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The paper aims to assess sources of error in attempting to meet standards for the measurement and reporting of negative sequence voltage unbalance. This is of importance when making use of low performance instrumentation where three difficulties may arise: (i) rms voltages rather than the fundamental is used; (ii) the magnitude but not the phase of line-neutral voltages are available; and (iii) voltage values are averaged over a period longer than standards require. The presence of harmonics at normal levels is shown to give negligible error on unbalance calculations. When lineneutral voltages are used, and zero sequence is present, the calculated unbalance can show significant errors under steady state conditions but the error can be much smaller under typical time-varying conditions. When line-line voltages are not available at high sampling rates, the unbalance calculated can be about 40% too small.

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SOURCES OF ERROR IN UNBALANCE MEASUREMENTS

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Abstract

The paper aims to assess sources of error in attempting to meet standards for the measurement and reporting of negative sequence voltage unbalance. This is of importance when making use of low performance instrumentation where three difficulties may arise: (i) rms voltages rather than the fundamental is used; (ii) the magnitude but not the phase of line-neutral voltages are available; and (iii) voltage values are averaged over a period longer than standards require. The presence of harmonics at normal levels is shown to give negligible error on unbalance calculations. When line-neutral voltages are used, and zero sequence is present, the calculated unbalance can show significant errors under steady state conditions but the error can be much smaller under typical time-varying conditions. When line-line voltages are not available at high sampling rates, the unbalance calculated can be about 40% too small.

1. INTRODUCTION

1.1 Overview

Three-phase voltage unbalance is a frequently encountered power quality issue in LV distribution networks and in MV power systems that supply large single phase loads. The causes of voltage unbalance are complex, but can be categorized as structural or functional. The former refers to the asymmetry in the three-phase impedances of transmission/ distribution lines, cables, transformers, etc. It occurs because it is neither economical nor necessary to maintain distribution system with perfectly symmetrical impedances. The latter refers to uneven distribution of power consumption over the three phases. Unbalance can appear as unequal voltage magnitudes at fundamental frequency, fundamental phase angle deviation and unequal voltage levels of harmonic distortion between the phases [1-3]. Its main effects are excessive heating and loss of insulation life in mains connected three-phase induction motors and asymmetrical conduction in multiphase rectifiers.

To reduce the degree of unbalance, efforts are made to distribute single phase loads among three phases as uniformly as possible. However this only ensures the average values of the loads in the three phases are to be approximately equal, with significant instantaneous unbalance since loads supplied by each phase vary in a random manner. Unbalance arising from this cause varies in a stochastic manner.

1.2 Definitions of unbalance

There are two widely accepted definitions for voltage unbalance, the IEC (International Electrotechnical Commission) and NEMA (National Electrical Manufacturers Association) definitions.

A. IEC definition

IEC definition of voltage unbalance factor (VUF) is the one most generally used and is given by the ratio of negative-to-positive sequence voltage.

i.e. $$VUF = \frac{V_n}{V_p} \qquad (1)$$

where, V_n is the negative sequence voltage and V_p is the positive sequence voltage. This also can be determined using set of line-line voltages of, V_{ab}, V_{bc} and V_{ca} and as given by,

$$\beta = \frac{V_{ab}^4 + V_{bc}^4 + V_{ca}^4}{(V_{ab}^2 + V_{bc}^2 + V_{ca}^2)^2} \quad VUF = \sqrt{\frac{1-\sqrt{3-6\beta}}{1+\sqrt{3-6\beta}}} \qquad (2)$$

B. NEMA definition

The NEMA definition of VUF is given by the ratio of the maximum deviation from average voltage, to the average of three voltages.

i.e. $$VUF = \frac{V_{Mean} - Max(V_{ab}, V_{bc}, V_{ca})}{V_{Mean}} \qquad (3)$$

Where, V_{Mean} - Mean of V_{ab}, V_{bc}, V_{ca}

The NEMA definition is simple to calculate and is sometimes used as an estimate of the more complex IEC quantity. A comparison of VUF calculated from both definitions shows a discrepancy of up to 13% [4]. However, the IEC definition is preferred as it is a direct measure of undesirable effects on customer loads such as an induction motor, and will be the definition used in the rest of the paper.

