Analysis of Induction Motor Performance under Unbalanced Supply Voltage Conditions and Its Impact on the Network Voltage Unbalance Propagation

K.G.Kattriarachchi, V.O.Arachchige, L.G.Kanchana, R.D.D.C.Y.Gunaratna
Department of Electrical Engineering
University of Moratuwa
Moratuwa,Sri Lanka
kattriarachchi@live.com,vibhanua@gmail.com,gaya3_1991@yahoo.com, dineshsmms@gmail.com

***Abstract*— Voltage unbalance (VU) is regarded as a power quality problem of significant concern at the electricity distribution level. Influence of unbalanced supply voltages on the adverse performance of power system and its equipment is intensified by the fact that a small unbalance in the phase voltages can cause a disproportionately larger unbalance in phase currents. Naturally, three phase Induction Motor (IM) loads which are considered to be the main work horses of many industrial environments, are symmetrical devices and do not possess any inherent unbalance. However, the operation of three-phase induction motor is adversely affected by the supply source unbalance. Voltage unbalance causes a lot of adverse effects on induction motor such as Overheating, line-current unbalance, derating, torque pulsation, and inefficiency. The overheating leads to winding insulation degradation. Despite the degrading of motor performance, it has been found that the existing level of the voltage unbalance (VU) at the point of common coupling (PCC) is attenuated due to the presence of induction motor load. The following analysis shows how VU is attenuated by three phase induction motors at the point of evaluation (POE). Finally this paper presents a practical approach to evaluate VU propagation at different points of the network in terms of the Voltage Unbalance Factor (VUF) and hence the level of attenuation made by induction motor loads.**

***Keywords*— Three-phase induction motor, Voltage unbalance factor, Power quality**

I. INTRODUCTION

Power quality problems and survey results have been reported in many publications. It is estimated that industrial and digital economy companies collectively lose $45.7 billion a year due to outages and another $6.7 billion each year due to power quality phenomena [1]. The unbalanced voltage gives a bad influence for the power quality.

Uneven magnitudes of the fundamental phase quantities or uneven distribution of phase angles between the three phases give rise to unbalanced voltages [1-4]. Voltage unbalance is mainly caused due to asymmetrical load distribution and un-transposed power lines.

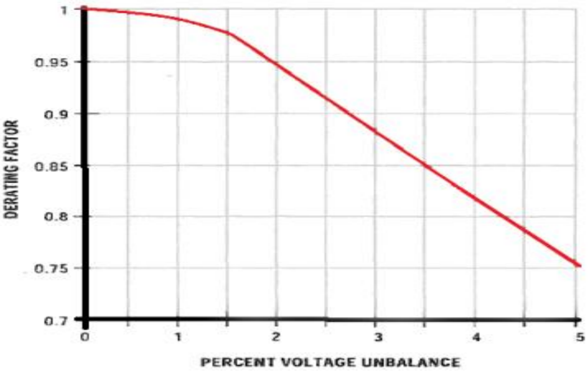

Fig. 1. NEMA Curve of the derating factor with the voltage unbalance

Because of various techno-economic benefits, the induction motors (IM) are widely used in industrial, commercial and residential systems. Once the supply voltage is unbalanced, the ill effects on induction motors will cause enormous impacts. Although induction motors are designed to tolerate a small level of unbalance, they are derated according to the level of unbalance present at the PCC as shown in Fig. 1 [1].

The following three definitions have been introduced according to different standards with the purpose of comprehending voltage and current unbalances and their effects.

