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Improved characterization of multi-stage voltage dips based on the space phasor model

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ABSTRACT

This paper proposes a method for characterizing voltage dips based on the space phasor model of the three phase-to-neutral voltages, instead of the individual voltages. This has several advantages. Using a K-means clustering algorithm, a multi-stage dip is separated into its individual event segments directly instead of first detecting the transition segments. The logistic regression algorithm fits the best single-segment characteristics to every individual segment, instead of extreme values being used for this, as in earlier methods. The method is validated by applying it to synthetic and measured dips. It can be generalized for application to both single- and multi-stage dips.

1. Introduction

Electrical faults (short circuits and earth-faults), starting of large induction motors, and such, cause a sudden short-duration increase in current and consequently a short-duration reduction in rms voltage which is called “voltage dip” or “voltage sag” [1,2].

Voltage dips are characterized by a limited set of values, so-called “single-event characteristics” [3,4]. Such characteristics, defined in international standards, are: “voltage-dip duration” and “residual voltage” [3,5]. Other examples discussed in the literature are characteristic voltage (CV), positive–negative factor (PNF), dip type (DT) [6–8], point on wave [9–13], phase-angle jump [15,16], and a number of indices that give a single-dimensional value for the dip severity, for example [3,9,16,17]. With the exception of the point-on-wave characteristics, the single-event characteristics are obtained from a characteristic versus time. As an example, the residual voltage is the lowest one-cycle rms voltage.

All these characterization methods suffer from two main limitations:

(i) Especially for multi-stage voltage dips, using one set of single-event characteristics for the whole event is not effective.

(ii) Even for single-stage voltage dips, the characteristics versus time are not constant and a “representative value” has to be selected. In each of the standard or proposed methods, this is the most severe value, which is a necessary but not satisfactory choice.

A general approach for characterizing multi-stage dips is proposed by an international working group (CIGRE/CIRED/UIE C4.110) [18]. The voltage dip is to be divided into “event segments” (during which the voltage waveform can be considered quasi-stationary) and “transition segments” (during which this assumption cannot be made) that separate the event segments. The parts of the recording before and after the actual dip are referred to as “pre-event segment” and “post-event segment”, respectively. The proposed general approach has not yet been implemented anywhere; an important barrier being the difficulties in detecting the transition segments [20–22]. See Ref. [19] for more details on segmentation.

The algorithm proposed in this paper addresses both before-mentioned limitations by using an alternative approach to voltage-dip characterization. Instead of calculating characteristics versus time, the three time-domain waveforms are transformed into the complex domain using the space-phasor model (SPM), as also used by Refs. [23] and [24]. A clustering method is next used to divide the time-domain waveform into event segments. For each of the resulting segments, a logistic regression method is next applied to obtain the parameters of the best fitting circle or

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ellipse. These parameters form the basis for calculating the 'single-segment indices' for each event segment of the voltage dip. The proposed algorithm calculates four single-segment characteristics: characteristic voltage (CV), positive negative factor (PNF), dip type (DT), and duration.

In the remainder of this paper, Section 2 provides a review of previous works on voltage dip characterization. Section 3 details the proposed method by explaining SPM and presenting a mathematical description of ellipses. This section also renders K-means clustering and logistic regression algorithms and the relations between ellipse parameters and single-segment characteristics. Section 4 presents simulation results for synthetic and measured dips. Finally, Sections 5 and 6 discuss the algorithms and conclude this paper.

2. Status of voltage dip characterization

The earliest works on voltage dip characterization used rms voltages to calculate residual voltage and duration of the dip as two single-event characteristics. The method proposed in Ref. [6], symmetrical component algorithm (SCA), uses symmetrical components to calculate three characteristics: CV, PNF and DT. Characteristic voltage (CV) can be considered as a generalized residual voltage. The difference between CV and PN Factor (PNF) quantifies the amount of voltage unbalance during the voltage dip. The dip type (DT) divides voltage dips into three basic types: typically referred to as Type *A*, Type *C* and Type *D* [1,6];

- Type *A* dips are balanced voltage dips; the same drop in magnitude for all three phase-to-neutral voltages. This is referred to as Type III in Ref. [19].
- Type *C* dips are unbalanced voltage dips with a significant drop in two of the three phase-to-neutral voltages and a lower or no drop in the third one, (Type II). Type *C* is subdivided into C_a, C_b, C_c. The subscript denotes the phase with small or no voltage drop.
- Type *D* dips are unbalanced dips with a large drop in magnitude for one phase-to-neutral voltage and a lower or no drop for the two other voltages (Type I). The *D* family is subdivided into D_a, D_b, D_c types. The subscript denotes the phase with a large voltage drop.

