Modeling and Simulation of Voltage Sag Assessment for Distribution Network Based on Total Coverage of Nodes

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Abstract. The evaluation of voltage sag of power grid is to analyze the situation of voltage sag, to guide the planning, construction and transformation of power grid, and further improve the power quality. It is an important content in the current power quality research. In this paper, the fault point is regarded as a new virtual node, and the fault location is described by fault location parameters $\lambda$. The system node impedance matrix is expanded by calculating the self impedance and mutual impedance between the virtual node and the concerned node. Through the modeling and simulation of distribution network, short-circuit faults are set to analyze the voltage sag. According to the three-phase voltage sag waveform recorded by power quality monitoring system (PQMS), the fault type can be identified, and the fault line can be determined according to the PDR of SCADA system. Without considering the fault resistance, the fault type and fault line are known, so the fault location can be found only by solving the fault location parameters $\lambda$. Because of its parallel processing and good robustness, particle swarm optimization algorithm can find the optimal solution of the problem with large probability and fast convergence speed, so this paper chooses to use particle swarm optimization algorithm to solve the fault location parameters $\lambda$.

1. Introduction

High-quality power is related to the interests of power generation, power supply and power consumption. Improving power quality is a necessary condition for the safe, stable and economic operation of power system. It is an important indicator of the level of power grid operation, and also an important standard for the assessment of management level of power enterprises [1, 2]. The evaluation of voltage sag of power grid is to analyze the situation of voltage sag, to guide the planning, construction and transformation of power grid, and further improve the power quality. It is an important content in the current power quality research. The analysis of voltage sag for concerned nodes can assist sensitive users to select suitable grid access points, avoid economic losses caused by voltage sag, and improve the overall economic benefits of industrial enterprises. Research on the possibility of using the increasingly abundant power quality monitoring data for fault location can provide a new scheme and way for the power supply department to quickly and accurately find the fault point and remove the fault point.

There are two main methods of voltage sag assessment. One is based on the measured data, the other is the random prediction evaluation analysis method based on mathematical simulation. The research on fault location is the same at home and abroad. The widely used artificial intelligence algorithms mainly include genetic algorithm, fuzzy theory, particle swarm optimization algorithm,
Empire competition algorithm, etc., but there are some problems in using artificial intelligence algorithm, such as incomplete fault model, complex model establishment and low location efficiency. The particle swarm optimization (PSO) method based on PQMS monitoring data can accurately locate the fault based on big data.

The first step of this paper is to establish the theoretical calculation model of power grid fault based on virtual nodes. The fault point is regarded as a new virtual node \([3]\), and the fault location parameter \(\lambda\) is introduced to calculate the voltage sag amplitude of sensitive node when short-circuit fault occurs. The second step is to determine the frequency of voltage sag and voltage sag area in voltage sag assessment, build IEEE-33 node distribution network model, and calculate the voltage amplitude, phase angle and node impedance matrix of each node in normal operation. The above data are used to solve the fault voltage, voltage sag frequency and voltage sag region of each node. The third step is to design particle swarm optimization algorithm based on PQMS monitoring data to identify complex fault locations. The fault type is identified according to PQMS, and the fault line is determined according to the SCADA system. Therefore, without considering the fault resistance, the fault location parameter is the key to solve the problem of fault location.

2. Theoretical calculation model of power grid fault based on virtual node

2.1. Virtual node impedance definition

As shown in Figure 1, a fault occurs at \(f\), \(Len_{pq}\) is the distance from node \(p\) to node \(q\), \(Len_{pf}\) is the distance from node \(p\) to fault point \(f\), the value of fault location parameter \(\lambda\) is \([0, 1]\). The fault location parameter \(\lambda\) is defined as:

\[
\lambda = \frac{Len_{pf}}{Len_{pq}}
\]  

(1)

![Diagram of transmission line fault](image)

**Figure 1.** Diagram of transmission line fault.

As shown in Figure 2 (a), according to the definition of mutual impedance, formula (2) is obtained. It can be seen that the mutual impedance between node \(f\) and node \(j\) is related to the fault location parameter \(\lambda\), and the mutual impedance between any node \(j\) and the nodes at both ends of the fault line.

\[
Z_{ij} = \frac{U_f}{I_f} = (1-\lambda)Z_{pj} + \lambda Z_{qj}
\]  

(2)

As shown in Figure 2 (b), according to the definition of self-impedance, formula (3) is obtained. It can be seen that the self impedance between fault node \(f\) and any node \(j\) is related to fault location parameter \(\lambda\), self impedance and mutual impedance of nodes at both ends of fault line, and line impedance \([4]\).

\[
Z_{sf} = \frac{U_f}{I_f} = (1-\lambda)^2 Z_{pf} + 2\lambda (1-\lambda)Z_{qd} + \lambda^2 Z_{qd} + \lambda (1-\lambda)Z_{pq}
\]  