The paper will discuss relevant standards and attempt to find a consistent framework for unbalance measurement and reporting. This is particularly important under the usual time-varying conditions when the timescale of measurement and the averaging procedure has to be carefully specified if consistent reporting is to be obtained. Attention is given to problems which might arise with the use of instruments which do not strictly conform to recognised standards. A possible source of error is the use of total rms voltage rather than the fundamental component. The use of line-neutral voltage values (easier to measure in LV systems) rather than the specified line-line values can give errors if there is significant zero sequence component present. Another source of error is the determination of unbalance from voltages averaged over a long timescale, such as 10 minutes, rather than over 0.2 sec as required by IEC standards.

2. STANDARDS

Unbalance needs to be consistent with existing and developing practices to allow comparisons with international performance levels and standards. There are several such standards, IEEE Std. 1159 [5], CENELEC EN 50160 [6], BS EN 50160 [7], and the Draft Std. IEC-61000-4-30 [8]. [6] is the only comprehensive voltage quality standard at present while [8] is a PQ measurement standard under development and being considered for eventual adoption by Australia. We will discuss [6] and [8] which are considered more relevant to this paper.

2.1 IEC 61000-4-30

This draft standard [8] defines the methods for measurement and interpretation of results for power quality parameters such as voltage unbalance in 50/60 Hz a.c. power supply systems. Two classes of instrument measurement performance are defined.

(i) Class A: having an accuracy and measurement procedures as defined in the standard, to be used where precise measurements are necessary and recommended for contractual purposes and for verifying compliance with standards.
(ii) Class B: having a lower accuracy and measurement procedures as specified by the instrument manufacturer, for use with statistical surveying and troubleshooting.

There are some difficulties with this classification. Class B accuracy and measurements procedure are given very loose specification. The Class A allowable instrumentation errors are very small, making such an instrument very expensive. However, Class B procedures are too loosely specified to allow consistent measurement and reporting across a number of sites. Hence [9] recommends that the industry should aim for Class B accuracy and Class A measurement procedures.

2.2 CENELEC EN 50160

The CENELEC standard [6] is the most comprehensive standard for utility voltage quality at present. It recognizes that the power system is subject to disturbing factors additional to network operations, for example load changes and external atmospheric events. Hence the utility cannot be expected to be able to control the level of PQ disturbances 100% of the time. The standard requires that the specified limits have to be met for 95% of the 10-minute values over each week, the limit being 2% for unbalance. Since unbalance variations tend to repeat each day, it is likely that the 5% overlimit value would occur for periods of no longer than 1.2 hours at a time.

3. MEASUREMENT OF INSTANTANEOUS UNBALANCE

3.1 Errors due to use of line-neutral voltages

There are two methods that can be used in a power quality monitor for calculation of unbalance strictly in accordance with standards.

(i) The measurement of fundamental line-line voltage for each cycle using equation (2).
(ii) Measurement of fundamental line-neutral voltages and fundamental phase angles and the use of symmetrical components to calculate VUF using equation (1).

Some instruments are only able to measure line-neutral voltages when used directly connected to a LV measurement point. We now investigate if it is possible to obtain reliable measurements of VUF when only magnitudes of line-neutral voltages are available. There are two plausible approaches that can be applied to the readings in order to make a VUF calculation possible

(i) assume the zero sequence component is negligible and use the line-neutral voltages directly in (2)
(ii) assume the relative phase angles to be insignificantly disturbed from 120°, determine line-line voltages and substitute into (2).

A. Use of line-neutral voltages in equation (2)

If no zero sequence voltages are present, the direct application of line-neutral voltages in formula (2) would give the correct unbalance factor. We have investigated the effect of zero sequence by studying several scenarios by means of a spreadsheet. Some results are given in Table I for fixed line-line voltages of 410, 415 and 420V, giving a negative sequence unbalance of 1.4%. We set-up a zero sequence component of 1% and with varying phase relative to the V_{ab} line-line voltage.

Table I – Calculated unbalance versus zero sequence phase angle

Zero sequence phase angle	Calculated unbalance (%)
0^0	1.25
60^0	0.39
120^0	1.24
180^0	2.17
240^0	2.39
300^0	2.10

It can be seen that the calculated unbalance varies from 0.4 to 2.4%, that is between the sum and the difference of the negative and zero sequence unbalance factors. We have made many other studies with similar results, and the observation is thought to be very general.

B. Use of line-neutral voltages with the assumption of 120^0 relative phase angles

As a preliminary investigation of the importance of phase angle deviations on VUF, phase angles have been determined to give unbalance factors of 1% and 2% with constant voltage magnitudes as shown in Table II. It is seen that small variation of phase angle causes higher VUF variations in relation to constant unbalance. For example a change of 2° can result in 2% unbalance and the assumption of 120° relative phase shift between line-neutral voltages may give an erroneous VUF value.