The other proposed algorithm, six-phase algorithm (SPA) [25], uses six rms voltages to calculate CV, PNF and DT. Both SCA and SPA calculate mentioned characteristics as a function of time. The proposed methodology in Ref. [26] codifies a systematic way, for implementation in international standards, to select a representative value as single-event characteristic.

The method presented in Ref. [23] uses the complex values of positive and negative-sequence voltages, as calculated from the SPM and the zero-sequence voltage, as part of an extended version of the before-mentioned ACD classification.

The algorithms in Refs. [27,28] are based on minimal phase-to-neutral (PN) and phase-to-phase (PP) voltages. Relations are derived between the smallest PN voltage and the smallest PP voltage, for each type of dip, starting from the expressions for the voltages during the dip according to the ABC classification [29].

The proposed method in Ref. [30], introduces five different parameters: "remain voltage" (RV), "inverse remain voltage" (IRV) and three angles between phases (α, β, δ). The residual voltage for each phase is calculated according to RV values. The two highest values of IRV and three angles are used to determine the dip type.

The method proposed in Ref. [31] characterizes voltage dips based on the CVUF ("complex value unbalanced factor"), three angles between phases and the original fault type.

The algorithm in Ref. [32] uses the polarized ellipse parameters, the fundamental frequency phasors, and some boundaries to characterize voltage dips.

The algorithms in Refs. [23] and [32] calculate the ellipse parameters as base for dip characteristics; however, the proposed algorithms require an additional technique such as the discrete Fourier transform (DFT) to extract the fundament component of the voltage. Also, these algorithms still need additional techniques to extract event segments from the event recording.

Moreover, according to our knowledge [33], there is no algorithm which aims particularly at characterizing multi-stage voltage dips in term of extracting 'single-event characteristics' for each event segment individually.

3. Characterization method for multi-stage dips

3.1. Space phasor model

The space phasor model (SPM) of three phase-to-neutral voltages, V_a, V_b and V_c, is obtained by:

$$SPM = \frac{2}{3}\left[V_a(t) + \alpha V_b(t) + \alpha^2 V_c(t)\right] \tag{1}$$

where $\alpha = e^{j2\pi/3}$ and $\alpha^2 = e^{j4\pi/3}$.

The shape of the SPM in the complex plane is either a circle or an ellipse. This offers a more intuitive model for clustering of a multi-stage voltage dip than voltage waveforms or rms values. The circle represents the normal voltages or a balanced voltage dip (Type *A*). The circle radius is equal to the residual voltage.

As shown in Refs. [34,35], the ellipse represents an unbalanced voltage dip (Type *D* and Type *C*), where the direction of the major axis indicates the dip type and the length of the axes is related to PNF and CV [23].

An example of a multi-stage voltage dip with two event segments is shown in Fig. 2. The SPM, according to Eq. (1), is shown on the right-hand side of Fig. 3. Three circles are visible and one ellipse: the circles are corresponding to the pre-event, post-event and second event segment; the ellipse corresponds to the first event segment. The left-hand side of Fig. 3 shows the modulus of the SPM as a function of time.

3.2. Ellipse and principal axis theorem

3.2.1. Standard quadratic form

The standard quadratic form of an ellipse that is aligned with the x-axis, in the coincident reference frame, is as follows:

$$\boldsymbol{X}^T\boldsymbol{M}\boldsymbol{X} = 1 \tag{2}$$

where $\boldsymbol{X} = \begin{bmatrix} \boldsymbol{x}_1 & \boldsymbol{x}_2 \end{bmatrix}^T$ is a variable matrix and $\boldsymbol{M}$ is a diagonal parameter matrix [36,37]:

$$\boldsymbol{M} = \begin{bmatrix} \frac{1}{a^2} & 0 \\ 0 & \frac{1}{b^2} \end{bmatrix} \tag{3}$$

where *a* and *b* denote the ellipse vertices in the coincident reference frame.

3.2.2. Rotating ellipse (general quadratic form)

The ellipse may be rotated over an angle φ by the following rotation matrix:

$$\boldsymbol{R} = \begin{bmatrix} \cos\varphi & -\sin\varphi \\ \sin\varphi & \cos\varphi \end{bmatrix} \tag{4}$$