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Evaluation of Different Methods for Voltage Sag Source Detection

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SUMMARY

This paper compares and evaluates three different methods for voltage sag source detection. First method (method I) is based on the assumption, that the energy flow at the monitoring point increases during downstream events and decreases during upstream events. Second and third method (methods II and III) are both based on the assumption that currents measured at the monitoring point increase during downstream events and decrease during upstream events. The slope of a current-voltage trajectory is investigated in method II, while a real current component is observed within method III. Both current-based methods (II and III) require fundamental harmonic components of sampled voltages and currents, which are extracted using discrete orthogonal series expansion, such as Fourier or Walsh. Algorithms of this type are especially appropriate for studying steady-state and periodically repeating conditions. Voltage sags are, on the contrary, transient disturbance events. Thus, usage of the discussed algorithms may not be appropriate. Furthermore, criteria within methods II and III are checked for each phase individually. In the cases of asymmetrical voltage sags exact interpretation of the obtained results, therefore, might not be possible. Method I is, on the contrary, based on instantaneous values of line voltages and currents, while three-phase criterion is used. An exact interpretation of the results obtained by this method is, therefore, also possible in cases of asymmetrical voltage sags. All the discussed methods for voltage sag source detection have been tested by applying extensive simulations and field tests. The results for ground faults, asymmetrical voltage sags, upstream events and motor starting have been analyzed in order to evaluate all the discussed methods. The obtained results show that all discussed methods are very successful in cases of heavy motor starting and other symmetrical voltage sags. In cases of asymmetrical voltage sags the methods II and III do not work well, especially for those originating from the upstream side, while the method I is not successful only in particular cases of voltage sags due to upstream ground faults. Based on the performed evaluation it can be concluded, that further development is still needed to increase the degree of confidence in the discussed methods.

KEYWORDS

Power – System, Power – Quality, Voltage Sag, Source, Detection.

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1. INTRODUCTION

Among the wide range of power quality disturbances voltage sags are the most frequent ones, since they can be provoked by different events throughout the network, such as faults, motor starting, transformer energizing and heavy load switching [1]. Despite their relatively short duration – usually less than one second [2], voltage sags might be detrimental to several industrial loads. The detection and measurement of voltage sags is, therefore, essential for possible mitigation [3],[4], as well as for further analysis [5]. Reliable information about a voltage sag source is indispensable in order to identify the responsible party for production losses or interruptions in the power supply. It has already been reported that it is possible to use sampled voltage and current waveforms to determine on which side of the recording device voltage sag originates, i.e. from the upstream or downstream side [6]-[8]. However, a methodology for pinpointing the exact locations of voltage sags does not yet as exist.

This paper compares and evaluates three different methods for voltage sag source detection. The method proposed in [6] (method I) is based on the assumption, that the energy flow at the monitoring point increases during downstream events and decreases during upstream events. The methods proposed in [7] and in [8] (methods II and III) are both based on the assumption that currents measured at the monitoring point increase during downstream events and decrease during upstream events. The slope of a current-voltage trajectory is investigated in method II, while a real current component is observed within method III. All the discussed methods have been tested by applying extensive simulations. The results for ground faults, asymmetrical voltage sags, upstream events and motor starting have been analyzed in order to evaluate all the discussed methods for voltage sag source detection. Results obtained from the field test are also included.

2. METHODS FOR VOLTAGE SAG SOURCE DETECTION

Let us consider the monitoring point shown in Fig. 1. Voltage sags might originate either from point A or from point B. In regard to energy flow direction in the steady-state, upstream and downstream events are defined in points A and B, respectively. A power-quality monitor or another recording device is placed at the monitoring point. Based on the recorded line voltages $u_k(t)$ and currents $i_k(t)$, where $k \in \{a,b,c\}$ (a, b and c denote individual phases), it is possible to determine on which side of the recording device the voltage sag originated.