A. NEMA Definition

The **NEMA** definition of voltage, also known as the line voltage unbalance rate (LVUR), is given by

$$\%LVUR = \frac{Max\ Voltage\ Deviation\ from\ avg.line \times 100\ voltage\ magintude}{Avg.line\ voltage\ magnitude} \quad (1)$$

B. *IEEE Definition*

The **IEEE** definition of voltage unbalance, also known as the phase voltage unbalance rate (PUVR), is given by

$$\%PVUR = \frac{Max\ Voltage\ Deviation\ from\ avg.phase\ voltage\ magintude \times 100}{Avg.phase\ voltage\ magnitude} \qquad (2)$$

C. *Exact (VUF %) Definition*

The Exact definition of voltage unbalance is defined as the ratio of negative sequence voltage component to the positive sequence voltage component. The percentage unbalance factor

(VUF), is given by

$$\%PVUR = \frac{Negative\ sequence\ voltage\ component \times 100}{Positive\ sequence\ voltage\ component} \qquad (3)$$

D. *Current Unbalance Factor (CUF) Definition*

It is defined as the ratio of negative sequence current and positive sequence current.

$$\%CUF = \frac{Negative\ sequence\ current\ \times 100}{Positive\ sequence\ current} \qquad (4)$$

Most of the regulations about voltage unbalance only specify the percentage of voltage unbalance factor (VUF) without indicating the unbalance conditions. However, the reality is that there are many combinations of unbalanced phase voltages and/or angles could exist which would give rise to the same voltage unbalance factor (VUF). If only the VUF is mentioned, then neither the exact voltage unbalance situation can be estimated nor can the impacts on the power system due to voltage unbalance not be evaluated. Hence, this paper discusses the VUFs under different unbalance conditions.

II. OPERATION OF THREE PHASE INDUCTION MOTORS UNDER UNBALANCED SUPPLY CONDITIONS

A. *Analysis of three phase induction motor operation under unbalanced voltages*

This is usually studied by analyzing the behavior of the positive and negative sequence components of the unbalanced supply voltage. The positive sequence voltage generates a positive torque and the negative sequence voltage generates a negative torque by giving rise to an air gap flux rotating against the forward rotating field. So when neglecting non-linarites for instance due to saturation, the motor behaves like a superposition of two separate motors, one running at slip *s* with terminal voltage V_p per phase and other running with a slip of (2-s) with a terminal voltage V_n. As a result of that the net torque and speed are reduced while registering torque pulsation and acoustic noise as shown in Fig. 3. Further, variation of the slip from locked rotor condition (S=1) to the normal operating point of the motor changes the positive and negative sequence impedances and given by and respectively which leads to give rise in high starting current. It has been found that the absolute values of negative sequence voltages/currents are not sensitive to the motor operating conditions (i.e. locked rotor, no load or full load conditions), however positive sequence quantities vary over the operating conditions which can influence the voltage unbalance at the POE [3].

$$Z_{1,m} = R_s + jX_s + jX_m\ //\ \left(\frac{R'_r}{s_1} + jX'_r\right) \qquad (5)$$

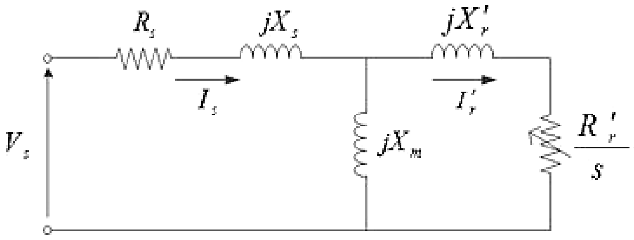

Fig. 2. Equivalent circuit of Induction Motor

$$Z_{2,m} = R_s + jX_s + jX_m\ //\ \left(\frac{R'_r}{s_2} + jX'_r\right) \qquad (6)$$

B. *Voltage unbalance attenuation provided by three phase induction motors*

Naturally, IM loads do not possess any kind of inherent unbalance despite being affected by the supply source unbalance. Operation of three-phase induction motor under unbalanced supply conditions can be studied by representing the motor as three decoupled impedances in the sequence domain [2-4].

