Voltage Sag Source Location based on Comprehensive Criterion and Neural Network Method

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Abstract. In order to solve the disputes caused by voltage sag, this paper proposes a comprehensive criterion of voltage sag location based on the traditional voltage sag location method. This criterion combines the characteristic information of voltage sag, and trains the neural network with the comprehensive criterion to locate the voltage sag source. Compared with the traditional methods, the simulation results show that the proposed method has higher accuracy and immunity to voltage sags under various faults, especially under asymmetric faults.

1. Introduction

In recent years, voltage sag has a huge impact on many sensitive loads, which has attracted the attention of researchers at home and abroad. Voltage drop is defined as the effective value of the supply voltage drops rapidly to 90%-10% of the rated value, and the duration is from half power frequency cycle to tens of seconds [1-3]. The task of locating the voltage sag source is to determine which side of the monitoring device causes the voltage sag disturbance, so as to divide the responsibilities of the power grid and users. At present, there are four methods to study the location of sag source at home and abroad, which are based on disturbance power and disturbance energy, impedance real part, sag classification and other methods. The location method based on disturbance power and disturbance energy is only suitable for the location of symmetrical voltage interference sources. The location method based on the real part of impedance only depends on the empirical formula, so it is difficult to determine the applicable range. The location method based on sag classification involves the selection of threshold value, so it is not suitable for practical engineering [4,5].

The principle of neural network voltage sag source location method is as follows. Based on the criterion of traditional voltage sag location method, combined with the characteristic information of voltage sag, a comprehensive criterion of voltage sag source location is formed. The neural network can be trained by using the synthetic criterion samples, and the trained neural network can be used to locate the voltage sag source.

2. Voltage sag location method

Check the voltage sag at M, as shown in Figure 1.

Figure 1. Diagram of voltage sag
Referring to the direction of power flow, if the voltage sag occurs between the power supply and M, it is considered that the voltage sag occurs in the upstream. If it occurs between M and the user, it is considered that the voltage sag occurs in the downstream.

2.1 Method based on disturbance power and disturbance energy

When the system is disturbed and voltage sag occurs, it usually accompanies the change of energy. Therefore, the source of voltage sag can be located by the direction of energy flow\cite{7}. The instantaneous disturbance power DP is defined as:

$$DP(t) = p(t)_f - p(t)_n$$ \hfill (1)

Where $p(t)_n$ is the power in normal operation and $P(t)_f$ is the power in case of disturbance and $p(t)_f$ is the power in case of disturbance. When the system is in normal operation, the value of DP is close to 0. When the value of DP changes, it means that the system is disturbed. The disturbance energy De is defined as:

$$De = \int DP(t) dt$$ \hfill (2)

By using the disturbance energy, the position of voltage sag source can be determined. When $De < 0$, the voltage sag source is located upstream. When $De > 0$, the voltage sag source is located downstream\cite{8}. This method can locate the disturbance of energy release type, but the judgment of disturbance of energy injection type is not accurate.

2.2 Method based on impedance real part method

According to the circuit shown in Figure 1, before the disturbance occurs, the fundamental frequency positive sequence component of M satisfies the (3). When voltage sag is caused by downstream disturbance, M satisfies the (4). The formula (5) can be obtained by calculation.

$$U = E_1 - lZ_1$$ \hfill (3)

$$U + \Delta U = E_1 - (I + \Delta I)Z_1$$ \hfill (4)

$$Z_1 = \frac{\Delta U}{\Delta I}$$ \hfill (5)

Similarly, formula (6) can be obtained when upstream disturbance occurs.

$$Z_1 = \frac{\Delta U}{\Delta I}$$ \hfill (6)

Define the equivalent impedance $Z_e$ as follows,

$$Z_e = \Delta U = \frac{U_{sag} - U_{pre}}{I_{sag} - I_{pre}}$$ \hfill (7)

Where, $U$ and $I$ are the fundamental positive sequence voltage and current respectively, the subscript sag represents the period of disturbance, and pre represents the period before disturbance. According to the above analysis, when the disturbance occurs upstream or downstream, the symbol of the calculated equivalent impedance $Z_e$ is different\cite{9-11}. Therefore, the location of the disturbance can be determined according to the real part of the equivalent impedance. When $Re(Z_e) > 0$, the disturbance occurs upstream, and when $Re(Z_e) < 0$, the disturbance occurs downstream.

