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A Methodology for Computation of Voltage Unbalance in Electric Motors

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ABSTRACT: Unbalanced voltages are unequal voltage values on 3-phase circuit that can exist anywhere in a power distribution system. They can cause serious problems particularly to motors and other inductive devices. Unbalanced voltages usually occur because of variations in the load. When the load on one or more of the phases is different than the others, unbalanced voltages will appear due to different impedances or type and value of loading on each phase. The resulting current unbalance is caused not only by the system voltage unbalance, but also by the system impedance, the nature of the loads causing the unbalance, and the operating load on equipment, particularly motors. This paper presents a methodology for computation of voltage unbalance in electric motor protection system. Current through the leads of each of the fifty selected electric motors used as case studies in this research paper were measured and recorded. All the three input power lines were rotated while ensuring that the order of the lead did not change. For each of the three rotation configurations, the average current was determined and the particular power line/motor –lead combination that had the maximum deviation from the average current was noted. The three power line/motor lead combination was then compared with the maximum current deviation. This is then used to compute the phase to phase voltage for the three input power line. The results of the paper show that electric motor number 32 has the least average voltage of 426V while electric motor number 6 has the highest average voltage of 511V which could be due to winding nature of the electric motors and the heat dissipation in them. Electric motor number 6 has the least percentage voltage unbalance of 2.15% while electric motor number 39 has the highest percentage voltage unbalance of 15.65%

I.INTRODUCTION

Voltage unbalance is the deviation of individual phase voltage magnitudes from the normal/rated values, with the individual phase voltage not being equal to each other either in magnitude and/ or in phase displacement [9], [20]. The presence of inequality among the phase voltages can be due to the unsymmetrical impedances of transmission and distribution lines, unbalanced or unstable power utility, unbalanced three phase loads, open delta transformer connections, blown fuses of three-phase capacitor banks, uneven spread of single-phase traction loads, weak rural power electric systems with long transmission lines or even unidentified single –phase-to-ground faults [4], [7], [13]. Single-phasing, which is the complete loss of a phase, is the ultimate voltage unbalance condition for a three phase circuit. Motor failure can be due to overloads, contaminants, single-phasing, bearing failure, old age and rotor failure. A motor that is allowed to operate at a temperature of 10^0C above the maximum temperature rating will reduce the motor's life span by 50%. The general life span of electric motor is estimated as 20 years.

The heat produced in the motor windings (copper losses), will continue to increase until the heat dissipation equals the heat being generated. The service factor of an elective motor is a multiplier which when applied to rated horsepower, indicates a permissible horsepower loading which may be carried under the conditions specified for the motor. Overloads as well as the resulting overcurrent, if allowed to continue will cause heat build-up within the motor which will lead to eventual early failure of the motor's insulation [16], [19].

A. Voltage Unbalance

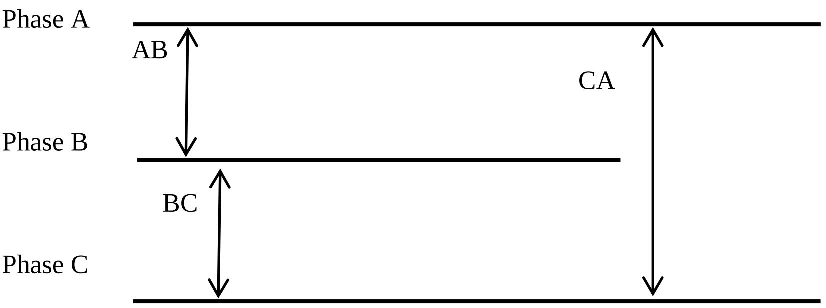
When the voltage between all three phases is equal (i.e balanced), current values will be the same in each phase winding. When the voltage between the three phases (AB, BC, CA) are not equal, there is "voltage unbalance". In this, the current increases in the motor windings and if allowed to continue, the motor will be damaged.

It is possible to operate a motor when the voltage between phases is unbalanced. In order to achieve this, the load must be reduced [8],[3],[12].