Considering a radial network connected to an IM load as shown in Fig. (4), the resultant VUF at the POE can be written as shown in as a portion of the VUF at the upstream busbar.

$$VUF_{POE} = \left(\frac{Z_{2,m}}{Z_{1,m}}\right)\left(\frac{Z_{1,m} + Z_{11,t}}{Z_{2,m} + Z_{22,t}}\right) VUF_{source} \qquad (7)$$

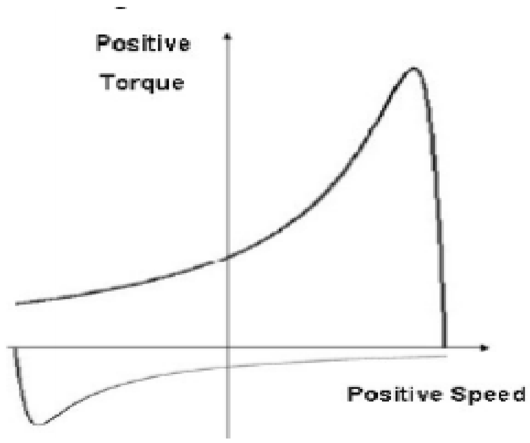

Fig. 3. Graphical representation of the positive and negative sequence torques of an induction motor subjected to unbalanced supply voltages

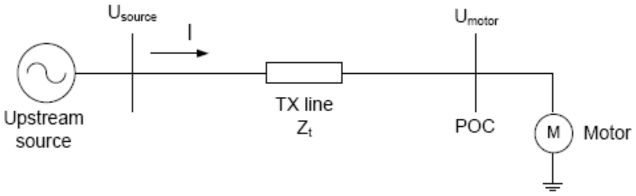

Fig. 4. A radial network connected to an Induction Motor

Here VUF_{source} is the upstream source voltage unbalance factor which can be calculated using pre-connection voltage measurements at the POE. $Z_{xy,t}$[1] is the sequence impedance of the transmission line and $Z_{x,m}$ is the sequence impedances of the motor.

The scaling factor associated with VUF_{source} in *(7)* can be shown to have a **magnitude less than unity** and incorporates only positive and negative sequence impedances of the line and the motor indicating the attenuation done by the IM connection.

III. SIMULATION ON EFFECTS OF VOLTAGE UNBALANCE ON INDUCTION MOTORS

The radial network configuration given in Fig. 4 was simulated in PSCAD simulation. The voltage attenuation was at a noticeable level with the presence of a three phase induction motor in the network shown in the Fig. 5.

This network (Fig. 5) consists of three voltage sources, a 12.47 kV/2.3 kV transformer, a three phase 2250hp induction motor and passive loads. The parameters were chosen in corresponding to a European Network in order to compare simulation results with some publications. [6] During simulation Voltage Unbalance Factor (VUF) is compared under different conditions with unbalanced loads and unbalanced supply

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Note that voltage unbalance is neglected which occurs due to transmission and distribution lines assuming transmission lines are properly transposed and short in length.

Following are the results of the simulation which was conducted in four steps by using unbalance loads and sources with different mixed loads (Passive Loads & Motor loads) and source values combinations.

1. Unbalanced supply and passive loads(balanced) with motor
2. Balanced supply and passive loads(unbalanced) with motor
3. Unbalanced supply and passive loads(unbalanced) without motor
4. Unbalance supply and passive loads(unbalanced) with motor

Here it can be clearly observed that the voltage unbalance at the POE is attenuated when the induction motor load is connected. And load A, B and C are PQ loads that are connected to the phase a, b and c.

