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An intelligent algorithm for fault location on VSC-HVDC system

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ABSTRACT

This paper proposes a novel intelligent algorithm for fault location on the voltage sourced converter-high voltage direct current (VSC-HVDC) system. This method with single-ended measurement makes full use of frequency, time and energy to capture the fault features via Hilbert-Huang Transform (HHT). The time delay, characteristic frequency, energy attenuation and high-frequency energy are used as the input of ε-support vector regression (SVR) to get fault distance. Then bat algorithm (BA) optimizes the parameters of the model with cross validation comparing with other optimization algorithm. Furthermore, high-frequency variance contribution rate (HVCR) is adopted to identify the fault area. The VSC-HVDC simulation system is constructed to verify the reliability and accuracy of the method and the expected accuracy of the proposed method is ±500 m. The results demonstrated that the proposed method still has reliability and accuracy for hybrid transmission line with a small amount of data.

1. Introduction

For the increasingly rapid growth of electricity load, HVDC is an effective way to solve the current problem by enhancing transmission capacity of existing transmission lines. VSC-HVDC adopts IGBT and PWM modulation widely used in power systems [1,2], thus it has flexible control and high reliability. Because VSC-HVDC transmission line has a long distance across the complex geographical terrain, the reliable fast action of breaker and fault location are indispensable conditions for the stable operation of the line. Currently, the methods of fault location on VSC-HVDC transmission lines normally utilize traveling-wave to get fault distance. While the other methods mostly need to know specific parameters of transmission lines.

For the traveling-wave fault-locating theory [3–6], it has highest precision and has been applied in practice. Then, by knowing traveling wave-head arrival time detected from the opposite bus and wave velocity, the fault distance is able to be identified. However, signal from the global positioning system may be lost, thus the fault-location under unsynchronized two-end measurement requires further research. The researchers reset zero time reference point and mix the traveling wave theory with the Bergeron time-domain for fault location [7]. But this approach still requires lines parameters. The natural frequency of the fault signal is related to the fault distance [8], however this method for fault location needs to pick up the precise frequency and the wave speed. The resonant characteristics of DC capacitance are exploited in the HVDC fault location [9], while there are dead zones in the application. A novel method based on double measurement points [10] still has the problem of fault resistance. Recently, the intelligent algorithm was widely used in all aspects of the power system. In the field of fault location, it is able to refrain the deviation by evaluating the lines parameters. To improve the accuracy of model, various approaches capture different fault features to train the model [11–14]. Energy percentage in each level is utilized for training the artificial neural network and the energy information is provided by wavelet multiresolution analysis of the recorded transient voltage signals [11]. The features of the traveling wave can be extracted from the voltage and current by using wavelet packet decomposition (WPD) algorithm. And they are as the input vectors of RBF (radial basis function) neural network [12]. These methods extract features by the wavelet. Another new approach is posed based on hyperbolic S-transform and the authors yield the change in energy and standard deviation to achieve fault location via RBF neural network [13]. Moreover, singular value decomposition (SVD) method can also be used for extracting the features of HVDC traveling wave [14]. On the other hand, the classifier (support vector machine, SVM) and regression (SVR) schemes have been trained with features and have favorable performance in the application of intelligent algorithm.

Generally the features of fault location are divided into frequency domain and time domain. Grounded fault can be located utilizing the time difference delay of modal components [15], and the characteristic frequency for the location is proposed [16]. This paper proposes a new scheme of extracting features through

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synthetical consideration. Hilbert-huang Transform (HHT) is a new non-stationary signal analysis method and it can also be considered as adaptive time–frequency analysis method. Its application to the transient signals from faulted power system is particularly advantageous. By using HHT algorithm, the time delay of different modal components and the information of frequency domain are used to train SVR. Besides, the attenuation of energy is also taken into account. The parameters of SVR are optimized by bat algorithm (BA) to obtain the best performance.

The main contribution of this paper is a new fault-location algorithm on HVDC transmission lines. The proposed method is a single ended method which makes full use of the frequency, time and energy to capture the fault features. HHT algorithm accurately gets the time difference delay of modal components and the information of frequency with the instantaneous frequency analysis as well as boundary spectrum. In addition, considering diversification of energy the features are used as input of BA-SVR algorithm. It is found that the time delay, characteristic frequency, high-frequency energy and the attenuation of energy are related with fault distance. Moreover, the high-frequency variance contribution rate (HVCR) of the Intrinsic Mode Function (IMF) proposed in this paper is a preparation for fault area identification. Comparing with former methods which are optimized by particle swarm optimization (PSO) and genetic algorithm (GA), the SVR optimized by BA has a faster convergence speed and better solutions.

The remainder of this paper is structured as follows: Section 2 introduces theoretical basis of the HHT, SVR, BA and HVCR. Then in the Section 3 the specific location scheme and preferences are presented, including the features extraction, parameter selection of model, the criterion validation and flow diagram. The simulation of VSC-HVDC system is constructed for the training and test using PSCAD/EMTDC in the Section 4. In the end, Section 5 reveals conclusion of this paper.

