

POWER QUALITY ANALYSIS OF MAGNITUDE IN UNBALANCED SYSTEM

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Abstract: A proposal is presented for characterization of voltage dips as experienced by three-phase load. The primary result of the method is a so-called "characteristic magnitude" which corresponds to the magnitude (remaining voltage) as used for the existing methods to characterize dips experienced by single-phase load. The proposed method may be extended by adding additional parameters where further accuracy is needed for characterization. The method is applied to the analysis of multi-stage voltage dips.

Key words: power quality, voltage sag, load flow, symmetrical

1. Introduction

Existing standard documents on voltage dips (sags) characterize a dip through one magnitude (remaining voltage or voltage drop) and one value for the duration [6,7,8]. There are obvious limitations to this method as one e.g. neglects the phase-angle jump [1] and the post-fault dip [2]. For the majority of sensitive single-phase equipment, the existing characterization enables a prediction of the behavior of the equipment during and after the event. Further, the phase-angle jump can be incorporated by using a complex dip voltage; the post-fault dip can be incorporated by giving the magnitude as a function of time. Three-phase equipment will typically experience three different magnitudes, as the majority of dips are due to single-phase or phase-to-phase faults. The existing method of characterization uses the lowest of the three voltages and the longest duration. An example of a three-phase unbalanced dip is shown in Fig. 1.

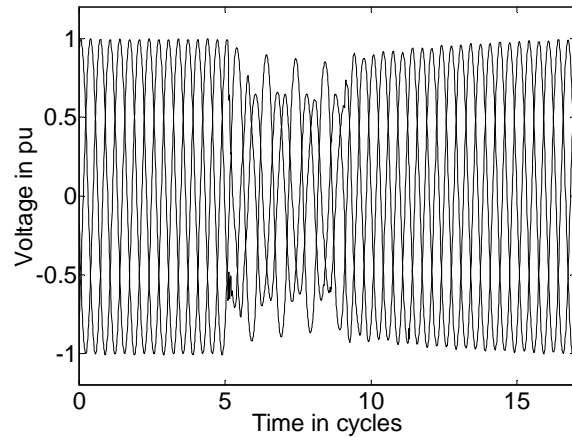


Fig. 1. Three-phase unbalanced sag.

Dip characterization is often part of the voltage characteristics / power quality in general. In that case, the results should be applicable both to single-phase and three-phase equipment. Using the lowest of the three voltages to characterize the dip will result in erroneous results for both single-phase and three-phase equipment. An alternative technique is proposed in this document, which enables a characterization through one complex voltage, without significant loss of information. Two methods are described for obtaining the characteristics: one mathematically correct method, one simple method. The characterization is applied to multi-stage voltage dips, enabling an explanation of the events behind the different stages.

2. Analysis

A. Basic Classification

A classification of three-phase unbalanced dips was proposed in [5]. The classification considers three-

phase, single-phase and phase-to-phase faults, star and delta-connected equipment and all types of transformer connection. It was further assumed that the non-faulted phase voltages would not be affected by the fault. This resulted in four types of three-phase unbalanced dip, shown in Fig. 2. Type A is due to three-phase faults, types B, C and D are due to single-phase and phase-to-phase faults. Type B contains a zero-sequence component which is rarely transferred down to the equipment terminals. Three-phase equipment is normally connected in delta or in star without neutral connection. Single-phase low-voltage equipment is connected between phase and neutral, but the number of dips originating in the low-voltage system is small. Therefore the vast majority of three-phase unbalanced dips at the equipment terminals are of type C or type D, so that a distinction between type C and D is sufficient, together with a characteristic magnitude and phase-angle jump. The definition of characteristic magnitude and phase-angle jump is such that these do not change when the dip transfers from one voltage level to the other. The characteristic magnitude and phase-angle jump are defined as the absolute value and the argument of the complex phasor representing the voltage in the lowest phase for a type D dip, and the voltage between the two lowest phases for a type C dip.

