Electric Power Systems Research 154 (2018) 391–400

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Analysis of the origin of measured voltage sags in interconnected networks

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ARTICLE INFO

Article history:
Received 24 January 2017
Received in revised form 21 July 2017
Accepted 7 September 2017

Keywords:
Interconnected systems
Power quality
Voltage sags

ABSTRACT

This paper deals with the assessment of the origin of voltage sags due to faults in real, interconnected networks. The first step in regulating such faults is to determine the origins of measured voltage sags. Thus, the challenge of this study was to use only the main measurements associated with voltage sags, i.e., the residual voltage, the time the voltage sags occurred, and their duration to detect their origins. No correlations with data from the existing protection systems were used because they were not available. Different operators who do not exchange any data with each other manage the interconnected networks that we considered, and this increased the complexity of the study.

In this paper, we analysed the main aspects of the propagation of voltage sags in interconnected networks, and we focused our attention on High Voltage (HV) and Medium Voltage (MV) systems interconnected by HV/MV stations. Two methods were used to determine where the voltage sags originated in the network, and the methods used only the measurements associated with the voltage sags. Both methods were used to evaluate the huge number of measured voltage sags that occurred in an MV distribution system over a period of one year. These two methods: are presented after a brief review of the theoretical methods for simulating the propagation of voltage sags among the nodes of an electrical network. This review is valuable for defining the rules associated with each method. The paper contributes to the literature by providing analyses of a huge number of voltage sags measured in interconnected systems. The main outcomes show that it is possible to detect the origin of the sags using the main measurements of the voltage during the fault only on the MV side of the transformers that are installed in the HV/MV stations. The statistical analysis of these measurements allowed us to classify the origins of the sags better than imposing any conditions on the value of the residual voltages of the sags. Conversely, the origin of the sags in the HV network can be identified better if limits are assigned to the residual voltages.

1. Introduction

Researchers recognize that power quality (PQ) disturbances are a crucial problem to all of the main stakeholders of the electrical energy system, including network operators, regulators, large industrial customers, and equipment manufacturers. Thus, it is imperative to determine what caused a PQ disturbance so that appropriate action can be implemented to establish adequate countermeasures. For example, regarding harmonics, a distorted voltage at the point of common coupling between the supply and the customer's facility can be due to the ambient harmonics of the voltage of the power supply, due to current harmonics injected by the customer's installation, or both. Having established the causes and their contributions to the resulting distortion of the voltage at the point of common coupling, the utility company and the customer can take action, as required, to mitigate the issues associated with the distorted voltage.

It is vitally important to identify short circuits that result in voltage sags whenever and wherever such sags are perceived or measured.

The interconnections among systems introduce additional difficulties in ascertaining the origins of the voltage sags measured at a given busbar. In fact, voltage sags pass across the transformers of the high voltage/medium voltage (HV/MV) stations and propagate through the interconnected networks. The types and the characteristics of voltage sags can change depending on the ways in which connections are made to the transformers and to the loads [1,2]. The propagation paths are not always linear or easily predictable,

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http://dx.doi.org/10.1016/j.epsr.2017.09.008
0378-7796/

especially in the presence of meshed configurations. This means that the network in which a voltage sag is measured is not always the network in which that voltage sag originated.

In the case of simulated voltage sags, the knowledge of the origin of the sags obviously is known since it corresponds to the node in which the short circuit was simulated. However, it is not easy to determine the origin of voltage sags that are detected in a real, interconnected network.

Theoretically, the data associated with the interventions of protection systems for short-circuit current could solve the problem. In fact, the origins of voltage sags can be identified by correlating their start times and durations with the start times and durations of the intervention of the protection system. However, this cannot always be done in actual interconnected networks, and, even when it can be done, the accuracy is inadequate even when the voltage sag is due to a short circuit that is internal to the same network. The reasons are linked to the errors of the measurement systems and the lack of exact synchronization between the measures of the times that the voltage sags occurred and the measures of the times protection systems were operational. Also, in cases in which the measures of the voltage sags and the measures of the protection systems are performed in different networks, i.e., the transmission network and the distribution network that are managed by different operators, the operators never exchange their measurement data, so no correlation is possible.

This paper deals with the problem of ascertaining the network in which a large number of measured voltage sags originated without using any additional information and without using data from the protection systems. The analyzed voltage sags were measured at several busbars at the MV level of real distribution networks interconnected with the transmission system.