Table II – Phase angle deviation

Line-neutral Voltage	Phase angle deviation		
	Constant Magnitude	Phase angle φ_1	Phase angle φ_2
V_{an}	240	0	0
V_{bn}	240	-119	-118
V_{cn}	240	+119	+118
VUF %		1%	2%

We have made a mathematical study of the use of line-line voltages calculated from line-neutral voltages with the assumption of 120° relative phase angles for the case of no zero sequence voltage (Appendix A). When the negative sequence unbalance is small (a few percent) it is possible to show that the unbalance computed is half of the correct value.

When zero sequence voltage is present, spreadsheet scenarios suggest that the calculated value varies from the half the difference to half the sum of the negative and zero sequence unbalance factors, depending on the relative phase angle of zero sequence. This is clearly an extension of the result from the preceding Subsection A.

We conclude that there is no reliable method of determining negative sequence unbalance from line-neutral voltages unless it is known that the zero sequence is relatively small. If this is the case line-line voltages should be substituted in to equation (2).

Although the above conclusion holds for the calculation of instantaneous VUF, we shall show in Section 4.2 that line-neutral voltages can be used for the measurement of average VUF over time periods such as 10 minutes.

3.2 Errors due to harmonic distortion

Measured data from PQ monitoring campaigns where there are low cost monitors used may have recorded the rms voltages with harmonics included. Harmonics can be balanced or unbalanced over the three phases. Detailed discussion on the VUF calculated for both situations is given with examples.

A. Unbalanced fundamental with balanced harmonics

In Table III, two cases have been selected giving both small and large values of VUF with balanced harmonic distortion on all three phases. It is seen that small VUF remain unchanged while large VUF will decrease on higher harmonic conditions. However, these changes are so small as to be negligible.

Table III – VUF with balanced harmonics

Line Voltage	V_{THD}					
	0%		2%		8%	
V_{ab}	415	415	415.08	415.08	416.33	416.33
V_{bc}	416	410	416.08	410.08	417.32	411.34
V_{ca}	414	424	414.08	424.08	415.33	425.30
V U F %	0.28	1.97	0.28	1.97	0.28	1.96

B. Unbalanced fundamental with unbalanced harmonics

Table IV shows that the VUF calculated with both a small and large voltage total harmonic distortion (VTHD) conditions respectively in relation to the unbalanced harmonics.

Table IV – VUF with unbalanced harmonics

Line Voltage	V_{THD}					
	0%, 0%, 0%		0%, 2%, 2%		0%, 8%, 8%	
V_{ab}	415	415	415	415	415	415
V_{bc}	416	410	416.08	410.08	417.32	411.34
V_{ca}	414	424	414.08	424.08	415.33	425.30
VUF %	0.28	1.97	0.28	1.97	0.14-0.47	1.76-2.13

In Table IV, the same voltages were selected as the previous example to give a good comparison on unbalanced harmonic distortion among three phases. The effect is given as a range of values since it depends on how the unbalance in the harmonics aligns with that in the fundamental voltage. The effect is negligible at medium levels of harmonics, but can approach ±0.2% at values near the harmonic limit.

The overall effect of harmonics on unbalance calculations can be seen to be negligible at normal harmonic levels.

4. REPORTING OF TIME-VARYING UNBALANCE

4.1 Errors due to incorrect averaging

IEC 61000-4-30 [8] recommends monitoring and reporting using 10-minute interval in relation to unbalance. The measurement aggregation algorithm is performed using the square root of the mean of the squared input values, in other words the rms average.

Let us consider the distinction between two possible methods of measuring VUF in a time-varying situation: (i) calculation from voltages averaged over 0.2 sec followed by averaging the VUF over 10 minutes ("Average of the Unbalance") or (ii) calculation directly from 10-minute rms average line-line voltage values ("Unbalance of the Average"). The first method follows [8] while the second might be used by cheaper instruments or for off-line calculation when only 10 minute average values of voltage are available.

The two methods will give different values for VUF under time-varying conditions. It is possible to have a situation where the three phase voltages vary differently and have identical 10 minute average values. In this situation the Unbalance of the Average will be zero while the Average of the Unbalance is non-zero. Since any unbalance in average voltages must be reflected in the instantaneous voltages, we can generalize and state that method (ii) will always give a VUF that is smaller than method (i).