2.3 Method based on the slope of system trajectory

Assuming that the disturbance is located downstream of the monitoring point M, it satisfies the (8).

$$U \cos \theta_2 = -l^2R + E_1I \cos \theta_1$$ \hfill (8)

Where, $\theta_1$ is the phase difference of the voltage and current of the power supply, $\theta_2$ is the phase difference of the output voltage and current of monitoring point m, $R$ is the real part of impedance $Z_1$. Since $\cos \theta_2 > 0$, the above formula can be transformed into formula (9).

$$U \cos \theta_2 = -lR + E_1 \cos \theta_1$$ \hfill (9)

The above formula can be regarded as the equation of $U \cos \theta_1$ and $I$, with a slope of $-R$. Similarly, when the disturbance is located upstream of the monitoring point, M meets the following requirements.

$$U \cos \theta_1 = lR + E_1 \cos \theta_1$$ \hfill (10)
At present, the slope of the equation for $|U \cos \theta|$ and $I$ will change to $R$. Therefore, when the disturbance occurs upstream or downstream, the positive and negative slope of the equation for $|U \cos \theta|$ and $I$ will change\textsuperscript{[12]}. The slope of the equation can be obtained by collecting $|U \cos \theta|$ and $I$ during voltage sag and fitting with the least square method. According to the positive and negative slope, the position of voltage sag source can be determined: if the slope is positive, the voltage sag source is located in the upstream; if the slope is negative, the voltage sag source is located in the downstream.

This method has high credibility by processing a large number of data. However, because the judgment is based on single phase, when asymmetric fault occurs, the three-phase judgment results will be inconsistent.

2.4 Method based on real part method of current
In Figure 1, when the fault occurs upstream, the direction of active current is opposite to that before the fault, while when the fault occurs downstream, the direction of active current is the same as that before the fault. Therefore, the voltage sag source can be located by judging the real part $I \cos \theta$ of the current. If $I \cos \theta > 0$ at the beginning of voltage sag, the voltage sag source is located at the downstream; if $I \cos \theta < 0$, the voltage sag source is located at the upstream\textsuperscript{[13]}.

This method is suitable for dual power system. Its disadvantage is the same as that of the track slope method, both of which are judged by phase, and the judgment results of asymmetric fault are inconsistent.

3. Comprehensive criterion of voltage sag
The traditional method of locating voltage sag source has some limitations, especially for asymmetric fault, using the real part method of current or the slope method of system track will result in inconsistent three-phase judgment results\textsuperscript{[14,15]}. Therefore, this paper proposes a method of locating voltage sag source by using comprehensive criteria. The synthesis criterion combines the characteristic criterion of traditional voltage sag source location and the characteristic quantity during voltage sag. Thus, the limitation of traditional voltage sag source location is overcome, and the accuracy of location is improved.

When voltage sag occurs, for different types of disturbances, the characteristics of electricity are different, mainly including the following centralized sag characteristics.

1) Voltage amplitude
The characteristic value of voltage amplitude includes the average value and the minimum value of voltage during the sag, as shown in formula (11)

$$
\begin{align*}
U_{ave} &= \text{ave}(U_i(t)) \\
U_{min} &= \min(U_i(t))
\end{align*}
$$

(11)

Where, $U_i$ is the instantaneous value of voltage fundamental wave during sag.

2) Voltage slope
The characteristic value of voltage slope includes two parts: the falling slope when voltage sag occurs and the rising slope when voltage recovers, as shown in formula (12).

$$
\begin{align*}
\gamma_1 &= \frac{U_{\text{sag}}}{T_d} \\
\gamma_2 &= \frac{U_{\text{sag}}}{T_u}
\end{align*}
$$

(12)

Where, $U_{\text{sag}}$ is the voltage amplitude, $T_d$ and $T_u$ are voltage drop time and voltage recovery time, respectively.

3) Harmonic content
Harmonic content refers to the change of harmonic content before and after voltage sag, as follows.

$$
\Delta h = \frac{h_{\text{during}}}{U_{\text{1, during}}} - \frac{h_{\text{pre}}}{U_{\text{1, pre}}}
$$

(13)

Where, $h$ represents the effective value of harmonic, $1$ represents the effective value of fundamental wave.

4) Phase jump
The phase change of the voltage fundamental wave before and after the sag is as follows,

$$\Delta \phi = \frac{\phi_{pre} - \phi_{sag}}{2\pi}$$  \hspace{1cm} (14)

(5) Three phase unbalance

$$U_{ab} = \max(U_{a1}, U_{b1}, U_{c1}) - \min(U_{a1}, U_{b1}, U_{c1}) \over \text{avg}(U_{a1}, U_{b1}, U_{c1})$$  \hspace{1cm} (15)

Where, $U_{a1}$, $U_{b1}$, $U_{c1}$ are the fundamental amplitude of A,B,C phase voltage.