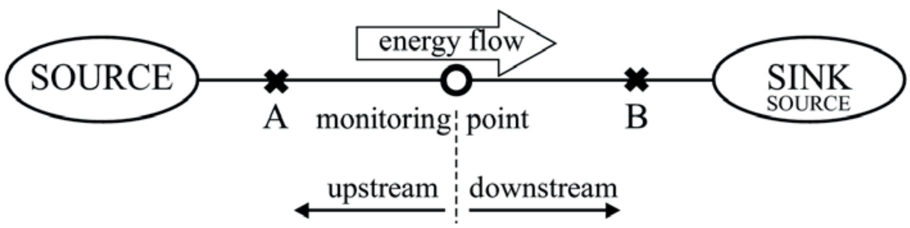

Fig. 1. Upstream event (A) and downstream event (B)

2.1 Energy-based method

The method which is based on the assumption, that the energy flow at the monitoring point increases during downstream events and decreases during upstream events is proposed in [6] (method I). The disturbance power $\Delta p(t) := p(t) - p_{ss}(t)$ is calculated, defined as the difference between the total three-phase instantaneous power $p(t)$ and the steady-state three-phase instantaneous power $p_{ss}(t)$. The disturbance energy $\Delta w(t)$ is used as the criterion (1).

$$\Delta w(t) = \int_0^t \Delta p(\tau) d\tau \begin{cases} < 0 \Rightarrow \text{ upstream} \\ > 0 \Rightarrow \text{ downstream} \end{cases} \quad (1)$$

2.2 Current-based methods

Two methods, proposed in [7] and in [8] (methods II and III), are based on the assumption that currents measured at the monitoring point increase during downstream events and decrease during upstream events, as it is shown in Fig. 2.

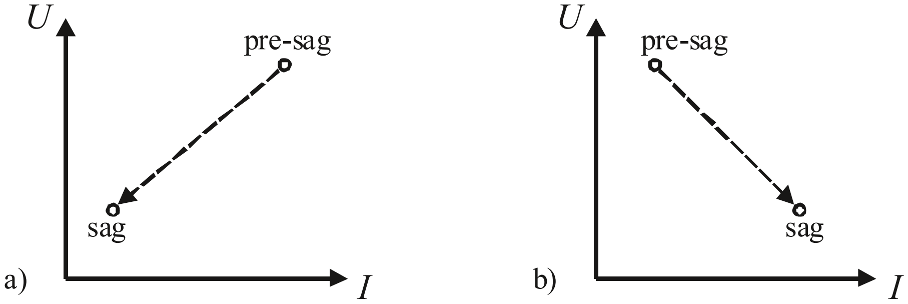

Fig. 2. *U–I* characteristics in case of upstream event (a) and downstream event (b)

Phasors for fundamental harmonic components of line voltages $\underline{U}_k = |\underline{U}_k|\, e^{j\varphi_{u,k}}$ and currents $\underline{I}_k = |\underline{I}_k|\, e^{j\varphi_{i,k}}$ are calculated within both methods, where $|\underline{U}_k|$ and $|\underline{I}_k|$ are phasor lengths, while $\varphi_{u,k}$ and $\varphi_{i,k}$ are phasor angles, where $k \in \{a,b,c\}$. A phase angle is defined as $\varphi_k := \varphi_{u,k} - \varphi_{i,k}$. In method II [7] the points of $(|\underline{I}_k|, |\underline{U}_k \cos\varphi_k|)$ are approximated during the voltage sag using the linear function. The slope of the obtained voltage-current characteristic is investigated for each phase individually (2).

$$\text{slope}\left(|\underline{I}_k|, |\underline{U}_k \cos\varphi_k|\right) \begin{cases} > 0 \Rightarrow \text{ upstream} \\ < 0 \Rightarrow \text{ downstream} \end{cases} \quad (2)$$

Within method III [8] waveform of a real current component is calculated for a few cycles prior and during the voltage sag. The sign of its first peak at the beginning of the voltage sag is used as the criterion for each phase individually (3).