B. Causes of unbalanced voltage conditions

Some of the causes of unbalanced voltage conditions are;

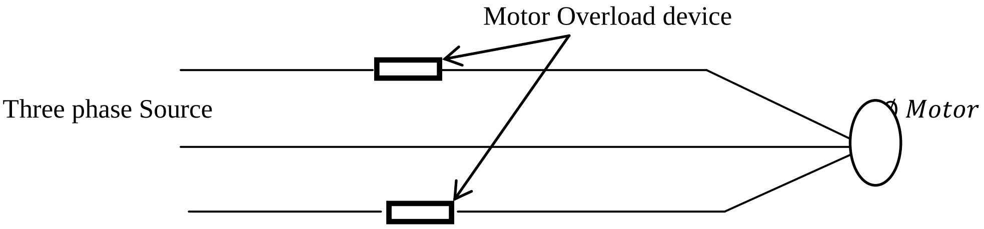
- Unequal single-phase loads: This is the reason why many consulting engineers specify that loading of panel boards be balanced to $\pm 10\%$ between all three phases
- Open delta connection
- Power factor fault correction capacitors not the same or off the line
- Transformer impedance of single-phase transformers connected into a “bank” not the same
- Improper tap settings on transformers.
- Transformer connections open, causing a single phase condition



Computation of the expected temperature rise in the phase winding with the highest current by taking $2 \times (percent\ voltage\ unbalance)^2$
There are two definitions for unbalance voltage based on the symmetrical components. They are;
(i). negative sequence voltage unbalance factors and;
(ii). Zero sequence voltage unbalanced factor
Negative sequence voltage unbalance factor $=\frac{V_2}{V_1}$ (1)
and zero sequence voltage unbalance factor $= \frac{V_0}{V_1}$ (2)
where V_1, V_2 and V_0 are positive, negative and zero sequence voltage respectively.
Zero sequence currents cannot flow in three wire systems such as three- phase induction motors; hence it is of little practical value. Negative sequence unbalance is the quantity of practical significance as it indicates the level of voltage that attempts to turn a three-phase induction motor in a direction opposite to that established by the positive sequence voltages [4], [13], [14] .

C. Motor Protection

Three – phase motors can be protected from overload (overcurrent) by two overload protective device in the form of properly sized time –delay dual- element fuses or overload heaters and relays



Two motor overload protective devices provide adequate condition where the voltage between phases is equal. When a balanced voltage overload persists, the protective devices usually open simultaneously. In some cases, one device opens and shortly thereafter, the second device opens. In either case, three-phase motors are protected against balanced voltage overload conditions [10].

D. Single-Phasing

Single-phasing is a condition where one of the phases of a three-phase system is open. A secondary single–phasing condition subjects an electric motor to the worst possible case of voltage –unbalance.Whenever a three-phase motor is running during the "single –phase" condition, it will deliver its full horsepower enough to drive its full horse power. The motor will continue to drive the load until the motor burns out or until the properly sized overload elements and/or properly sized dual element; time-delay fuses take the motor off the line. For lightly loaded three-phase motors, square root of three ($\sqrt{3}$) under secondary single-phasing conditions will result in a current more than the nameplate full load current [3],[9].

E. Causes of single-phasing on Transformer Secondary

Single- phasing can occur on either the primary side or secondary side of a distribution transformer. Three-phase motors, when not individually protected by three time-delay, dual element fuses or three overload devices are subject to damaging overcurrents caused by primary single-phasing or secondary single-phasing.

The causes of single –phasing on transformer secondary are [11] [17]; [21].