Each method has its own use. The Average of the Unbalance gives a measure of the effect on induction motor loads as it is required for the setting of acceptable limits by [8]. The Unbalance of the Average gives a measure of the unbalance which stays constant over 10 minute period which is most likely due to unbalanced connection of loads and the intrinsic unbalance in the power system.

We have attempted to gain insights into how much the Average of the Unbalance can exceed the Unbalance of the Average. Figure 1 shows field measurements that were taken from the Arbiter Systems Inc. GPS synchronized advanced power quality analyser connected to a 415V three-phase line. This instrument gives voltage readings every second.

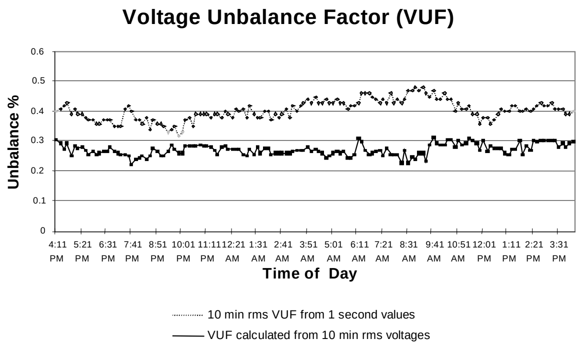

Figure 1. VUF calculated by different algorithms

Figure 1 shows the Average of the Unbalance (grey) with unbalance calculated from 1 second voltage readings and then averaged over 10 minutes, and also the Unbalance of the Average (black) calculated from the 10 minute voltage readings. It is observed that the Average of the Unbalance always higher than the Unbalance of the Average by about 50%. We do not know yet if this ratio holds across a wide variety of sites. [8] actually specifies the Average of the Unbalance using 0.2 second readings rather than the 1 second readings that we were able to achieve. It could be possible that the unbalance readings required by [8] are even larger than the grey curve shown. A provisional recommendation following this study is that where Unbalance of the Average readings are available, the Average of the Unbalance readings are estimated to be 50% larger.

4.2 Errors due to use of line-neutral voltages

Field measurements were taken using two CHK PM30 POWERmonics which were connected to the same point in a laboratory supply to measure line-line and line-neutral voltages over 10 minute intervals. Figure 2 shows the comparison of VUF calculated from both average rms line-line and line-neutral voltages with the assumptions of (i) negligible zero sequence and (ii) negligible deviation of relative phase angles from 120^0.

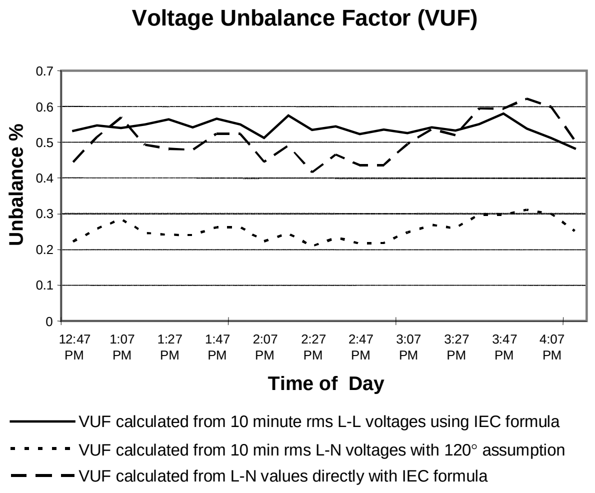

Figure 2 – VUF calculated from 10 min voltages

Figure 2 shows that the calculation from the use of line-neutral values directly in (2) gives almost exactly twice the value as for the use of line-line values inferred from the assumption of 120° relative phase angles. We also see that the first approach gives a trend which is reasonably close to that of the correct use of line-line values. The agreement is sufficiently close that one could consider the use of line-neutral values to estimate the 95% values of unbalance. This suggests that the zero sequence magnitudes and phase angles vary quickly and randomly over the 10 minute interval so that their average effect on the unbalance calculation is very small.

It appears that, where only 10 minute line-neutral voltage values are available, the Unbalance of the Average" can be estimated closely by substitution of these values directly into (2), even when there is zero sequence present. It would be useful to explore this hypothesis with a wide variety of other LV sites.