2. Mathematical model and traveling wave theory

2.1. HHT instantaneous frequency and boundary spectrum

HHT was utilized for analyzing the nonlinear and non-stationary signals created in 1996 [17]. Firstly, this algorithm needs Empirical Mode Decomposition (EMD) to pretreat the signals. Then IMF decomposed by EMD executes Hilbert transform to get the information of frequency and amplitude.

The time signals $x(t)$ can be expressed as the sum of empirical modes and a residue:

$$x(t) = \sum_{j=1}^{n} c_j(t) + r_n(t) \tag{1}$$

Hilbert transform make each IMF sub value to get the following formula:

$$y_j(t) = \frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{c_j(\tau)}{t-\tau} d\tau \tag{2}$$

$$z_j(t) = c_j(t) + iy_j(t) \tag{3}$$

where $z_j(t)$ is the analytic signal constructed by Hilbert transform.

From the above equations, the original signal $x(t)$ without the residue $r_n(t)$ and the instantaneous frequency $f_j(t)$ can be explained as the follows:

$$x(t) = \sum_{j=1}^{n} a_j(t) e^{i\int_T \omega_j(t)dt} \tag{4}$$

$$f_j(t) = \frac{1}{2\pi}\omega_j(t) \tag{5}$$

Taking the real part of the Eq. (4), there is only instantaneous amplitude a corresponding to the instantaneous frequency. Then the regularity that signal amplitude variation with frequency and time over the entire frequency domain can be accurately described:

$$H(f,t) = RE\sum_{j=1}^{n} a_j(t) e^{i2\pi\int_T f_j(t)dt} \tag{6}$$

The Hilbert boundary spectrum is obtained by solving the formula (6):

$$h(f) = \int_0^T H(f,t)dt = \sum_{j=1}^{n}[RE\sum_{j=1}^{n} a_i(t)e^{i\int_T \omega_j(t)dt}]dt = \sum_{j=1}^{n} h_j(f) \tag{7}$$

where T is the length of the signal sequences and $h_j(f)$ is the boundary spectrum of jth IMF. Then the traits of signal frequency domain can be captured clearly.

2.2. SVR and BA

To enhance the generalization ability of model, the standard form of SVR adopted in this paper is

$$\begin{aligned} &\min_{w,b,\xi_i,\xi_i^*} \tfrac{1}{2}\|w\|^2 + C\cdot\sum_{i=1}^{n}(\xi_i+\xi_i^*) \\ &\text{subject to} \begin{cases} y_i - w\cdot\varphi(x) - b \leqslant \varepsilon + \xi_i^* \\ w\cdot\varphi(x) + b - y_i \leqslant \varepsilon + \xi_i \\ \xi_i, \xi_i^* \geqslant 0, \varepsilon > 0,\ i = 1,2,\ldots,n \end{cases} \end{aligned} \tag{8}$$

where C is the penalty factor, ε is the insensitive loss coefficient, ξ and ξ^* are the introduction of slack variables.

To a certain extent, the accuracy of the model depends on the choice of kernel. Though new kernels are being proposed by researchers, most of them are changed based on the following four basic kernels:

- linear: $K(\boldsymbol{x}_i, \boldsymbol{x}_j) = \boldsymbol{x}_i^{\mathrm{T}}\boldsymbol{x}_j$.
- polynomial: $K(\boldsymbol{x}_i, \boldsymbol{x}_j) = (\gamma\boldsymbol{x}_i^{\mathrm{T}}\boldsymbol{x}_j+r)^d$, $\gamma > 0$.
- RBF: $K(\boldsymbol{x}_i, \boldsymbol{x}_j) = \exp(-\gamma\|\boldsymbol{x}_i-\boldsymbol{x}_j\|^2)$, $\gamma > 0$.
- sigmoid: $K(\boldsymbol{x}_i, \boldsymbol{x}_j) = \tanh(\gamma\boldsymbol{x}_i^{\mathrm{T}}\boldsymbol{x}_j+r)^d$.

here, γ, r, and d are kernel parameters.

Because of the mathematical relationship between fault distance and fault features, it is necessary to obtain the specific model by SVR. When the fault occurs, the relevant fault features can be extracted to obtain specific fault distance via SVR. Support vector regression, which based on statistical learning theory and structural risk minimization principle, is of the good extension ability and the better accuracy in the fault location.

BA is a novel optimization algorithm by imitating the bats' hunting behavior [18]. The bats get the information of prey by using echolocation. However each virtual bat in BA flies randomly with velocity v_i at position X_i. And the velocity v_i is affected by a fixed frequency $f_{\min}$. The bat keep searching for food according to its wavelength λ and loudness A_0.

2.3. Time-frequency characteristics analysis and HVCR

Fig. 1 is the schematic diagram considering unipolar fault on VSC-HVDC. It is consisted of exchange station, AC filter, converter reactor, converter transformers, DC capacitor and DC lines, etc. The fault in the segment of hj is an external fault and the segment of jk is the internal area.

For the AC system, the fault location needs the decoupling of signals to obtain the aerial mode and zero mode [3]. However, this