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Detection of voltage sag sources based on the angle and norm changes in the instantaneous current vector written in Clarke's components

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ABSTRACT

The presented research reflects those methods for detecting voltage sag sources that only use measurements of line currents. It is shown that the phasor-based method known from the literature is unsatisfactory, especially in the cases of transient voltage sag events. Therefore, a generalised method is proposed that is based on the instantaneous current vector written in Clarke's components. The phasor-based method and the proposed method for voltage sag source detection were evaluated by applying extensive simulations, laboratory tests, and field testing. The obtained results show considerably higher effectiveness for the proposed method. The correctness of the instantaneous vector-based approach is verified in this way. Moreover, the proposed method that uses only measurements of line currents is just as effective as some other instantaneous vector-based methods that use measurements of line currents and line voltages.

Introduction

Voltage sags (dips) are a decrease in the supply rms voltage between 90% and 1% of the declared value, and with durations of mostly less than 1 s. The characteristics of voltage sags are determined by the power quality standards [1,2].

Voltage sags can be caused by different events related to the system, whereas their origins occur in the distribution or transmission system or on the customer's side. Consequently, the frequency of voltage sags can be between a few tens and even several thousand times per year [3]. The majority of voltage sags are due to faults in the distribution and transmission systems. The durations of these voltage sags can be as short as three to four cycles and associate with the fault clearing time. In the cases of phase-to-phase or phase-to-earth faults, which are the more frequent, the resulting voltage sags are asymmetrical. Furthermore, due to high values of the magnetising (inrush) currents, the energising of a transformer is another source of voltage sags, which are asymmetrical and last between 100 ms and 500 ms. Voltage sags caused by a heavy motor starting (and loading) last longer; a few seconds or several tens of seconds. These voltage sags are symmetrical because electrical motors are generally balanced loads.

The impacts of disturbances caused by voltage sags on the production losses have already been reported [4–8]. For example, some parts of computer-based and electronic equipment trip even when the rms voltage drops slightly below 80% for only a few cycles [3]. The disturbing effects of voltage sags are also noticed on three-phase transformers [9,10], induction machines [11,12], doubly-fed induction generators [13–15] adjustable-speed drives [16,17], and different types of industrial equipment [18].

Reducing the severities of voltage sags and decreasing their ride-through capabilities requires various improvements in the entire power system. The best possible solution for utilities and customers might be the installation of mitigation equipment, which should be based on a careful techno-economic assessment [19–21]. In those cases where the mitigation equipment is not installed any disputes can only be resolved fairly if the voltage sag source is reliably detected. Several methods for detecting and tracking voltage sag sources have already been reported and reviewed [22–57]. A brief review of methods for the upstream–downstream detection of voltage sag sources [22–41,47] is also given in the next chapter.

The majority of methods for detecting voltage sag sources require information on line voltages and currents [22–36]. Measurements of line currents are available at all voltage levels of the power system, whereas measurements of line voltages are not. Two methods that use only measurements of line currents have already been proposed [39,40]. However, they are based on phase and magnitude changes in a positive-sequence current phasor. Because voltage sags are transient disturbance events the phasor-based methods might, due to the inherent averaging caused by

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the harmonic analysis of the input signals, produce inconclusive results. A vector-space approach [58–60] is applied for overcoming this difficulty. A generalised method for detection of voltage sag sources is introduced by using the instantaneous current vector written in Clarke's-$\alpha\beta$ components. Note that Clarke's-$\alpha\beta$ components are also used within the methods proposed in [33,34], where instantaneous current and voltage vectors are both applied. These methods are based on orthogonal decomposition of the current vector using criteria that mainly considers the norm changes of two collinear vectors, i.e. the active current vector and the voltage vector. Within the proposed method the voltage vector is unavailable. Consequently, two criteria are used, i.e. the angle change and the norm change of the instantaneous current vector written in Clarke's-$\alpha\beta$ components.

The phasor-based method [40] and the proposed instantaneous vector-based method that use only current measurements were tested for voltage sags due to different types of power system faults, heavy motor loading and starting, as well as transformer energising. In order to determine the effectiveness of the discussed methods extensive numerical simulations, laboratory testing and field testing were performed. Moreover, on the basis of the performed evaluation results and the results presented in [34] a comparison is made with other instantaneous vector-based methods that use measurements of line currents and line voltages.