$$\text{first peak}\left(|\underline{I}_k| \cos\varphi_k\right)(t) \begin{cases} < 0 \Rightarrow \text{ upstream} \\ > 0 \Rightarrow \text{ downstream} \end{cases} \quad (3)$$

3. NUMERICAL SIMULATIONS AND FIELD TESTING

A testing-network, shown in Fig. 3, was selected for numerical simulations of voltage sags. MATLAB/Simulink-based calculations were performed using a sampling time of 0.1 ms. An extensive number of tests were performed for different combinations of loads and for different events. Different types of loads were used in the cases of voltage sags due to faults:

RL-load, induction motor (IM), induction generator (IG), synchronous motor (SM) and synchronous generator (SG). Four types of faults were applied in four different locations (FL1-FL4): ground fault, phase-to-phase-to-ground fault, phase-to-phase fault and three-phase fault. Voltage sags due to motor starting and loading were also calculated, where IM was used. Line voltages and currents were captured at all four monitoring points (MP1-MP4). All discussed methods for voltage sag source detection were, thus, tested for altogether 417 different examples of voltage sags.

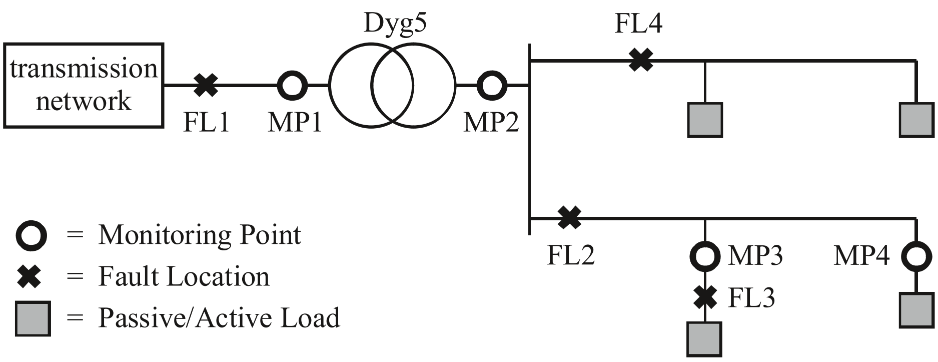

Fig. 3. Testing-network for simulations of voltage sags

Field tests of the discussed voltage sag source detection methods were also performed, as shown in Fig. 4. Voltages and currents were captured in a 20 kV network and in the neighbouring 100 kV and 0.4 kV networks (MP1-MP3). A sampling frequency of 5 kHz was used. During the field test a ground fault was generated in the 20 kV network, provoking extremely deep voltage sag at the 20 kV bus (MP2). This event lead to the protection-relay trip and then to the successful auto-reclosure. Consequently, a power transformer 110/20 kV, connected to the 20 kV bus, was energized. Another voltage sag was thus provoked through the 20 kV bus and a 20/0.4 kV transformer in the neighbouring 0.4 kV network (MP3).

