INTEGRAL energy

Power Quality Centre

Technical Note No. 6 **October 2002**

VOLTAGE UNBALANCE

This Technical Note discusses voltage unbalance, its causes and effects, and what can be done to reduce it. Integral Energy, your local Network Operator or the Integral Energy Power Quality Centre can give you advice if you have particular concerns with this issue

Summary

Voltage unbalance is regarded as a power quality problem of significant concern at the electricity distribution level. Although the voltages are quite well balanced at the generator and transmission levels the voltages at the utilisation level can become unbalanced due to the unequal system impedances and the unequal distribution of single-phase loads.

An excessive level of voltage unbalance can have serious impacts on mains connected induction motors. The level of current unbalance that is present is several times the level of voltage unbalance. Such an unbalance in the line currents can lead to excessive losses in the stator and rotor that may cause protection systems to operate causing loss of production. Although induction motors are designed to tolerate a small level of unbalance they have to be derated if the unbalance is excessive. If operated at the nameplate rated capacity without derating the useful life of such induction motors can become quite short. If an induction motor is oversized to a given application then some level of protection is built into its operation although the motor does not operate at the best efficiency and power factor.

Voltage unbalance also has an impact on ac variable speed drive systems where the front end consist of three-phase rectifier systems. The triplen harmonic line currents that are uncharacteristic to these rectifier systems can exist in these situations leading to unexpected harmonic problems.

Although it is practically impossible to eliminate voltage unbalance it can be kept under control at both utility and plant level by several practical approaches.

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University of Wollongong

1. Introduction

In a balanced sinusoidal supply system the three line-neutral voltages are equal in magnitude and are phase displaced from each other by 120 degrees (Figure 1). Any differences that exist in the three voltage magnitudes and/or a shift in the phase separation from 120 degrees is said to give rise to an unbalanced supply (Figure 2).

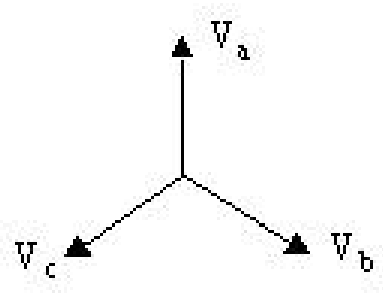


Figure 1 A balanced system

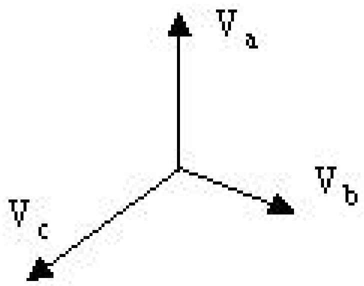


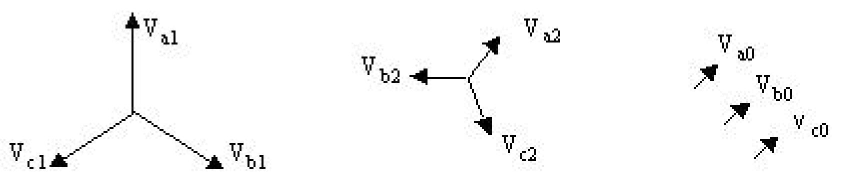
Figure 2 An unbalanced system

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. While it is difficult or virtually impossible to provide a perfectly balanced supply system to a customer every attempt has to be taken to minimise the voltage unbalance to reduce its effects on customer loads.

2. Definitions of voltage unbalance

The level of voltage unbalance that is present in a system can be specified using two commonly used definitions.

Widely used in European standards, the first definition originates from the theory of Symmetrical Components which mathematically breaks down an unbalanced system into three balanced systems as shown by Figure 3. These three are called positive sequence, negative and zero sequence systems. For a perfectly balanced system both negative and zero sequence systems would be absent.



positive sequence negative sequence zero sequence

Figure 3 Symmetrical components of an unbalanced system of voltages

These sequence systems can be given some physical interpretation. The direction of rotation of a three-phase induction motor when applied with a negative sequence set of voltages is opposite to what is obtained when the positive sequence voltages are applied. Having no phase displacement between the three voltages in the zero sequence system, when applied to a three-phase induction motor, it will not rotate at all as there will be no rotating magnetic field.