5. CONCLUSION

The paper has given a discussion of standards applicable to the calculation of voltage unbalance. An important requirement is the method of averaging to be used under time-varying conditions. The paper examines possible errors which can arise with incorrect averaging procedures and the use of line-neutral voltages in VUF calculations.

The work described in this paper has given following important conclusions.

1. Negative sequence VUF calculated from 10 minute average voltages ("Unbalance of the Average") gives a lower value than the correctly calculated 10-minute rms average VUF determined from voltages over a small time scale ("Average of the Unbalance") for the sites investigated.

2. The use of rms voltage measurements in the presence of harmonics (to be compared with the more correct use of fundamental voltage measurements) gives negligible error in VUF calculations providing the harmonics are within acceptable limits.

3. When only line-neutral voltages are available, there are two proposals for determining VUF. The direct use of line-neutral voltages in the standard equation gives twice the value when line-line voltages use used calculated with the assumption that the relative phase angles remain at 120°. This seems to hold even when there is zero sequence present.

4. Under time-varying conditions, the effect of zero sequence seems to be small if calculations are made using line-neutral voltages.

5. The best accuracy in determining VUF is to use line-line voltage calculations made over small intervals, preferably 0.2 sec. If fast sampling values are not available, then either line-line or line-neutral values averaged over 10 minutes can be used directly in the standard equation. They can be scaled up by 40-50% to account for the incorrect sampling times.

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Appendix A: Assumption of equal relative phase angles

Assume that a three phase set of voltages has symmetrical components $\mathbf{V}_1 = \angle 0°$, $\mathbf{V}_2 = U\angle\theta$ and no zero sequence. Then

$$\begin{aligned}\mathbf{V}_a &= 1 + U\angle\theta \\ \mathbf{V}_b &= 1\angle 4\pi/3 + U\angle(\theta+2\pi/3) \\ \mathbf{V}_c &= 1\angle 2\pi/3 + U\angle(\theta+4\pi/3)\end{aligned} \quad (4)$$

Taking magnitudes, using the cos rule where necessary

$$\begin{aligned}V_a^2 &= 1 + 2U\cos\theta + U^2 \\ V_b^2 &= 1 + 2U\cos(\theta-2\pi/3) + U^2 \\ V_c^2 &= 1 + 2U\cos(\theta+2\pi/3) + U^2\end{aligned} \quad (5)$$

For small U

$$\begin{aligned}V_a &\sim 1 + \alpha \\ V_b &\sim 1 + \beta \\ V_c &\sim 1 + \gamma\end{aligned} \quad (6)$$

where

$$\begin{aligned}\alpha &= U\cos\theta + U^2/2 \\ \beta &= U\cos(\theta-2\pi/3) + U^2/2 \\ \gamma &= U\cos(\theta+2\pi/3) + U^2/2\end{aligned} \quad (7)$$

Let us determine what unbalance factor would be calculated if it was assumed that the relative phase angles remained at 120°, ie

$$\begin{aligned}\mathbf{V}_a &= (1 + \alpha)\angle 0° \\ \mathbf{V}_b &= (1 + \beta)\angle -2\pi/3 \\ \mathbf{V}_c &= (1 + \gamma)\angle 2\pi/3\end{aligned} \quad (8)$$

Ignoring 2nd order terms and using the convention $a = 1\angle 2\pi/3$

$$\begin{aligned}\mathbf{V}_1 &= \tfrac{1}{3}(\mathbf{V}_a + \mathbf{V}_b + \mathbf{V}_c) \\ &= \tfrac{1}{3}(1 + \alpha + \beta + \gamma) \sim 1\end{aligned} \quad (9)$$

$$\begin{aligned}\mathbf{V}_2 &= \tfrac{1}{3}(\mathbf{V}_a + a\mathbf{V}_b + a^2\mathbf{V}_c) \\ &= \tfrac{1}{3}(\alpha + \beta\angle 2\pi/3 + \gamma\angle -2\pi/3) \\ &= \tfrac{1}{3}\left(\alpha - \frac{\beta}{2} - \frac{\gamma}{2} + j\frac{\sqrt{3}}{2}(\beta - \gamma)\right) \\ &= \tfrac{1}{3}\left(\tfrac{3}{2}U\cos\theta + j\tfrac{3}{2}U\sin\theta\right)\end{aligned} \quad (10)$$

Hence

$$V_2 = U/2 \quad (11)$$

From (9) and (11)

$$VUF = V_2/V_1 = U/2 \quad (12)$$