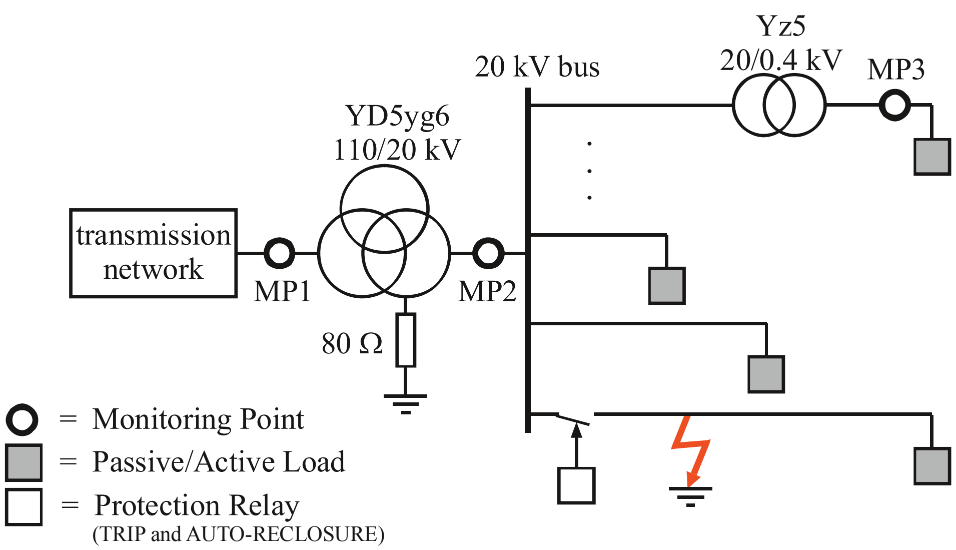

Fig. 4. Field testing

4. RESULTS

A typical example of the simulation results is shown in Fig. 5a for the upstream phase-to-phase-to-ground fault in location FL2 (Fig. 3). Voltages and currents were captured at MP3, while SM, IM and IG were used as active loads. The results obtained using methods II and III can not be interpreted exactly, since they are different for individual phases. On the contrary, method I gave us an exact and correct result for this case.

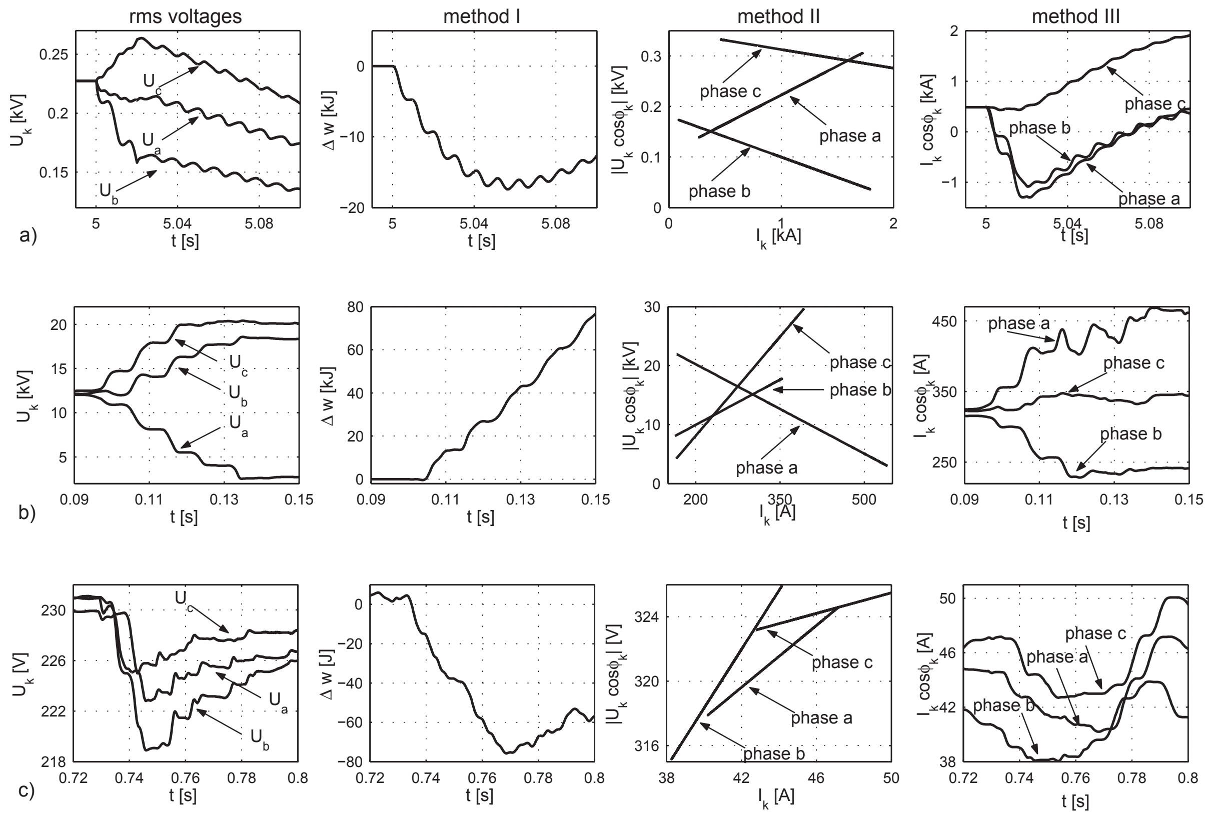

Fig. 5. Simulation results for the upstream phase-to-phase-to-ground fault (a), and filed testing results for the downstream ground fault (b) and the upstream transformer energizing (c)