Strictly speaking, there should be two definitions for unbalance based on the symmetrical components. They are: (a) negative sequence voltage unbalance factor $= \frac{V_2}{V_1}$ and (b) zero sequence voltage unbalance factor $= \frac{V_0}{V_1}$ (where V_1, V_2 and V_0 are positive, negative and zero sequence voltages respectively). However, as zero sequence currents cannot flow in three wire systems such as three-phase induction motors the zero sequence voltage unbalance is of little practical value. The 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. The negative sequence voltage unbalance [1] can also be expressed in a more user-friendly form as given by equation (1) which requires only the three line-line voltage readings.

$$Negative\ sequence\ voltage\ unbalance = \frac{V_2}{V_1} = \sqrt{\frac{1-\sqrt{3-6b}}{1+\sqrt{3-6b}}} \quad where\ b = \frac{V_{ab}^4 + V_{bc}^4 + V_{ca}^4}{(V_{ab}^2 + V_{bc}^2 + V_{ca}^2)^2} \quad (1)$$

This is also sometimes known as the Voltage Unbalance Factor (VUF) or the IEC definition in some literature.

The second definition [2] is the NEMA (National Electrical Manufacturers Association of USA) standard definition that is given by equation (2).

$$Voltage\ unbalance = \frac{Maximum\ deviation\ from\ mean\ of\ \{V_{ab}, V_{bc}, V_{ca}\}}{Mean\ of\ \{V_{ab}, V_{bc}, V_{ca}\}} \quad (2)$$

Line-neutral voltages should not be used with equations (1) and (2) as the zero sequence components can give incorrect results.

It is also important to note that the IEC definition is mathematically rigorous compared to the NEMA definition and when calculating the voltage unbalance the two definitions can cause different results.

As an example, consider a three-phase supply system having the line-neutral voltages (in volts):

$$V_a = 232\angle 0^0 \quad V_b = 240\angle -121^0 \quad V_c = 242\angle +119^0$$

The corresponding line-line voltages are:

$$V_{ab} = 410.83\angle 30.05^0 \quad V_{bc} = 417.43\angle -90.86^0 \quad V_{ca} = 408.44\angle +148.79^0$$

Hence the voltage unbalance according to the NEMA definition is 1.26% and the same according to the IEC definition is 1.31%.
In the case of resistive type loads such as three-phase electric heaters the supply voltage unbalance is of no major concern except for the unequal heating in the different phases and the unbalanced nature of the line currents. With the practical levels of voltage unbalance that is present in supply systems there is no real threat on the successful operation of such heaters as the level of resulting current unbalance is proportional to the level voltage unbalance.

proportional to the level voltage unbalance.

3. Effects of voltage unbalance on induction motors

The greatest effect of voltage unbalance is on three-phase induction motors. Three phase induction motors are one of the most common loads on the network and are found in large numbers especially in industrial environments. 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. This can be explained with reference to the two contra-rotating fields established when the motor is subjected to voltage unbalance. In relation to the positive sequence set of voltages if the motor slip is:

$$s_1 = \frac{N_s - N_r}{N_s} \qquad (3)$$

N_s - synchronous speed
N_r - the rotor speed

the slip corresponding to the negative sequence set of voltages would be

$$s_2 = \frac{-N_s - N_r}{-N_s} \quad .$$

Slip s_2 can be expressed in terms of slip s_1 and hence

$$s_2 = \frac{-N_s - N_r}{-N_s} = (2 - s_1) \qquad (4)$$

As the positive sequence slip s_1 is normally very small (close to zero) the negative sequence slip s_2 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 (eg. at start or under locked rotor conditions) it is small and conversely at low slip it is very large. Hence it can be approximately stated [3] that the ratio of the positive sequence impedance to negative sequence impedance is given by:

$$\frac{Z_1}{Z_2} \approx \frac{I_{start}}{I_{running}} \qquad (5)$$

As the positive sequence current is given by $I_1 = \frac{V_1}{Z_1}$ and the negative sequence current is given by $I_2 = \frac{V_2}{Z_2}$ it can be quickly shown that:

$$\frac{I_2}{I_1} = \frac{V_2}{V_1} x \frac{I_{start}}{I_{running}} \qquad (6)$$

As an example, a motor with a locked rotor current that is 6 times the running current would give rise to a very significant 30% unbalance in the motor line current if the voltage unbalance is 5%.

If the motor is fully loaded some stator 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. It is worth noting that average expected life of insulation halves for every 10°C of temperature increase as depicted in Figure 4.

