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New smart fault locator in compensated line with UPFC

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ABSTRACT

In this paper, a new smart fault locator in a compensated transmission line with a Unified Power Flow Controller (UPFC) is proposed. Three types of features are extracted from the captured fault signals at one-end of the compensated line by using a time-frequency signal processing tool known as the Hyperbolic S-Transform (HST). The HST, with an asymmetrical window, is an improved version of the S-transform. Then, the regression model of the Support Vector Machines (SVMs) with a non-linear kernel function is applied for the fault location estimation. The proposed smart fault locator gives accurate estimation results by involving hidden statistical features which comprise a new type of time-frequency features. The evaluation of the features and the estimation error obtained under different conditions confirm the efficacy of the proposed smart fault locator.

1. Introduction

Transmission lines often experience electrical faults in a power system. If the fault point can be located with high accuracy, the system restoration will be expedited and, hence, the system operation will be improved. As the Flexible AC Transmission Systems (FACTS) advances, the compensated transmission lines are faced with challenges for the fault analysis [1,2].

The Unified Power Flow Controller (UPFC), a versatile compensator with three control variables (active, reactive power, and voltage), can overcome the power transfer limitations. A UPFC with Static Synchronous Series Compensator (SSSC) and STATic synchronous COMpensator (STATCOM) connected to a common dc-link can independently and simultaneously control the power flow in a line, leading to symmetrical three-phase compensations during asymmetrical faults. Accordingly, it is imperative to reconsider the transmission line protection and fault locators [2–5].

From the viewpoint of signal availability, the fault locators utilize the signal(s) from the one- or two-end of the protected line. The most significant advantage of the one-end-based methods is that communication channels and remote data are not required. Therefore, the implementation procedure of these methods is easier than the two-end-based methods. Furthermore, the integration of the one-end methods into the numerical relays or the digital fault recorders is possible. The one-end fault locators yield acceptable fault location estimation but the estimation is not as accurate as the one yielded by the two-end fault locators.

There are various methods for addressing the fault location problem based on the one-end captured signals: impedance- [6], travelling wave- [7], high frequency components- [1], and artificial intelligence-based [8–15] methods. In the next section, these methods will be discussed in more details. Some methods locate the faults in the UPFC-embedded line by using the two-end captured signals [3,4] but there is no study of one-end-based fault location in the compensated line with the UPFC. When the UPFC is absent in a fault loop, the fault location algorithm observes the fault loop as an un-compensated case. Therefore, some fault location algorithms from the category of artificial intelligence methods in the un-compensated line are reviewed. Extracting features from the one-end captured signal(s) and feeding them into the estimator model is the common procedure used by these algorithms. The features extracted by the Discrete Fourier Transform (DFT) tool contain different frequency components [8,9,11]. The distribution of each frequency component in the time domain can improve the performance of estimators. Therefore, the S-Transform (ST), as a time-frequency tool, is applied for feature extraction purposes in [12].

The smart fault locator performance and its generalization capability are highly depended on the efficacy of the extracted features. In this paper, using the Hyperbolic S-Transform (HST) as an improved version of the ST with an asymmetrical window, an accurate smart fault locator based on captured signals at one-end of the UPFC-embedded line is proposed. Three types of features including impedance, time-frequency, and hidden statistical fea-

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tures are fed into the Support Vector Machines (SVMs) with a non-linear kernel function. To evaluate the extracted feature vector, different fault conditions are analyzed. Moreover, the accuracy of the proposed smart fault locator is examined under various scenarios.

2. Statement of the problem

Today, the FACTS technology is increasingly applying in the power systems to provide an affordable, reliable, and sustainable increase in the capacity of networks. On the other hand, fault location methods in compensated lines, in comparison to un-compensated lines, are faced with more challenges. The conventional fault location methods in the compensated line with the UPFC have additional uncertain parameters related to the series and shunt parts of the UPFC [28]. Despite the fact that the one-end-based methods are more preferred for locating faults in the UPFC-embedded line, more research attention is paid to the two-end data-based methods but these methods suffer from the limitation of requiring reliable communication channels [3,4]. The one-end-based fault locators can be classified according to their techniques as follows:

– The methods based on the travelling wave require a high sampling rate. Moreover, in a compensated line, when a compensator device presents in the fault loop, discrimination between the reflected waves from the fault point and the remote bus is a challenging issue in the fault location [1,7].
– The methods based on the generated high-frequency components in the signals during faults are not widely used due to the bandwidth limitation of the transducers [1]. However, the high-frequency information of fault signals is more accessible to the fault locators as the technology of the transducers is advanced [16,17].
– The one-end impedance-based methods are commonly used by the fault locators in a transmission network. Different one-end methods such as simple reactance, Takagi, modified Takagi, Erikson, and Novosel have been proposed [6,19]. Some assumptions need to be met to calculate the fault location and, hence, these methods suffer from estimation errors. In the UPFC-embedded transmission line, due to series injected voltage by series part of the UPFC and shunt injected current by shunt part of the UPFC, the impedance-based methods fail to calculate the fault location.
– The artificial intelligent-based methods employ the useful features of fault signals in the relaying point to locate the faults accurately. When there is no direct relationship between the input data and the target value, these methods can be useful [8–15].

In this paper, a smart fault locator is proposed by using some advantages of the aforementioned methods and new extracted time-frequency features.

3. Pattern-recognition tools

3.1. Hyperbolic S-transform

A short time Fourier transform with a Gaussian window is introduced as an S-Transform. The ST is a multi-resolution time-frequency technique which is given as follows:

$$S(\tau,f) = \int_{-\infty}^{+\infty} h(t)w(\tau - t)\exp(-2\pi jft)dt \tag{1}$$

where t is time, τ is an index of the window position control on the time axis, f is a frequency symbol, S is the ST of input signal $h(t)$ as a continues function of t, j is a unit imaginary number, and $w(t)$ is a Gaussian symmetrical window. The ST applies a narrower Gaussian window to provide appropriate time resolution. On the other hand, the narrower window gives good time resolution but poor frequency resolution. To overcome this problem, the "hyperbolic" window, as an asymmetrical window with a sharper taper in the forward direction and a compensating slower tapper in the backward direction, is used. More details regarding the HST are described in [20].

Usability of HST: The HST with an asymmetrical adjustable window width provides a multi-resolution of non-stationary signals such as fault signals. For a signal of length N, the HST generates a $N/2 \times N$ matrix contained complex numbers. The rows and columns of a HST-Matrix (HSM) represent time and frequency domains respectively. The HSM provides the time-frequency information on the signal impressively.

3.2. Support vector machines

The SVMs, as powerful machine learning models, perform the regression task by the same principles used in the classification case. The SVM regression uses $\varepsilon -$ insensitives function to fit a function which approximates the relation inherited between the data set points and associated targets. The function estimates the output for a new input data point. In a non-linear problem, the training patterns are mapped into a feature space by a kernel function and then, the standard SVM regression model will be applied to solve the problem. More details are described in [21].

Why SVM? First, compared to Neural Networks (NNs), the SVMs are free of local minima. Moreover, the tuning parameters of SVMs are less than ones in NNs. Second, the SVMs do not need expert knowledge for the regression problems, in contrast to the fuzzy-based methods which need prior expert knowledge. Finally, the selection of Radial Basis Function (RBF) kernel makes an appropriate SVM model for a non-linear problem. Furthermore, the combination of the margin parameter of SVMs (C) and the RBF parameter (γ) achieves a good generalization capability in complex regression problems such as the fault location estimation.

4. Proposed smart fault locator

The structure of the proposed smart fault locator is shown in Fig. 1. When a fault occurs at the transmission line before the UPFC installation point, the UPFC device is absent in the fault loop. Therefore, the UPFC controllers have no effect on the voltage and current signals at the relaying point. On the other hand, when a fault occurs at the transmission line after the UPFC installation point, the UPFC device is in the fault loop. A symmetrical or an asymmetrical fault, which is occurred after the UPFC installation point, leads the UPFC to a symmetrical compensation due to three-phase nature of the controllers. Therefore, in this case, the sampled signals at the relaying point differ from the sampled signals corresponding to the faults before the UPFC installation point. From the viewpoint of the installation location of the UPFC, two sections are possible for the fault points: "before" and "after" the UPFC installation point. In this paper, accordingly, two parallel subroutines are needed to locate the faults before and after the UPFC installation point. SVM-1, 2, 3, and 4 are trained for single-phase-to-ground (LG), phase-to-phase (LL), phase-to-phase-to-ground (LLG), and three-phase/three-phase-to-ground (LLL/LLLG) faults before the UPFC installation point, respectively. SVM-5, 6, 7, and 8 are trained for the faults after the UPFC installation point similar to SVM-1, 2, 3, and 4. Furthermore, it is assumed that the fault inception time, fault type, and fault loop status (loop including UPFC or not) are known by auxiliary functions proposed in [2].