Field testing results are presented in Figs. 5b and 5c. Results for the downstream ground fault (voltage sag at the 20 kV bus – MP2 in Fig. 4) are shown in Fig. 5b, where an extremely deep voltage sag can be noticed in phase *a*. Method I gave us an exact and correct result for this case, while the results obtained using methods II and III can not be interpreted exactly, since they are different for individual phases. Results for the upstream transformer energizing (voltage sag at the 0.4 kV level – MP3 in Fig. 4) are shown in Fig. 5c. Even though the resulting voltage sag was quite shallow, the obtained results show typical waveforms for the rms voltages during the transformer energizing, while all methods gave us correct results.

All the discussed methods for voltage sag source detection were tested by applying extensive numerical simulations and measurements of voltage sags. Successfulness was determined for all three methods, where all 417 different examples of simulation-based voltage sags were considered. The obtained results are shown in Fig. 6, where the results for the total successfulness are given for all types of faults (ground fault, phase-to-phase-to-ground fault, phase-to-phase fault and three-phase fault) in all fault locations (FL1–FL4) and for all monitoring points (MP1–MP4 in Fig. 4). It can be concluded, that method I works fine in almost all cases, except in particular cases of voltage sags due to upstream ground faults. Methods II, and III, as already mentioned, do not work well in cases of asymmetrical voltage sags, especially for those originating from the upstream side. However, let us emphasize that all discussed methods are very successful in cases of heavy motor starting and other symmetrical voltage sags.

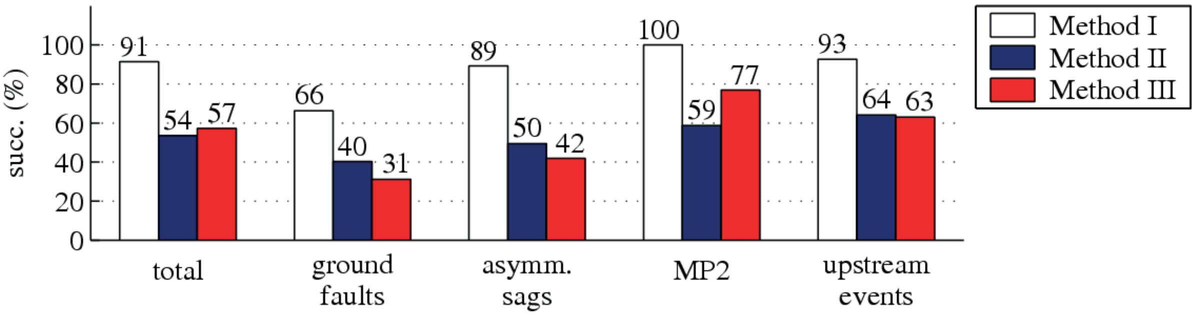

Fig. 6. Successfulness of the discussed methods for voltage sag source detection

5. CONCLUSION

Three different methods for voltage sag source detection are studied in this paper. For this purpose, the discussed methods for voltage sag source detection are tested by applying extensive simulations and field tests. The obtained results show that methods II and III do not work well, particularly in cases of asymmetrical voltage sags due to upstream events. Furthermore, methods II and III are both phasor-based and might, therefore, give us questionable results. Method I works fine in almost all cases, except in particular cases of voltage sags due to upstream ground faults. Based on the performed evaluation it can be concluded, that further development is still needed to increase the degree of confidence in all the discussed methods.

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