(i). Open winding in motor
(ii) Open winding in one phase of transformer
(iii). Any open circuit in any phase anywhere between the secondary of the transformer and the motor
(iv). Open connection in wiring such as in motor junction box
(v) Open cable caused by overheated lug on secondary side connection to service
(vi) Open cable or bus on secondary of transformer terminals.
(vii) Open fuse or open pole in circuit breaker on main feeder or motor branch circuit
(viii) Damaged switch or circuit breaker on the main feeder or motor branch circuit
(ix) Burned open overload relay from a line-to-ground fault on a 3 or 4 wire grounded system
(x) Damaged motor starter contact –one pole open

F. Causes of single-phasing on transformer primary

Single-phasing on transformer primary can be caused by the following;

(i) Opening of the primary fuse
(ii) Open winding in one phase of transformer
(iii) Open pole on 3-phase automatic voltage tap changer
(iv) Failure of 3-shot automatic recloser to make up on all 3 poles
(v) Defective contacts on primary breaker or switch –failure to make up to on all poles
(vi) Primary wire burned off from short-circuit created by bird or animals
(vii) Primary wire broken by storm (wind), ice- steel, lightning, vehicles or airplane striking pole; falling trees, construction of mishaps

When primary single- phasing occurs, an unbalanced voltage appears on the motor circuit, causing excessive unbalanced currents [2], [18].

G. Effect of single-phasing on three-phase motors

The effect of single-phasing on three-phase motors varies with service conditions and motor terminal capacities. When single-phased, the motor temperature rise may not vary directly with the motor current; the motor temperature rise may increase at a rate greater than the increase in current. In some cases, protective devices which sense only current may not provide complete single-phasing protection.

H. Effect of Voltage Unbalance

The effects of voltage unbalance are associated with three phase motors. These effects are;

- Increased motor losses, reduced efficiency and therefore increased running costs
- Increased losses results in additional heating and loss of motor insulation life
- Effective torque and speed will be reduced
- Increased motor noise

I. Induction Motor

The three-phase induction motor is rated 25Hp, 240 volts. The rotation losses of the motor are 2.95kW. The stator, rotor and magnetizing impedance are as follows;
Stator: $R_s = 0.0774\ \Omega, X_s = 0.1843\ \Omega$
Rotor: $R_r = 0.0908\ \Omega, X_m = 4.8384\ \Omega$
The positive sequence slips is assumed to be
$S = 0.03845$
The induction motor "phase form impedance matrix" in Ohms is computed [3],[6],[9],[20]

II. MATHEMATICAL BACKGROUND

When a three-phase induction motor is supplied by an unbalanced system, the resulting line currents show a degree of unbalance that is several times the voltage unbalance. Consider a positive sequence set of voltages; If the motor slip is

$$S_1 = \frac{N_s - N_r}{N_s} \tag{3}$$

Where
$N_s = synchronous\ speed$
$N_r = rotor\ speed$
The slip corresponding to the negative sequence set of voltages would be;

$$S_2 = \frac{-N_s - N_r}{-N_s} \tag{4}$$

Slip S_2 can be expressed in terms of slips and hence;

$$S_2 = \frac{-N_s - N_r}{-N_s} = (2 - S_1) \tag{5}$$

Since the positive sequence slip S_1 is normally very small (close to zero) the negative sequence slip would be very large, close to 2.

From the basic theory of induction motors, the impedance of an induction motor is very dependent on the slip where at high slip (at start or under locked rotor conditions), it is small and at low slip, it is very large.
The ratio of the positive sequence impedance to negative sequence impedance is given by;

$$\frac{Z_1}{Z_2} \approx \frac{I_{start}}{I_{runing}} \tag{6}$$

The positive sequence current is given by;

$$I_1 = \frac{V_1}{Z_1} \tag{7}$$

The negative sequence current is given by

$$I_2 = \frac{V_2}{Z_2} \tag{8}$$

$$:-\frac{I_2}{I_1} = \frac{V_2}{V_1} \times \frac{I_{start}}{I_{runing}} \tag{9}$$

If the motor is fully loaded, some start phase windings and the rotor will carry more current than that is permitted, thus causing extra motor losses. This will lead to a reduction in motor efficiency while reducing the insulation life caused by overheating.

$$:-\frac{V_2}{V_1} = \sqrt{\frac{1-\sqrt{3-6\beta}}{1+\sqrt{3-6\beta}}} \tag{10}$$

Where $\beta = \frac{V_{ab}^4 + V_{bc}^4 + V_{ca}^4}{(V_{ab}^2 + V_{bc}^2 + V_{ca}^2)^2}$ (11)