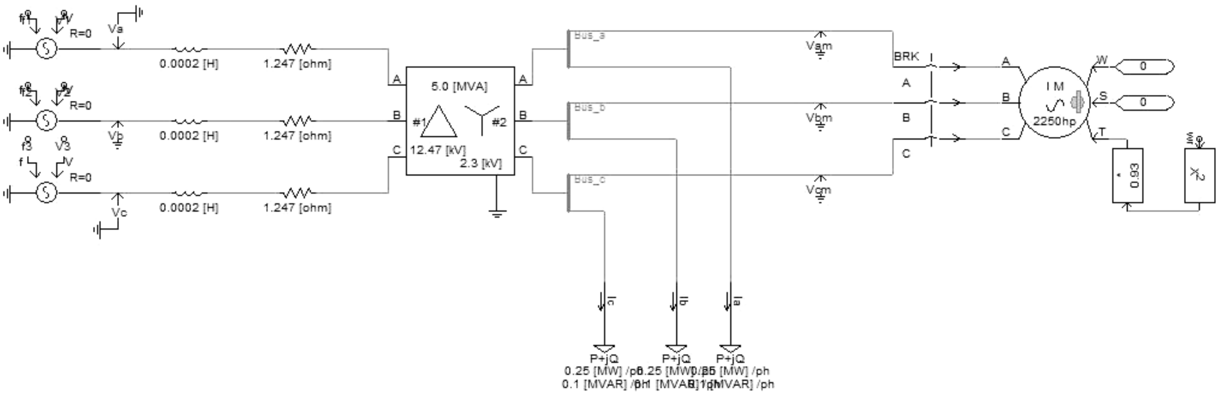

Fig.5. PSCAD Simulation

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[1] x and y are replaced by 1 and 2 which stand for positive sequence and negative sequence respectively,

TABLE I. VUF AT SOURCE SIDE AND POE-WHEN THE SUPPLY IS UNBALANCED AND CONNECTED TO A BALANCED PASSIVE LOAD WITH THE MOTOR (P=1MW AND Q=0.4MVAR)

Supply (unbalanced) and Load (balanced)	
VUF at source side	VUF at load side
0.49	0.37
0.88	0.67
1.29	0.99
1.71	1.31
2.13	1.63
2.56	1.94
2.98	2.27

TABLE II. CUF AND VUF AT POE -WHEN SUPPLY IS BALANCED AND CONNECTED TO AN UNBALANCED PASSIVE LOAD WITH THE MOTOR

Supply (balance) and Load (unbalance)		
CUF of passive loads	VUF load side without motor	VUF load side with motor
1.1	0.19	0.11
1.3	0.25	0.14
3.27	0.31	0.23
6.15	0.45	0.35
7.12	0.56	0.42
8.69	0.71	0.53
14.8	1.37	1.1

According to the simulation, it can be observed that the VUF at the supply side was attenuated by the presence of three phase induction motor the POE (Table I).

Further, referring to Table II, attenuation in the VUF at the POE is still observed in the presence of a mixed load. However, the level of attenuation provided by three phase induction motors will depend on the power ratings of the passive and motor load and the level of unbalance of the passive load.

TABLE III. VUF AND CUF AT SOURCE SIDE AND POE-WHEN THE SUPPLY IS UNBALANCED AND PASSIVE LOADS ARE UNBALANCED WITHOUT THE MOTOR AND WITH MOTOR (PASSIVE LOADS FROM 0.6 MW AND 0.2 MVAR)

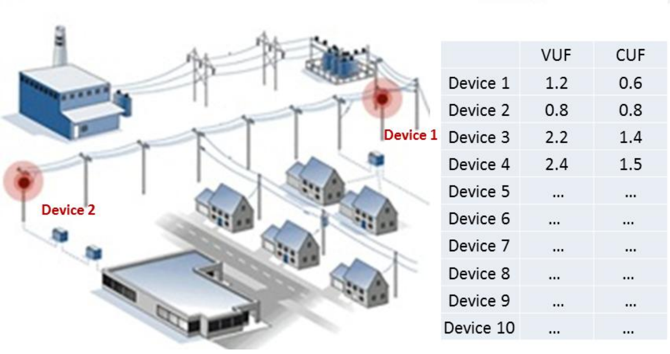
Supply (unbalanced) and Load (unbalanced)			
VUF at source side	CUF of passive load	VUF at load side without motor	VUF at load side with motor
1.06	1.06	1.08	1.06
4.41	1.34	4.44	4.42
2.16	3.3	2.29	2.26
1.81	3.4	1.9	1.87
0.94	4.4	0.97	0.94
2.25	5.62	2.31	2.29
2.26	6.19	2.26	2.25
1.5	6.2	1.67	1.62
1.5	7.77	1.71	1.67
1.51	9.89	1.48	1.45
0.47	11.03	0.55	0.54
2.24	13.53	2.26	2.22

As in Table III, VUF from unbalanced voltage supply the unbalanced passive loads can also be attenuated by having an induction motor at load side.