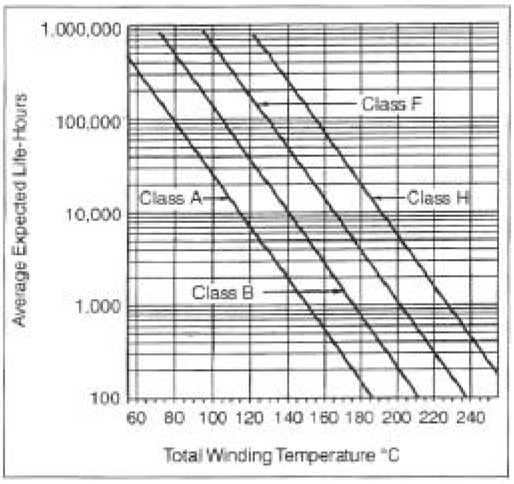


Figure 4 Variation of insulation life with temperature [4]

In addition to reduced efficiency, overheating and loss of insulation life, induction motors operating with unbalance will be noisy in their operation caused by torque and speed pulsations. Obviously in such situations the effective torque and speed will be less than normal.

Realising that voltage unbalance causes extra losses, in order to safeguard motors from overloading NEMA has developed a derating curve [2] as shown by Figure 5. This curve assumes that the motor is already delivering the rated load. According to this curve it is required that any motor should be built to handle 1% unbalance and thereafter it should be derated depending on the level of unbalance. For example if the unbalance is 3% a 10kW motor should be loaded up to only 9kW. If 10kW of power is to be developed with 3% unbalance the motor should be rated to about 12kW or should have a service factor of 1.15. Operation of an induction motor above 5% voltage unbalance is not recommended.

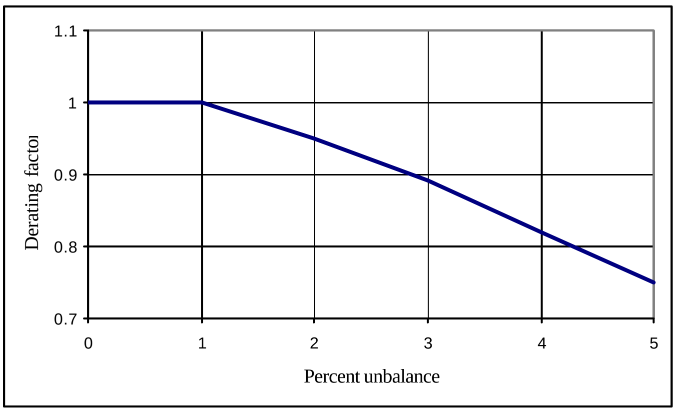


Figure 5 NEMA induction motor derating curve

Although the curve given by Figure 5 seems universally applicable, recent studies indicate [5] that the level of derating applicable to a motor depends on its size and design.

4. Effects of voltage unbalance on AC variable speed drive systems

Three-phase diode rectifier systems are an essential part of AC variable speed drives and uninterruptible power supplies. These rectifier systems draw non-sinusoidal current waveforms from the ac mains. If the ac supply system is balanced the line current waveform may take the "double pulse per half cycle" shape as shown in Figure 6 that contain characteristic harmonic orders given by:

$$h = 6k \pm 1 \qquad (7)$$

where h = harmonic order and k = 1, 2,….

giving only 5^{th}, 7^{th}, 11^{th}, 13^{th} …order harmonics.