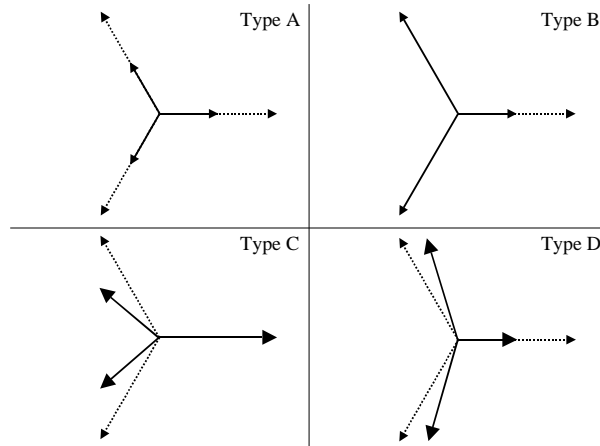


Fig. 2. Four types of three-phase unbalanced voltage dips in phasor- diagram form.

The complex voltages for a three-phase unbalanced dip of type C with characteristic voltage \bar{V} are as follows:

$$\begin{aligned}\bar{V}_a &= 1 \\ \bar{V}_b &= -\frac{1}{2} - \frac{1}{2} j\sqrt{3} \\ \bar{V}_c &= -\frac{1}{2} + \frac{1}{2} j\sqrt{3}\end{aligned}\quad (1)$$

For a dip of type D the complex voltages are:

$$\begin{aligned}\bar{V}_a &= \bar{V} \\ \bar{V}_b &= -\frac{1}{2}\bar{V} - \frac{1}{2}j\sqrt{3}\bar{V} \\ \bar{V}_c &= -\frac{1}{2}\bar{V} + \frac{1}{2}j\sqrt{3}\bar{V}\end{aligned}\quad (2)$$

B. Generalization

The classification is generalized by introducing a second characteristic, the so-called PN factor. By introducing a second characteristic, three additional effects are included:

- Positive and negative-sequence impedance are not exactly equal. As shown in most books on power system analysis, this e.g. leads to a drop in non-faulted phase voltage during a phase-to-phase fault. In Fig. 2, the voltage in phase a will also drop, thus (1) no longer completely holds. The name PN factor (positive-negative factor) comes from this effect.
- The slowing down of induction motors due to the dip, leads to an apparent drop in source voltage. This will cause all three voltages to drop, but the effect is most obvious in the phases with a small initial drop.
- Two-phase-to-ground faults lead to a relatively large drop in voltage magnitude in the non-faulted phase.

The introduction of the PN Factor \bar{F} leads to the following general expression for a type C dip:

$$\begin{aligned}\bar{V}_a &= \bar{F} \\ \bar{V}_b &= -\frac{1}{2}\bar{F} - \frac{1}{2}j\sqrt{3}\bar{F} \\ \bar{V}_c &= -\frac{1}{2}\bar{F} + \frac{1}{2}j\sqrt{3}\bar{F}\end{aligned}\quad (3)$$

and for a type D dip:

$$\begin{aligned}\bar{V}_a &= \bar{V} \\ \bar{V}_b &= -\frac{1}{2}\bar{V} - \frac{1}{2}\bar{F}j\sqrt{3} \\ \bar{V}_c &= -\frac{1}{2}\bar{V} + \frac{1}{2}\bar{F}j\sqrt{3}\end{aligned}\quad (4)$$

C. Symmetrical Phase

Expressions (1) through (4) are valid for a fault in phase a or between phases b and c, i.e. with phase a as the symmetrical phase. Including all three possible symmetrical phases results in six (sub)types of three-phase unbalanced dips: C_a, C_b, C_c and D_a, D_b, D_c. Expressions (1) and (3) describe a dip of type Ca; (2) and (4) a dip of type Da.