Above observations lead to make general conclusions with regard to the operation of induction motors under unbalanced supply voltages that the voltage unbalance occurs on the networks is attenuated in presence of induction motors.

IV. A PRACTICAL APPROACH TO CALCULATE UNBALANCE FACTORS AND MONITOR VU ATTENUATION

Under this section, a device is proposed to monitor the unbalance propagation of an electrical network. The intention of this device is to measure synchronized voltages and currents of the three phases and to calculate the voltage unbalance factor (VUF) and the current unbalance factor (CUF) of a point of a distribution line in the system. By using several devices and transferring all the data to one database, we can observe and analyze the unbalance propagation along the network so that the unbalance mitigation actions can be taken place in order to improve the power quality of the system.



	VUF	CUF
Device 1	1.2	0.6
Device 2	0.8	0.8
Device 3	2.2	1.4
Device 4	2.4	1.5
Device 5	...	...
Device 6	...	...
Device 7	...	...
Device 8	...	...
Device 9	...	...
Device 10	...	...

Fig.6. Expected outcome of a network and its collected data

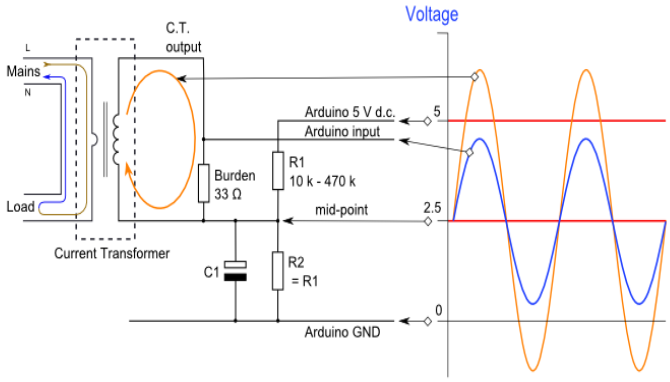


Fig.7. Current measuring circuit

Voltage and current measurements need to be taken in order to calculate VUF and CUF. For this, the device consists of current measuring circuits with current transformers and voltage dividers to measure voltages. The main objective of those circuits is to step down both current and voltage signals into voltage signals within measurable range for a microprocessor (0-5V).

In the current measuring circuit, the current transformer will step down the current signal 2000:1. But with an Arduino (as the microprocessor) current signals cannot be directly read, thus a voltage signal is needed to be given to the analog read pin. Therefore the secondary of current transformer needs to be connected to a burden resistor as shown in the Fig. 7. Value of the burden resistor will be changed depending on the maximum current willing to be measured by the device.

