Electric Power Systems Research 145 (2017) 122–136

Contents lists available at ScienceDirect

Electric Power Systems Research

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

A novel method for voltage-sag source location using a robust machine learning approach

Younes Mohammadi [a], Mohammad H. Moradi [a], Roberto Chouhy Leborgne [b,*]

[a] Faculty of Engineering, Department of Electrical Engineering, Bu-Ali Sina University, Hamedan, Iran
[b] Federal University of Rio Grande do Sul, Porto Alegre, RS, Brazil

ARTICLE INFO

Article history:
Received 19 September 2016
Received in revised form
28 November 2016
Accepted 28 December 2016
Available online 7 January 2017

Keywords:
Voltage sag source location
Support vector machine (SVM)
Positive sequence
k-Fold
Radial basis function (RBF)

ABSTRACT

In this paper, a comprehensive review on methods for voltage sag source location is presented and also nine generalized methods using positive sequence phasors, instantaneous positive sequence components, Clarke's components and integration are introduced. Most discussed methods use single criteria, and as results will show, their accuracy is limited. Therefore, this paper proposes another novel method using a robust support vector machine (SVM) in which many features are extracted, based on previously described methods. Then, the source location by machine learning technique is discussed with two steps in detail and the SVM with the linear, polynomial, and radial basis function (RBF) kernels are applied along with optimal genetic search. Also, the k-fold cross validation is used to prevent over fitting. The effect of principal component analysis (PCA) is investigated, too. A comparative analysis is performed between the existing methods, the nine generalized methods and the novel method, by applying extensive numerical simulations in a Brazilian regional utility, by using PSCAD/EMTDC and MATLAB. Finally, effectiveness of all methods was obtained, reactive power based on generalized methods using instantaneous positive sequence components and Clarke's components gave the right location in 88% of total simulated cases, whereas the robust SVM based method with RBF kernel without PCA had the highest accuracy (95%).

1. Introduction

Voltage sag is a decrease in RMS voltage between 0.1 and 0.9 pu at the power frequency for a duration of 0.5 cycles to 1 min. They can occur in systems or even in the customer end with a frequency of even several thousand times per year [1]. This phenomenon can also cause substantial product loss in a typical industrial installation [2–4]. Starting/loading of heavy induction motors, transformers energizing, capacitor switching, overloads and faults may cause voltage sags. Voltage sags caused by faults are propagated through the system affecting connected loads far away from the fault location, causing many disagreements between utilities (transmission–distribution, distribution–distribution and distribution-micro grids) and also between utilities and consumers. Therefore, identification of the responsible agent for the voltage sag occurrence and identification of the source of sags is crucial to solve such issues. Location of sag source is an important topic and is the first step toward mitigation of power quality problems [5,6].

Many studies have been done [7–34] on the subject of voltage sag source location. A review of methods along with an introduction of generalized methods [7–9,14,16–19,21,27,28,30–33] can be found in the next section. These methods can be divided into five categories. The first category was based on changes of energy, during a voltage sag, by investigating the concepts of "disturbance power and energy" [7]. Later, researchers perfected this method [8–13] and Leborgne et al. [14,15] investigated an alternative approach based on power flow information.

The second category utilized changes of current. The method introduced by Li et al. [16] relies on the slope of voltage-current fitting to determine the sag sources. In Ref. [17], the polarity of variation of the active current is used to locate the sag source. The third type focused on the changes of impedance during sag. The method [16] was generalized by the same authors of the "resistance sign" approach [18]. In this method, sag source location is found using the sign of incremental resistance. Another method [19] based on negative sequence components was introduced. Later, Zhu et al. [20] determined the sag source location applying the same theory, according to the neutral point operation mode. In Ref. [21] the locations are found using the apparent impedance seen by a

---

* Corresponding author.
E-mail addresses: Mohammadi.yunes@gmail.com (Y. Mohammadi), Mh_moradi@yahoo.co.uk (M.H. Moradi), roberto.leborgne@ufrgs.br, rchouhy@hotmail.com (R. Chouhy Leborgne).

http://dx.doi.org/10.1016/j.epsr.2016.12.028
0378-7796/© 2016 Elsevier B.V. All rights reserved.