A mathematically elegant method for obtaining dip

type, characteristic magnitude and PN factor from measured voltages, is given in [3,4,10]. The dip type is determined from the angle between positive-sequence and negative-sequence voltage, according to

$$k = \text{round}\left(\frac{\angle(\bar{V}_2, 1 - \bar{V}_1)}{60^\circ}\right) \quad (5)$$

where,

- k=0: type Ca
- k=1: type Dc
- k=2: type Cb
- k=3: type Da
- k=4: type Cc
- k=5: type Db

Knowing the dip type, the negative-sequence voltage can be calculated back to the corresponding value for the prototype dip:

$$\bar{V}_2' = \bar{V}_2 e^{-jk60^\circ} \quad (6)$$

where k is obtained according to (5) and the negative sequence voltage of the measured dip. Characteristic voltage \bar{V} and PN-factor \bar{F} are obtained from:

$$\begin{aligned} \bar{V} &= \bar{V}_1 - \bar{V}_2' \\ \bar{F} &= \bar{V}_1 + \bar{V}_2' \end{aligned} \quad (7)$$

D. Overview of Characterization

The characteristic magnitude (the absolute value of the characteristic complex voltage \bar{V}) can be used to characterize three-phase unbalanced dips without loss of essential information. Using characteristic magnitude and duration for three-phase unbalanced dips, corresponds to the existing classification (through magnitude and duration) for single-phase equipment. Where needed the characterization for three-phase unbalanced dips may be extended in several ways:

- the characteristic phase-angle jump may be defined as the argument of the complex characteristic voltage in the same way as the phase-angle jump may be used as an additional characteristic for dips experienced by single-phase equipment.
- the PN-factor may be used as an additional characteristic in systems with a large amount of induction motor load or to identify two-phase-to-ground faults.
- the zero-sequence voltage is needed as an additional characteristic for specific system

configurations in combination with three-phase star-connected load.

- characteristic magnitude, characteristic phase-angle jump and PN-factor may all be given as a function of time.

3. An Alternative Method

The voltage dip characteristics can be obtained through an alternative method. To understand this method, consider the two basic types of three-phase unbalanced dips as shown in Figure 2. For the type C dip the characteristic voltage is the lowest phase-to-phase voltage, and the PN-factor the highest phase voltage. For the type D dip the characteristic voltage is the lowest phase voltage, the PN-factor the highest phase-to-phase voltage. Not knowing which type a certain unbalanced event is, the characteristic voltage can be obtained as the highest, in rms value, of six voltages. The six voltages are the three phase voltages and the three phase-to-phase voltages. Any zero-sequence component needs to be subtracted from the phase voltages, and the phase-to-phase voltages need to be divided by the square root of three to enable a comparison with the phase voltages.

- calculate the zero-sequence component of the voltage:

$$v_0(t) = \frac{1}{3} \{v_a(t) + v_b(t) + v_c(t)\} \quad (8)$$

- calculate the remaining phase-voltages after removing the zero-sequence voltages.

$$\begin{aligned} v_a'(t) &= v_a(t) - v_0(t) \\ v_b'(t) &= v_b(t) - v_0(t) \\ v_c'(t) &= v_c(t) - v_0(t) \end{aligned} \quad (9)$$

- calculate the three phase-to-phase voltages:

$$\begin{aligned} v_{ab}(t) &= \frac{v_a'(t) - v_b'(t)}{\sqrt{3}} \\ v_{bc}(t) &= \frac{v_b'(t) - v_c'(t)}{\sqrt{3}} \\ v_{ca}(t) &= \frac{v_c'(t) - v_a'(t)}{\sqrt{3}} \end{aligned} \quad (10)$$

- calculate the rms values for the three phase voltages and the three phase-to-phase voltages:

$$V_a(t) = \sqrt{\frac{1}{T} \int_{t-T}^t \{v_a(\tau)\}^2 d\tau} \quad (11)$$

- The characteristic magnitude is the lowest of the six rms voltages; the PN-factor is obtained as the highest of the six rms voltages. The dip type is found from the phase or phases in which the characteristic voltage occurs.
 - phase a voltage is lowest: dip type D_a ;
 - phase b voltage is lowest: dip type D_b ;
 - phase c voltage is lowest: dip type D_c ;
 - phase bc voltage is lowest: dip type C_a ;
 - phase ac voltage is lowest: dip type C_b ;
 - phase ab voltage is lowest: dip type C_c .