Brief review of methods for detecting voltage sag sources

A description of methods for upstream–downstream detection of voltage sag sources (Fig. 1) is given in Table 1. In order to increase the effectiveness, statistical techniques were applied to different methods. Methods with combined rules were determined in this way, however, they are all based on phasors [35,36,47]. Another method [41] is based on the statistical properties of measured rms values within distribution and transmission systems. Furthermore, higher effectiveness was also achieved by applying instantaneous vectors instead of phasors for several types of methods [33,34].

Detection of voltage sag sources using only measurements of line currents

Let us consider that the energy flow at the monitoring point (MP) is normally from the utility to the customer, as shown in Fig. 1. The voltage sag events originating from side A are defined as upstream, while those originating from side B are defined as downstream in this case. Based on the measured line currents it is possible to determine on which side of the MP the voltage sag originated, when the pre-sag energy flow at MP is defined.

Two methods that use only current measurements have already been reported [39,40], which both require computation of the phasors for the fundamental frequency component. Phasor estimation is typically performed using discrete Fourier transform (DFT) [61] or signal least-square (LSQ) [62]. In the cases of non-stationary input signals a considerable time delay (1.5 cycles at least) is expected for algorithms of this type. Kalman filtering [63] was therefore applied within the method proposed in [39]. However, parameterisation of such filters requires a priori information about the signal's harmonic content and noise properties, which is a serious obstacle in practice.

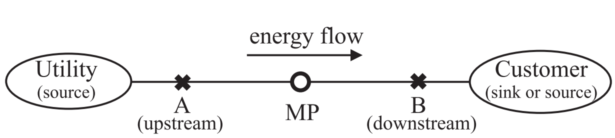

Fig. 1. Upstream (A) and downstream (B) voltage sag events.

Since voltage sags are transient disturbance events, the phasor-based methods might produce inconclusive results. A vector-space approach [58–60] is applied in order to overcome this difficulty, similarly as in [33,34]. Thus, the extended method [40], which is phasor-based, is generalised by introducing an instantaneous current vector written in Clarke's-$\alpha\beta$ components.

Existing methods based on current phasor

Voltage sags are due to short-duration increases in currents. Currents measured at the MP therefore increase during downstream events and decrease during upstream events. Furthermore, in systems that are supplied from two sides the phase change in the positive-sequence current, with reference to the expected normal phase, is negative for downstream events whereas it is positive for upstream events. Two methods [39,40] have already been proposed based on these assumptions. The first method [39] is based on the phase change in the positive-sequence current phasor. It has been developed for fault direction estimation and can also be used for detecting voltage sag sources. Its application is, however, limited to systems supplied from two sides such as radial distribution systems with distributed generation (DG). The second method [40] uses magnitude change in the positive-sequence current phasor as an additional criterion. The extended method [40] is proposed by the rule (1), where 'US' and 'DS' denote upstream and downstream voltage sag events, respectively. The magnitude change in the positive-sequence current $\Delta|\underline{I}_+|$ is defined by the difference $|\underline{I}_{+,\text{sag}}| - |\underline{I}_{+,\text{pre}}|$, where the subscripts 'pre' and 'sag' denote pre-sag and during-sag states, respectively. Furthermore, the phase change $\Delta\angle\underline{I}_+$ is defined by the difference $\angle\underline{I}_{+,\text{sag}} - \angle\underline{I}_{+,\text{pre}}$ within the interval $[-\pi, +\pi]$. Note that only the extended method [40], (1) is discussed further on.

$$\begin{aligned}&\text{if } \Delta\angle\underline{I}_+ > 0 \text{ or } \Delta|\underline{I}_+| < 0 \Rightarrow \text{US}\\&\text{else if } \Delta\angle\underline{I}_+ < 0 \text{ and } \Delta|\underline{I}_+| \geqslant 0 \Rightarrow \text{DS}\end{aligned} \tag{1}$$

Current vector written in Clarke's components

The currents of a three-phase system can be expressed by a vector [58–60]. The instantaneous current vector contains instantaneous line currents i_a, i_b, i_c, [1] as defined by (2). Fig. 2a shows the current vector, where components *abc* denote the individual phases of a three-phase system.

$$\mathbf{i}_{abc} = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{2}$$

The current vector normally lies within the plane defined by Clarke's-$\alpha\beta$ components (grey area in Fig. 2). In cases such as phase-to-earth faults or asymmetrical operation in four-wire systems, the current vector leaves the $\alpha\beta$-plane as the zero-sequence current appears. The current vector written in Clarke's components is defined by (3), where the transformation matrix is orthogonal.

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{3}$$

[1] For simplicity, i is used instead of $i(t)$ for denoting instantaneous values, and $\mathbf{i}$ instead of $\mathbf{i}(t)$ for denoting instantaneous vectors.