β is called the voltage unbalance factor (VUF).
Similarly,
Voltage unbalance = Maximum deviation form

$$\frac{mean\ \ of\ (V_{ab}, V_{bc}, V_{ca})}{mean\ \ of\ (V_{ab}\ .V_{bc}\ .V_{ca})} \quad (12)$$

The following steps were taken in the analysis;

(i) Fifty typical electric motors were used as case studies in this research paper.
(ii) Currents through each motor lead were measured and recorded
(iii) All the three input power lines A, B and C were rotated while ensuring that the order of the leads did not change because changing the order will change the motor's rotation
(iv) The currents in each lead in the new configuration were measured and recorded
(v). All the three input power lines were rotated by one more position
(vi) The current in each lead in the new configuration was measured and recorded
(vii) For each of the three rotation configurations, the average current was determined and the particular power-line/ motor-lead combination that had the maximum deviation from the average current was noted
(viii) The three power –line /motor lead combination was then compared with maximum current deviation
(viii) Compute the phase –to-phase voltage across each of the three lines i.e $V_{\phi-\phi}(A-B), V_{\phi-\phi}(B-C)$ and $V_{\phi-\phi}(C-A)$ for each of the fifty selected electric motors.
(ix) Compute the percentage voltage unbalance for each of the fifty selected electric motors used on case studies.

If the combination always contains the same motor lead, it indicates a problem with the motor. If the combination always contains the same power line, then the power supply may be at fault.

III. DISCUSSION OF RESULTS

The Phase to phase voltages of the electric motor across lines A to B is displayed in Figure1. The phase to phase voltage of the electric motor fluctuates appreciably as indicated. Electric motor 1,2,3,4 and 5 have phase –to –phase voltage of 497 V, 465V, 462v, 460v and 458V respectively. Motor 10,25, 20 25 and 30 have phase –to-phase voltage of 440V, 413V, 417v, 428V and 415v respectively across line A-B.

Electri motor 39 has the least phase-to-phase voltage of 404V while electric motor 1 has the highest phase-to-phase voltage of 479V across the lines A-B. Figure 2 illustrate the phase –to-phase voltage of the electric motors across lines B-C. Electric motors 2,4,6,8,10 and 12 have phase-to-phase voltages of 458V, 453V, 549V, 542V, 533V and 521V respectively. In addition, electric motors 15, 20, 25, 30, 40 and 50 have phase –to-phase voltages 406V, 410V, 421V, 408V, 463V and 541V respectively. Thus, electric motor 27 has the least phase-to-phase voltages of 404V across line B-c while the electric motor number 45 has the highest phase-to-phase voltage of 546V across the lines B-C. This could be due to the configuration and ordinary nature of electric motors.

The phase –to-phase voltages of the fifty related electric motors across line C-A are shown in figure 3. The voltage profile in this case does not follow a sequential order. 405V, 511V, 488V, 486V, 443v and 511V are the phase –to-phase voltages across lines C-A for electric motors 1, 10, 20, 30, 40 and 50 respectively. The least voltage in this case is 427V and it is increased on electric motor number 41 while 531v is increased as the higher phase-to-phase voltage on electric motor number 4. The combined phase-to-phase voltages of electric motors across the three lines A-B, B-C and C-A is illustrated in Figure 4.

Figure 5 shows the average voltage of electric motors. The average voltages fluctuate with electric motors 1,2,3,4 and 5 have average voltages of 467V, 453V, 451V, 481V and 479V respectively. Electric motor number 32 has the least average voltage of 426V while electric motor number 6 has the highest average voltage of 511V which could be due to the winding nature of the electric motors and the heat dissipation in them. The maximum voltage deviations of the motors are illustrated in Figure 6. The maximum voltage deviations of the motor did not follow a definite sequence as it fluctuates with electric motor number 6 having a maximum voltage deviation of 11V which appeared to be the least in this range. Electric motor number 32 has the highest maximum voltage deviation of 69V.