The results of applying this method to the dip shown in Fig. 1 are given in Fig. 3 through 5.

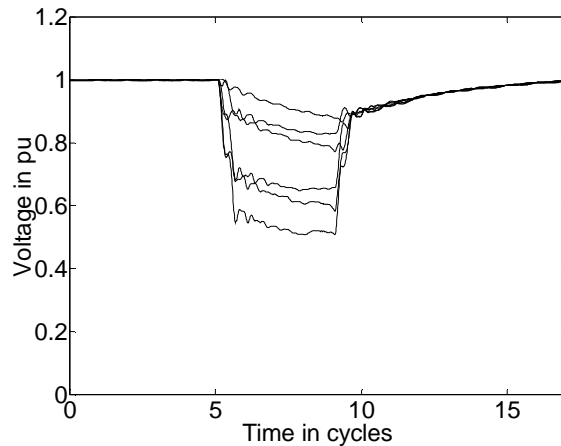


Fig. 3. The six rms voltages versus time

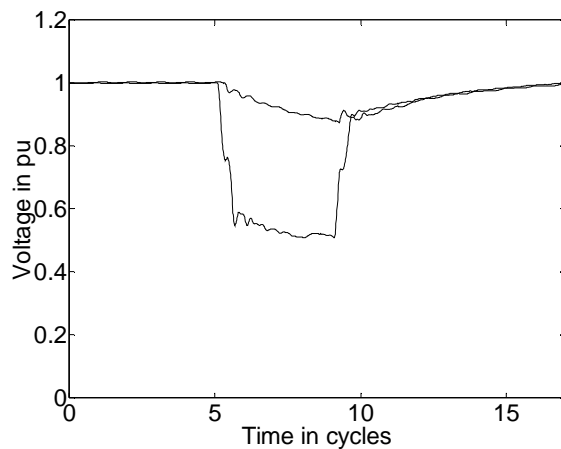


Fig.4. Characteristics magnitude of PN factor versus time

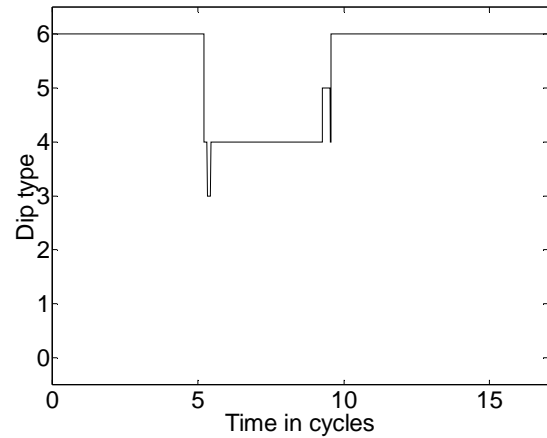


Fig. 5. Sag type as a function of time.

The six rms voltages as a function of time are shown in Fig.3. The lowest and highest of these six values are shown as characteristic magnitude and PN factor, respectively in Fig.4. In this, and all forthcoming figures, the top curve is the PN factor, the bottom curve the characteristic magnitude. The slow decay in PN factor is a very common characteristic of voltage dips. It is explained through the apparent decay in source voltage when induction motors slow down during the dip. Upon fault-clearing the characteristic voltage recovers to a value equal to the PN factor just before fault clearing. The post-fault dip has been described earlier and is due to the re-acceleration of induction motor load. The dip type as a function of time is shown in Fig.5. The numbers refer to the list below expression (5). The “erroneous values” at dip initiation and voltage recovery are due to the different rms voltages not decaying equally fast, as visible in Fig.3. Dip type 6 is a balanced dip where all six rms voltages are about equal. A separate criterion with threshold is needed to detect balanced dips.