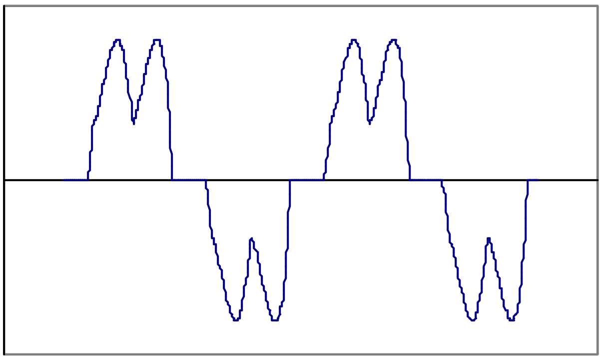
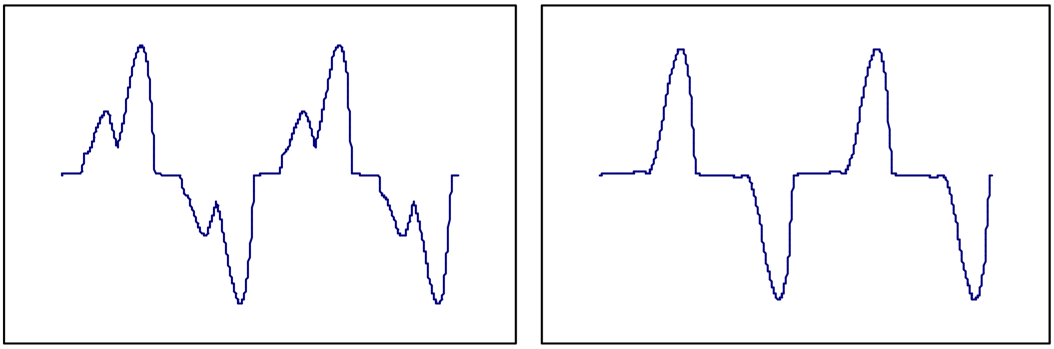


Figure 6 Line current waveform of a three-phase diode rectifier system when the supply system is balanced

As the supply system becomes unbalanced the line current waveform deviates away from the double pulse formation of Figure 6 to single pulse formation as shown by Figures 7(a) and 7(b) leading to uncharacteristic triplen harmonics. Supply voltage unbalance can lead to tripping of drive systems that is caused by excessive ac line currents on some phases and under voltage on the dc link. This can also lead to excessive thermal stress on diodes and dc link capacitor. Increase in the unwanted triplen harmonic currents can also lead to undesirable harmonic problems in the supply system.



(a) Voltage unbalance – 5% (b) Voltage unbalance – 15%

Figure 7 Line current waveforms of a three-phase diode rectifier system when the supply system is unbalanced

In modern ac drive systems with PWM rectifier front ends (instead of diode rectifiers), the effects of supply system unbalance include increased line current distortion, generation of 100Hz ripple on the dc link and increase in the reactive power.

5. Mitigation of voltage unbalance and its effects

Establishment of zero voltage unbalance on a distribution system is clearly impossible due to (a) randomness of the connection and disconnection of single-phase loads (b) uneven distribution of single-phase loads on the three phases and (c) inherent asymmetry of the power system. However, there are utility system level mitigation techniques as well as plant level mitigation techniques [2] that can be used to improve the voltage unbalance and its effects.

Utility level techniques:

- Redistribution of single-phase loads equally to all phases.
- Reduction of the system unbalance that arise due to system impedances such as those due to transformers and lines.
- Single-phase regulators have been suggested as devices that can be used to correct the unbalance but care must be exercised to ensure that they are controlled carefully not to introduce further unbalance.
- Passive network systems and active power electronic systems such as static var compensators and line conditioners also have been suggested for unbalance correction. Compared to passive systems, active systems are able to dynamically correct the unbalance.

Plant level techniques:

- Load balancing.
- Use of passive networks and static var compensators.
- Equipment that is sensitive to voltage unbalance should not be connected to systems which supply single-phase loads.
- Effect of voltage unbalance on ac variable speed drives can be reduced by properly sizing ac side and dc link reactors.

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.

6. References

1. A. Robert and J. Marquet, 'Assessing Voltage Quality with relation to Harmonics, Flicker and Unbalance, WG 36.05, Paper 36-203, CIGRE 92.

2. Annette von Jouanne and Basudeb Banerjee, 'Assessment of voltage unbalance', IEEE Trans. on Power Delivery, Vol. 16, No. 4, pp. 782-790, Oct. 2001

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Jose Policarpo G de Abreau and Alexander Eigeles Emanuel, 'Induction motor loss of life due to voltage imbalance and harmonics: A preliminary study', Proceedings of the 9th International Conference on Harmonics and Quality of Power', Vol. 1, pp. 75-80, 2000.

7. Integral Energy Power Quality Centre

In July 1996, Integral Energy set up Australia's first Power Quality Centre at the University of Wollongong. The Centre's objective is to work with Industry to improve the quality and reliability of the electricity supply to industrial, commercial and domestic users. The Centre specialises in research into the control of distortion of the supply voltage, training in power quality issues at all levels, and specialised consultancy services for solution of power quality problems. You are invited to contact the centre if you would like further advice on quality of supply.

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