In conclusion, the following comprehensive criteria can be obtained,

$$F = F_1 + F_2 = \alpha_1 f_1 + \alpha_2 f_2 + \cdots + \alpha_n f_n$$  \hspace{1cm} (16)

Where, $F_1$ is the characteristic criterion of voltage sag source location, including disturbance energy, real part of impedance calculated by three phases, slope of system track calculated by three phases and real part of three phase current calculated by three phases respectively. $F_2$ is the sag characteristic quantity during voltage sag, including voltage amplitude characteristic, slope characteristic, harmonic characteristic, phase jump and three-phase imbalance degree of three-phase. $f_i$ is each eigenvalue of the comprehensive criterion, and $\alpha_n$ is the weight corresponding to each eigenvalue.

4. Neural network

Neural network refers to that, based on the training of samples, by changing the number and connection relationship of internal nodes, a reasonable network structure is established to achieve the goal of sub criteria [16,17]. The nodes inside the neural network, also known as neurons, each neuron is an excitation function, and the neural network is a nonlinear adaptive processing system composed of a large number of nodes [22].

In this paper, a simple feedforward neural network is selected. The basic structure of the common feedforward neural network is multi-layer, which is composed of input layer, hidden layer and output layer. The input layer receives a large number of nonlinear input vectors, and the hidden layer has a large number of neuron nodes to process information, and the output layer finally outputs vectors, as shown in Figure 2. Through data collection, a large number of samples of voltage sag can be obtained. After inputting them into neural network, the neural network can be trained to obtain the training model. Compared with the results of comprehensive criteria, the training accuracy can be obtained [18-20]. Finally, the trained neural network can be used to locate the unknown sag source.

![Neural network structure](image)

![Simulation model diagram](image)

5. Simulation analysis

The system simulation model is built in the simulation software. The model is improved on the basis of IEEE14 node model. M is the detection point of voltage sag, as shown in Figure 3. As shown in Figure 3, fault points are respectively set in all parts of the system, and the fault types are respectively set as three-phase ground fault, two-phase ground fault, two-phase fault and single-phase ground fault. 80 sets of voltage sags data samples can be obtained by simulating voltage sags caused by different faults and different ground resistances and voltage sags caused by the input of simulation transformer. The hidden layer of neural network is set as one layer, and the number of neurons is set as 10. When the voltage sag source is upstream, the target value of the neural network is -1. When the voltage sag source is downstream, the target value is 1. Firstly, 80 groups of data are normalized according to the following formula.
\[ x' = \frac{x - \mu}{\sigma} \]  

(17)

Where, \( X \) is the data sample before normalization, \( \mu \) is its average value and \( \sigma \) is its standard deviation. 48 of the 80 normalized samples are used for neural network training, 16 for verification and 16 for testing. The results are shown in Figure 4-6.

The regression value \( R \) is used to represent the correlation between the output value and the target value of the neural network. When the value of \( R \) is 1, it means close relationship, and when it is 0, it means random relationship. In Figure 4, \( r = 1 \), indicating that the output of the trained neural network is consistent with the target value. In Figure 5, \( r = 0.99905 \), and in Figure 6, \( r = 0.99988 \), which shows that the difference between the output of neural network and the target value is very small. The test shows that the trained neural network can effectively locate the voltage sag source.

In order to verify the effectiveness of the trained neural network, 5% random noise is added to 80 groups of normalized samples, that is, the maximum increase or decrease of the original data is 5% of the data. Similarly, 10%, 50% and 100% random noise are added respectively. The output of the neural network is shown in Figure 7. The \( R \) values of the four conditions are 0.99977, 0.99972, 0.99971 and 0.99911 respectively. From the output results, after adding noise, the output error of neural network increases with the increase of noise. When adding 100% random noise, the error is the largest. At this time, the neural network can still effectively locate the voltage sag source, which shows that the neural network has good anti-interference performance.

### 6. Conclusion

This paper combines the characteristic criterion of traditional voltage sag source location and the characteristic quantity of voltage sag, forms the comprehensive criterion of voltage sag source location, and trains the neural network by collecting the characteristic value during voltage sag. The following conclusions are obtained through the simulation of an example.

The location method of voltage sag source based on comprehensive criterion can break the limitation of traditional voltage sag source location, especially for asymmetric fault, this criterion can locate well. And the location method of voltage sag source based on comprehensive criterion has better anti-interference performance.

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