4. Application to Sag Statistics

The voltage-dip co-ordination chart is a very suitable method for assessing the compatibility between supply and equipment, as far as voltage dips are concerned. The voltage tolerance curve of a piece of equipment is compared with the cumulative number of events as a function of event magnitude and duration. The method is part of IEEE std 493 and IEEE Std 1346. Extending the voltage-dip co-ordination chart to three-phase unbalanced dips is straightforward. Instead of one

chart, three charts are needed, one for each of the dip types A, C and D as described above. Cumulative number of events are obtained for each type, either through monitoring or through stochastic prediction. Also equipment performance needs to be known for the three types of dips. The tests leading to the three voltage-tolerance tests can be performed as before, e.g. in accordance with IEC 61000-4-11.

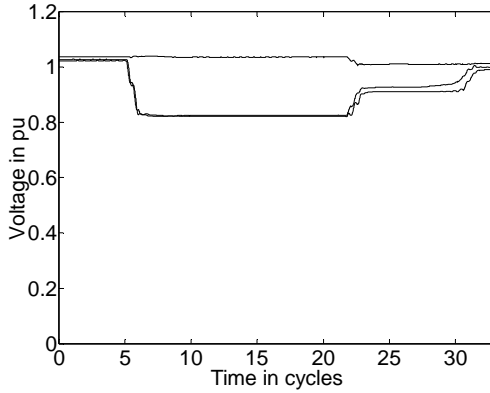


Fig. 6. Multi-stage voltage sag.

The resulting characteristic voltage and PN factor are shown in Fig. 7. The dip type was shown to be a drop of the ac voltage. The dip type did not change when the rms voltages changed. The conclusion is that the change in rms voltage is due to the opening of the circuit breaker on one side of the faulted line.

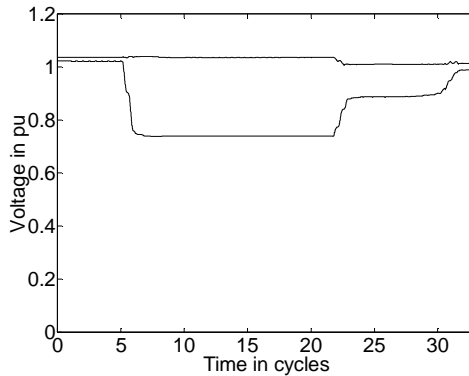


Fig. 7.Characteristic voltage and PN factor

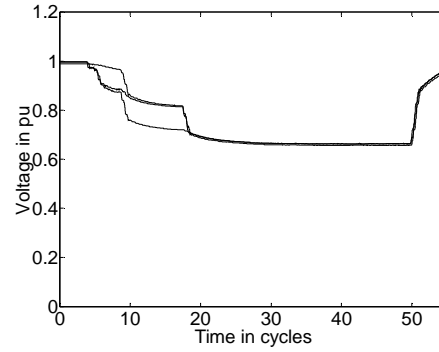


Fig.8. Example of a multi-stage voltage dip

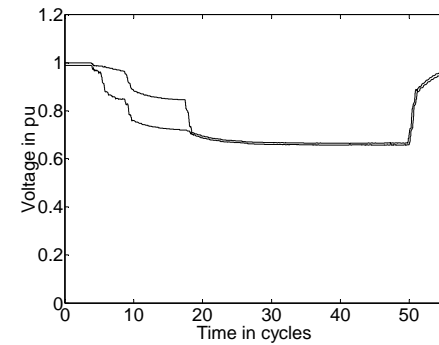


Fig.9.Characteristic voltage and PN factor for the dip shown in Fig.8

5. Conclusion

A new method has been proposed for characterization of three-phase unbalanced voltage dips. The result of the characterization is a simple characteristic magnitude. This single value enables a prediction of the effect of the event on most single-phase and three-phase equipment. When more detailed characterization of the event is required, additional parameters can be added. For three-phase balanced dips, the proposed characterization corresponds to the methods currently in use and recommended by international standards.

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