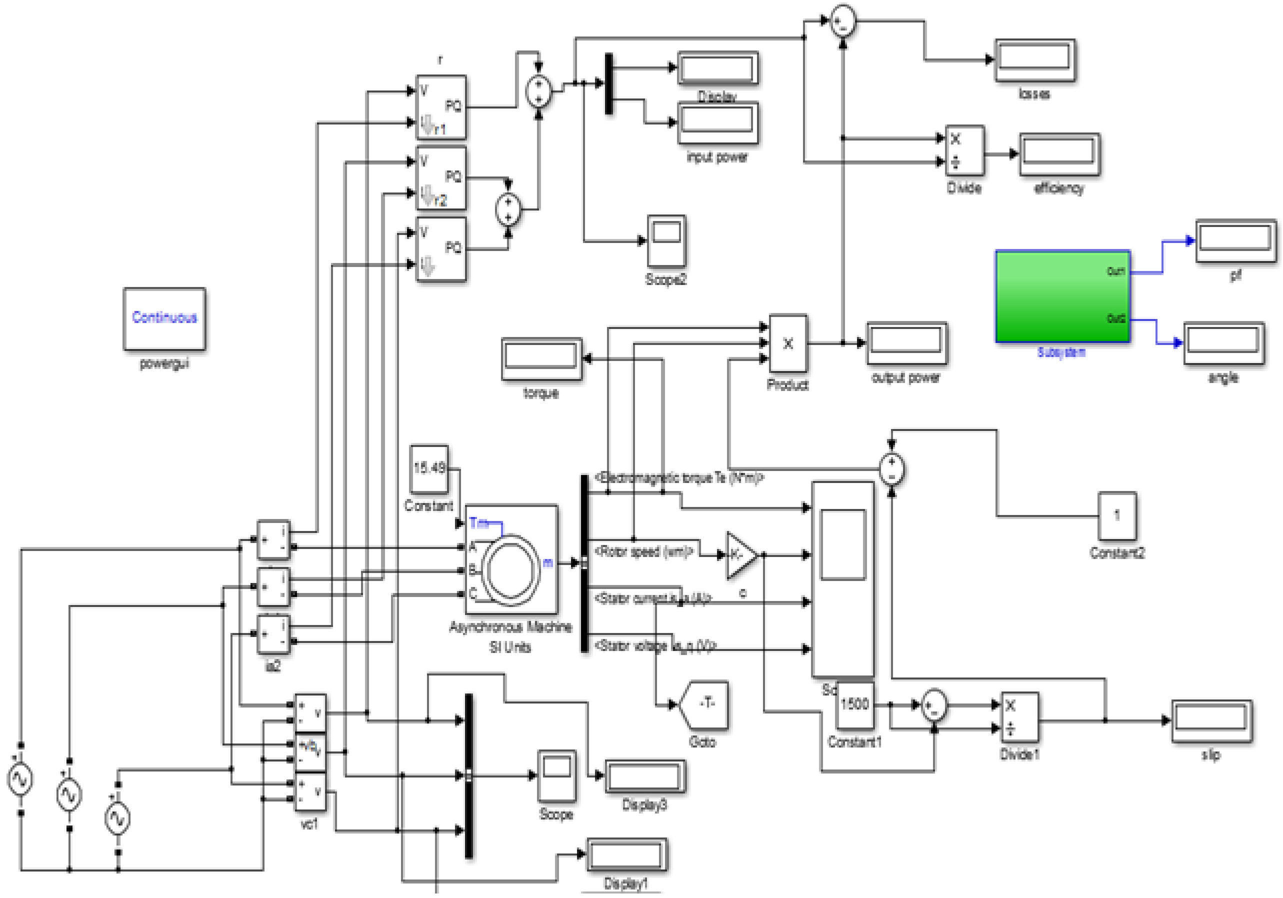
## Appendix -A



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