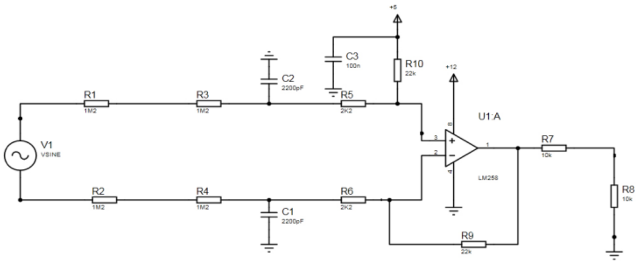


Fig.8. Voltage measuring circuit

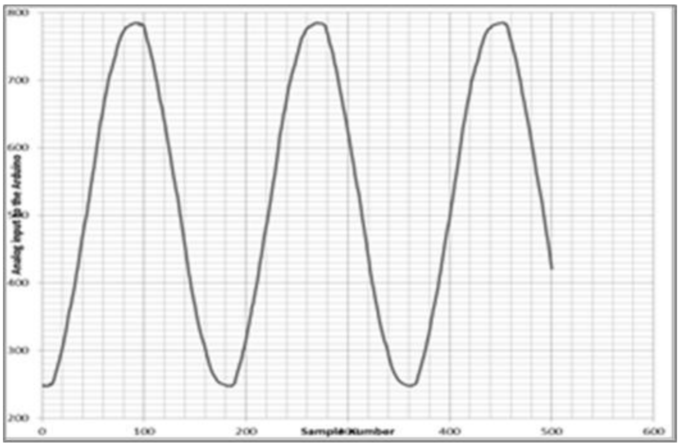


Fig.9. Observed signal through the Arduino

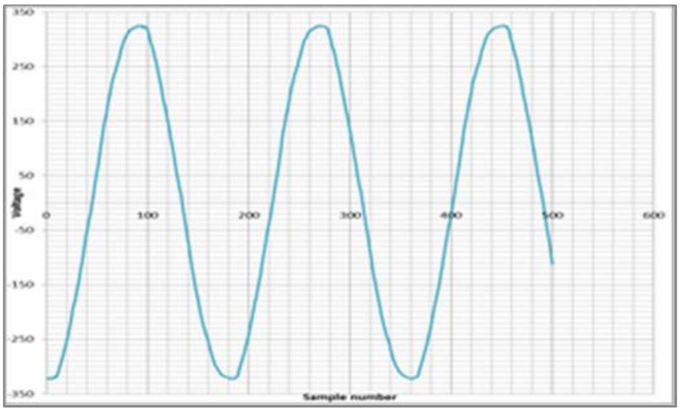


Fig.10. Single phase voltage waveform

When the voltage signal is measured using the circuit in the Fig. 8, output signal of the circuit is measured through the analog pin of an Arduino. It will provide a digital value from 0 to 1023 (Fig. 9) corresponding to the signal input. Taking it to the real range (+325V ~ -325V) can be done either using the mapping function of the Arduino or mathematical calibrations corresponding. Here (Fig. 10), mapping is done using the equation; (x-245)/ (785-245)*(325+325)-325. It will provide the actual voltage wave form as the output.

Even though RMS vale of the waveform can be calculated using the microcontroller there are separate kinds of IC's for instance ADE7753, which can be used for the purpose of getting much accurate readings. When Arduino is used for RMS calculations, <math.h> library can be used. Using double or float type variables RMS value can be calculated; otherwise the data will be lost.

Those measured values can be used to calculate the RMS values of three phase currents and voltages so that they can be used later on in the current and the voltage unbalance factor calculations.

$$f_{\mathrm{rms}} = \lim_{T\to\infty} \sqrt{\frac{1}{T}\int_0^T [f(t)]^2\,dt}. \tag{8}$$

To advance further into the simulation, sequential components of the calculated three phases need to be found. To calculate the unbalance factors, positive and negative sequence components are required.

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{9}$$

Where V_0, V_1 and V_2 are zero, positive and negative sequences of voltages and α is the 120^o rotation operator.

$$\mathrm{VUF} = \frac{\text{negative sequence voltage component}}{\text{positive sequence voltage component}} \tag{10}$$

$$\%\ \mathrm{VUF} = \frac{\text{negative sequence voltage component}}{\text{positive sequence voltage component}} \times 100 \tag{11}$$

Current unbalance factors can also be found using the current sequential components. Using a SIM 900, GSM/GPRS module, the calculated current and voltage unbalance factors can be transferred through GPRS to a server as shown in Fig. 4, so that the data can be accessed online, monitored and analyzed. With the knowledge of the load composition at the POE where the measurements are taken, VU attenuation provided by IM loads can be further validated using (7).

V. CONCLUSION

In this paper, an overview of factors affect voltage unbalance and the attenuation of voltage unbalance provided by induction motors were comprehensively discussed. Also a PSCAD simulation was conducted in order to investigate the attenuation provided by the induction motors. Finally a practical approach to calculate unbalance factor and monitor VU attenuation was proposed.

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