Figure 7 illustrates the percentage voltage unbalance of the electric motors. Electric motor numbers 2, 4,6,8 and 10 have percentage voltage unbalance of 6.84%, 2.91%, 2.15%, 3.57% and 5.45% respectively. Electric motor number 6 has the least percentage voltage unbalance of 2.15% while electric motor number 39 has the highest percentage voltage unbalance of 15.65% .

The relationship between the average voltage and the maximum voltage deviation of the electric motors is shown in Figure 8. The average voltage and the maximum voltage deviation of the electric motors do not follow a sequential order. Electric motor number 32 has the least average voltage of 426V with electric motor number 6 having the highest average voltage of 511 V. Electric motor number 6 has the least maximum voltage deviation of 11% with electric motor number 32 having the highest maximum voltage deviation of 69V due to the configuration of the electric motors. Figure 9 shows the variation of the average voltage with the percentage voltage unbalance of the motors. Electric motor number 6 has the highest average voltage of 511V which corresponds to the least percentage voltage unbalance of 2.15% for the same electric motor with electric motor number 32 having the least average voltage of 426V. Electric motor number 6 has the highest average voltage of 511V corresponding to the least percentage voltage unbalance of 2.15%

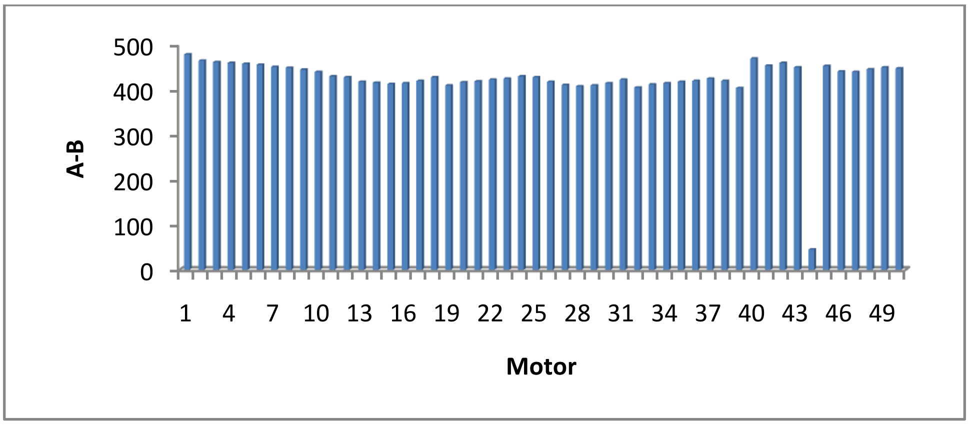


Figure1; Phase-to-phase voltage of motors across lines A-B

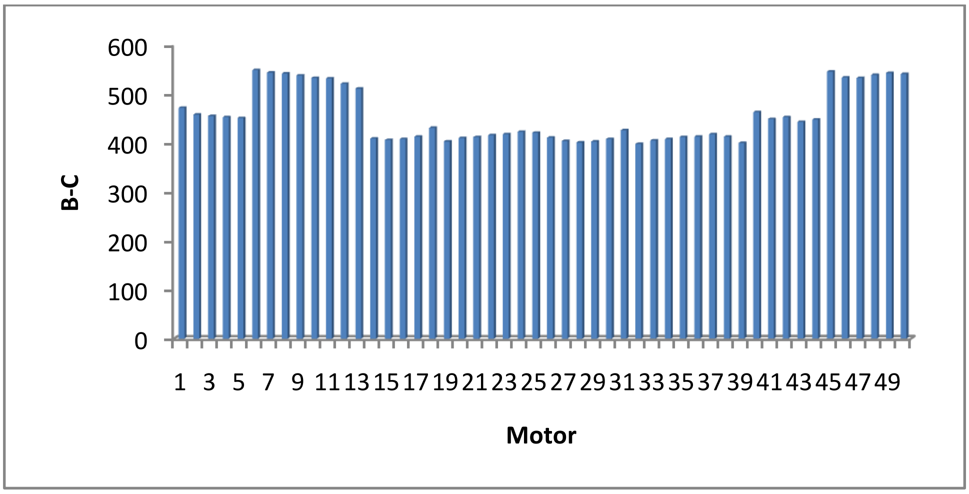


Figure 2; Phase –to-phase voltage of the motors across lines B-C

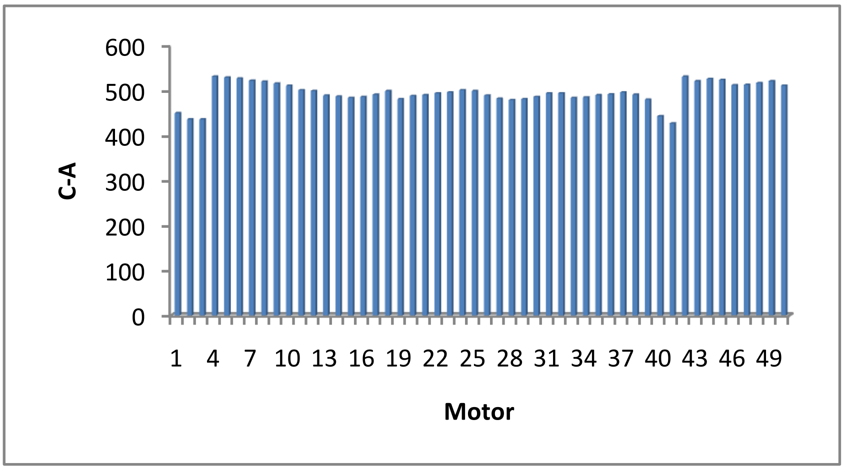


Figure3: Phase –to-phase voltage of the motors across lines C-A

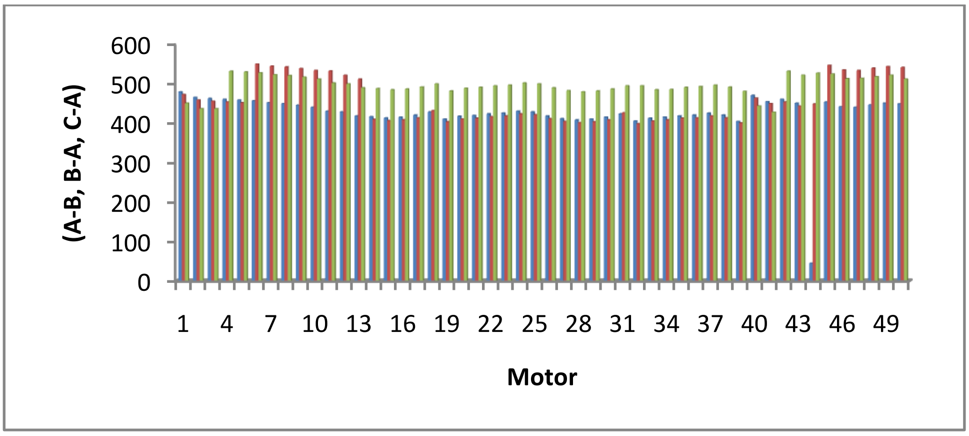


Figure 4:Combined phase-to-phase voltages of the motor across the three line A-B, B-C and C-A