Nomenclatures

SVM	Support vector machine
RBF	Radial basis function
PCA	Principal component analysis
PQM	Power quality monitor
DS	Downstream
US	Upstream
DPE	Disturbance power and energy
RP	Reactive power
RCC	Real current component
SST	Slope of system trajectory
DR	Distance relay
RS	Resistance sign
PCSC	Phase change in positive sequence current
CBM	Current based method
( )	Number of equation in relation to the rule of methods
$(.)_{sag}, (.)_{presag}$	During sag and pre-sag
$\Delta(.) = (.)_{sag} - (.)_{presag}$	Change due to the sag
$\angle(.)$	Phase angle
V, I	Voltage and current phasor
ξ	Bandwidth in SVM parameters
θ	Phase angle between voltage and current
Z, R	Impedance and resistance
Z_e^+, Z_e^-	Incremental impedance obtained from positive and negative sequence components
z_e^+	Incremental impedance obtained from instantaneous positive sequence components
$(.)_{\alpha\beta}$	Clarke's components
$(.)^+, (.)^-$	Positive and negative sequence components
v, i, z, r	Instantaneous voltage, current, impedance, resistance $\Delta s = i_{\alpha presag}.i_{\beta sag} - i_{\beta presag} i_{\alpha sag}$
ΔP, ΔQ	Active and reactive disturbance power
ΔE	disturbance energy on ΔP
$\Delta p_{\alpha b,}$ on $\Delta q_{\alpha\beta}$,	Active and reactive disturbance power obtained from Clarke's components
$\Delta e_{\alpha\beta} p$	Disturbance energy on $\Delta p_{\alpha\beta}$
$\Delta e_{\alpha\beta} q$	Disturbance energy on $\Delta q_{\alpha\beta}$
ΔP^+ and ΔQ^+	Positive sequence disturbance active and reactive power
ΔE^+	Positive sequence disturbance energy on ΔP^+
$p^+ = v^+ i^+ \cos(\theta)^+$, $q^+ = v^+ i^+ \sin(\theta)^+$	Active and reactive power obtained from instantaneous positive sequence components
Δp^+ and Δq^+	Disturbance active and reactive power obtained from instantaneous positive sequence components
$\Delta e^+ - p$	Disturbance active energy on Δp^+
$\Delta e^+ - q$	Disturbance reactive energy on Δq^+
c	Regularized constant in SVM parameters

distance relay. This method was tested by a case study using the Brazilian network in Refs. [22,23]. Later in Ref. [24] the variation of impedance angle was used instead of the angle.

The fourth category is based on only voltage measurements. In Ref. [25] a method based on the information of the voltage magnitude and phase-angle jump was proposed. Also, another method [26], using voltage information at both sides of a transformer was introduced.

The fifth type locates the sag source according to only current measurements. The first method in this field [27] is based on the phase change in the positive-sequence current phasor. Its application is, however, limited to systems supplied from two sides. Moradi et al. proposed the second method [28], which uses magnitude change in the positive-sequence current phasor as an additional criterion to the method proposed by Pradhan et al. [27].

The testing of some discussed methods for sag source location known from the literature shows that in the cases of asymmetrical sags, these methods are rather ineffective [29]. Therefore, Polagzer et al. [8] generalized the methods based on positive sequence components. Moreover, since voltage sags are a transient event, the methods based on phasor or positive sequence phasor might give questionable results. Thus, the same authors generalized the methods of Refs. [7,16–18] based on Clarke's components [9,30] in systems with DG and active loads, as well as [28] based on a vector written in Clarke's components [31] and on instantaneous positive sequence components [32]. These generalizations will generate better results for sag source location. Also, in this way, Shao et al. developed the method in Ref. [21] based on Park's components [33]. In Ref. [34] method features of sag source location have been analyzed in the Catalan power network. In Ref. [35], a method using pattern recognition which applied an easy and non-robust structure including features of only five methods is presented [7,16–18,21].

This paper explains the rules of earlier methods for voltage sag source location (22 cases). In turn, nine generalized methods are introduced in this paper, using positive sequence phasors, Clarke's components, instantaneous positive sequence components and integration. The discussed methods are divided into several categories and their rules are extracted and clearly defined. However, the discussed methods use single or two criteria and as the results will show, their effect will be limited. Hence, this paper proposes a novel sag source location method by machine learning approach based on artificial intelligence in which many features for pattern recognition are extracted first, based on the 31 methods (22 methods known from the literature and 9 generalized methods). Then, pattern classification is discussed with two steps, and the SVM with kernels of linear, polynomial and RBF are applied in the case. In order to select the optimal parameter for each kernel configuration in SVM, an optimal genetic search is used and in order to prevent over fitting the k-fold cross validation is applied. Also, the effect of PCA is investigated. After showing the results of generalized methods, a comparative analysis is performed between all the discussed methods and the novel robust method, by applying extensive numerical simulations in a Brazilian regional power network. The obtained effectiveness of the discussed methods along with the novel method for all type of faults is fully presented and a main comparison is performed between them.

2. Review along with generalization of methods for voltage-sag source relative location

The relative location of the sag source as observed from a PQM is defined as DS or US, using the steady state active power flow direction as reference. DS is the region in the direction of the power flow and US is the region against it.

The methods for relative sag source location can be divided into several categories based on various criteria such as instantaneous values, positive and negative sequence phasors, instantaneous positive sequence values, and Clarke's components. All methods are extracted from literature or are the authors' own development as generalized methods. A description of all the methods for DS/US location of voltage sag sources is given in Table 1. Generalized