Some methods for doing this have been proposed in the literature. As described in Section 3, these methods can be grouped into two main categories, i.e., Single Monitor-based (SM-based) and Multiple Monitor-based (MM-based) methods [3–24]. An SM-based method uses only one point of measurement to determine whether a measured voltage sag originated upstream in the system or downstream of the measurement point. However, an MM-based method uses measurements at several points in different busses to identify the exact origin of the voltage sag rather than just making measurements in the part of the system where the voltage sag originated [4–20]. Some authors identified the source of voltage sags by modeling a state estimation problem [21,22]. Since voltage sags measured at every node of a system are unavailable, first, the characteristics of sags at unmetered nodes were obtained. In Ref. [22], the proposed estimation of voltage sag was applied only to radial distribution systems, and the search for the source of the voltage sag, namely the fault path, was proposed as an interesting practical application of the method. In Ref. [21], the exact locations of the sources of the voltage sags were obtained by fully-trained, multivariable models that determined the maximum deviation of the voltage and the minimum standard deviation. Both of the methods were used only in the simulation of test systems.

Note that most scientific papers in the literature refer to studies of simulated voltage dips on electrical networks [11,19–21,23]. Only a few papers have considered measured voltage sags on real or laboratory networks that consist of a small number of nodes [5,9,10,12,14,24].

This paper presents two methods, i.e., M1 and M2, with M1 being an SM-based method and M2 being an MM-based method. These methods only use the measurements of voltage sags obtained in real, interconnected networks; they do not use any additional measurements or estimates of the state of the voltage sags.

In particular; in this paper, we present the data obtained by the most extensive programs in the world for monitoring power quality, i.e., the programs established by the largest distribution company in Italy, Enel Distribuzione (ED). The installation of about 3500 power quality analysers (class A IEC 61000-4-30 [25]) at all of the MV busbars of all of the HV/MV substations was completed in 2014.[1] The primary goal was to be able to analyse voltage sags as required by resolution 198/2011 of the Italian Authority of Energy [26]. The key points of this paper relate primarily to the presentation and use of two innovative methods for analysing voltage sags. The first key point is the presentation of a method that can determine the origins of voltage sags by using only the fundamental features of the sags, i.e., the amplitude of the residual voltage, the times when the sags occurred, and the duration of the sags. These fundamental features are measured only at the MV busbars of the HV/MV stations, and no other measured quantities are used, which eliminates the need for measuring currents, pre-fault voltages, impedances, or the voltages at the primary and secondary windings of the HV/MV stations. The second key point is the application of the stated approach to a huge number of real voltage sags measured on a real power system.

The paper is structured as follows. Section 2 presents the methods and tools for the simulation of voltage sags in interconnected networks; it presents the theoretical background of the analysis of the origin of voltage sags in interconnected networks. Section 3 considers methods and criteria to ascertain the origin of the measured voltage sags in real systems. Section 4 reports the results of the analysis of the data that were recorded at an actual MV distribution system.

2. Theoretical background: methods and tools for the propagation of simulated voltage sags

Voltage sags due to faults propagate through networks following non-linear paths, and, generally, it is not a trivial matter to predict such sags. Due to the propagation of sags, even one single node in which a fault occurred can be the origin of several voltage sags.

The Fault Position Method (FPM) furnishes detailed and accurate information on the propagation of simulated voltage sags. FPM obtains the voltage sags, which are caused by faults at any bus, in all nodes of the system. The FPM offers a global vision of the electrical power system's response to faults, even for radial networks [25]. For each position "f" of the fault, a short circuit simulation is performed to obtain the voltages for all electrical power system nodes during the fault. The during-fault voltages that have amplitudes less than a given threshold (typically 90% of the declared voltage) are defined as voltage sags. The position "f" obviously corresponds to the origin of these voltage sags.

An important tool derived from the FPM is the During-Fault Voltage (DFV) matrix, which contains all of the voltages obtained in all of the nodes; each element (i,j) of the DFV represents the vector of the during-fault voltage in node i when a short circuit occurs at node j. The DFV gives the immediate measure of the propagation of voltage sags throughout the network.

In the literature, color schemes have been proposed that provide compact and immediate visualization of the propagation of the voltage sags around the network [27–30]; Fig. 1 shows an example of the color scheme applied to a DFV matrix obtained by FPM applied to the system in Ref. [27].

There are two main concerns associated with the origin of voltage sags, i.e., the affected area and the exposed area.

The affected area of node k is the region of the electrical power system in which voltage sags occur due to faults at node k. Node k is the origin of all the voltage sags of its affected area.

[1] In resolution 198/11, the Italian Energy Authority refunded the distribution companies up to 50% of the final cost of € 2400 for the installation of each measuring system.