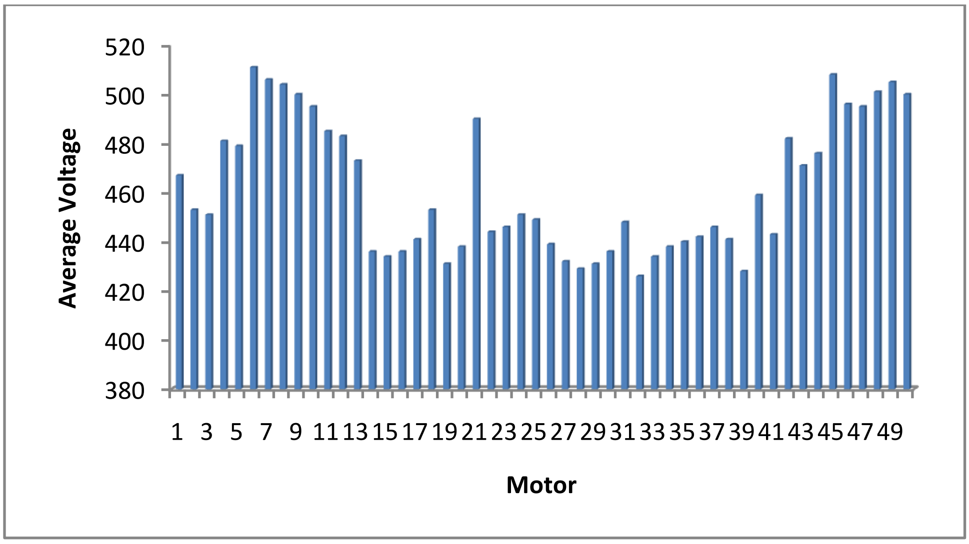


Figure 5: Average voltage of the motors

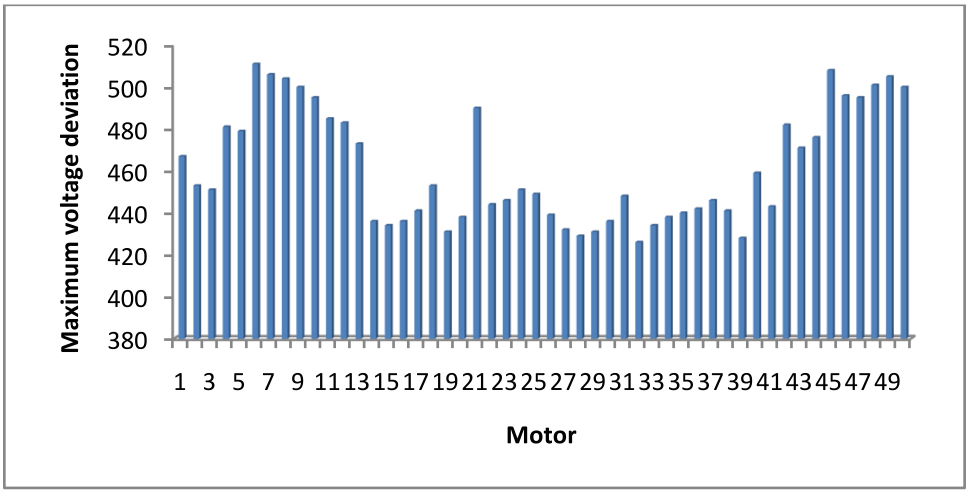


Figure 6: Maximum voltage deviation of the motors

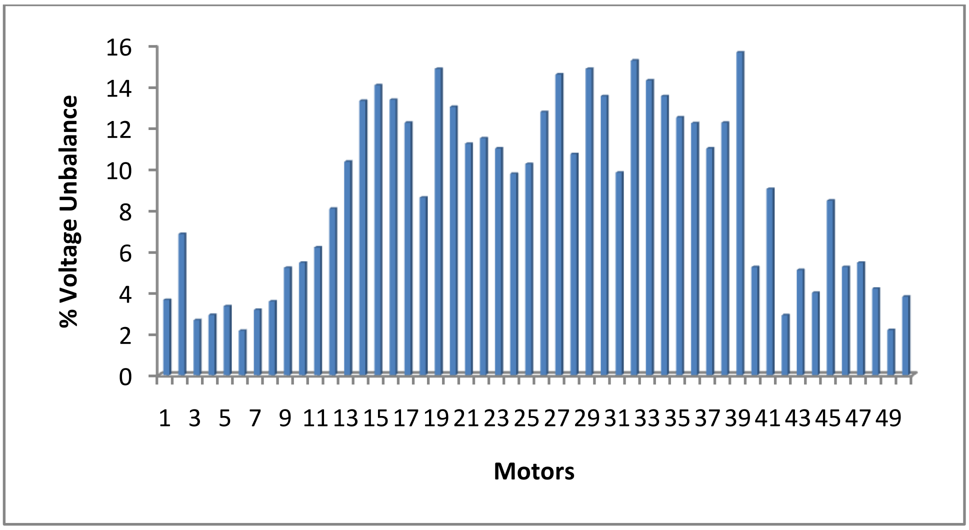


Figure 7: Percentage voltage unbalance of the motors

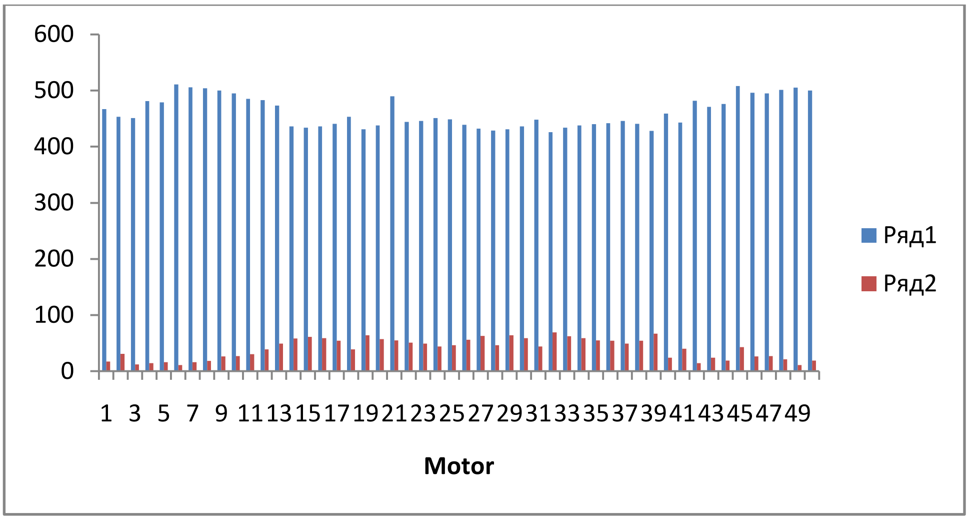


Figure 8: Variation of average voltage with the percentage voltage unbalance of the motors

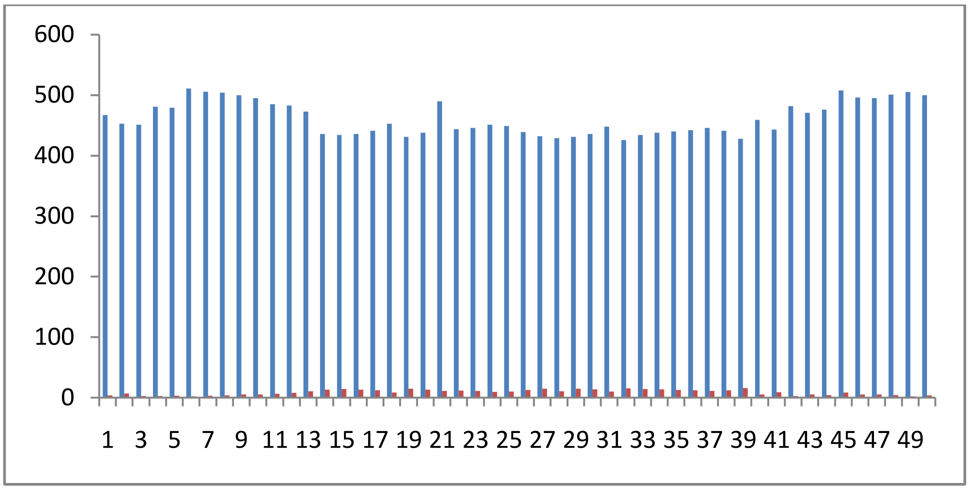


Figure 9: Variation of the average voltage with the percentage voltage unbalance of the motors

IV. CONCLUSION

A methodology for computation of voltage unbalance in electric motor protection system has been presented. Currents through the leads of the motors were measured and recorded. All the three input power lines were rotated thus ensuring that the order of the leads did not change.

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