(3)
2.2. Mathematical model of system fault voltage calculation

In the n-node system with complex topology, let node j be the access point of sensitive load to be investigated randomly. Any fault at p in the power grid may lead to voltage drop at j of the sensitive load node. The voltage of node p is:

\[ U_p = Z_{p1}I_1 + \ldots + Z_{pq}I_q + \ldots + Z_{pn}I_n \]  

(4)

For a single-phase ground fault, the phase A voltage of the fault node is expressed as:

\[ U_{ja} = (1-\lambda) U_{ja}^n + \lambda U_{ja}^q A \]  

(5)

Two-phase short circuit fault, the three-phase fault voltage of any node j in the sequence network is:

\[ U_{ij} = U_{ij}^n - \frac{Z_{i(1)} Z_{j(2)} - Z_{i(2)} Z_{j(1)}}{Z_{i(1)} + Z_{i(2)}} U_{ja} \]

\[ U_{ij} = \alpha U_{ij}^n - \frac{Z_{i(1)} Z_{j(2)} - Z_{i(2)} Z_{j(1)}}{Z_{i(1)} + Z_{i(2)}} U_{ja} \]

\[ U_{ij} = \alpha^2 U_{ij}^n - \frac{Z_{i(1)} Z_{j(2)} - Z_{i(2)} Z_{j(1)}}{Z_{i(1)} + Z_{i(2)}} U_{ja} \]  

(6)

Two-phase short-circuit grounding fault, the three-phase fault voltage of any node j in the sequence network is:

\[ U_{ij} = U_{ij}^n - \frac{Z_{i(1)} Z_{j(2)} - Z_{i(2)} Z_{j(1)}}{Z_{i(1)} + Z_{i(2)}} U_{ja} \]

\[ U_{ij} = \alpha U_{ij}^n - \frac{Z_{i(1)} Z_{j(2)} - Z_{i(2)} Z_{j(1)}}{Z_{i(1)} + Z_{i(2)}} U_{ja} \]

\[ U_{ij} = \alpha^2 U_{ij}^n - \frac{Z_{i(1)} Z_{j(2)} - Z_{i(2)} Z_{j(1)}}{Z_{i(1)} + Z_{i(2)}} U_{ja} \]  

(7)

A three-phase short circuit is symmetrical short circuit. In the sequence network, the three-phase fault voltage at any node j is:

\[ U_{ij} = U_{ij}^n - \frac{Z_{i(1)} Z_{j(2)} - Z_{i(2)} Z_{j(1)}}{Z_{i(1)} + Z_{i(2)}} U_{ja} \]

\[ U_{ij} = \alpha U_{ij}^n - \frac{Z_{i(1)} Z_{j(2)} - Z_{i(2)} Z_{j(1)}}{Z_{i(1)} + Z_{i(2)}} U_{ja} \]

\[ U_{ij} = \alpha^2 U_{ij}^n - \frac{Z_{i(1)} Z_{j(2)} - Z_{i(2)} Z_{j(1)}}{Z_{i(1)} + Z_{i(2)}} U_{ja} \]  

(8)

3. A method of voltage sag evaluation

3.1. Evaluation of voltage sag frequency

One of the core tasks of voltage sag evaluation is to give the number of voltage sags per year for each PCC node in a certain range of sags [7]. According to the evaluation results, if the voltage sag frequency is greater than the range, the node cannot be used as the access point of the sensitive load.

From the previous analysis, it can be seen that the three-phase voltage of any node can be written as the function of fault location parameter \( \lambda \): \( U_{ja}(\lambda) \), \( U_{jb}(\lambda) \), \( U_{jc}(\lambda) \). Therefore, it is assumed that the user of the sensitive load requires phase voltage amplitude to be in \([U_{\text{low},A}, U_{\text{high},A}]\), \([U_{\text{low},B}, U_{\text{high},B}]\), \([U_{\text{low},C}, U_{\text{low},C}]\). The corresponding fault interval \([\lambda_{\text{low}}, \lambda_{\text{high}}] \), \([\lambda_{\text{low}}, \lambda_{\text{high}}]\), \([\lambda_{\text{low}}, \lambda_{\text{high}}]\) of the corresponding fault location parameter \( \lambda \) can be obtained [6]. The interval corresponding to the fault location parameter \( \lambda \) represents the line location region where the voltage sag phase voltage amplitude is between \([U_{\text{low}}, U_{\text{high}}]\) when the fault occurs.

The annual total number of three-phase voltage sags at any node j is as follows:

\[ N_{j, pq(U_{\text{low}}, U_{\text{high}})} = N_{pq} \left[ \int_{\lambda_{\text{low}, A}}^{\lambda_{\text{high}, A}} \mu(\lambda) d\lambda + \int_{\lambda_{\text{low}, B}}^{\lambda_{\text{high}, B}} \mu(\lambda) d\lambda + \int_{\lambda_{\text{low}, C}}^{\lambda_{\text{high}, C}} \mu(\lambda) d\lambda \right] \]  

(9)

The analysis steps are as follows:

(1) Set the balance node, PQ node, PV node, etc. to calculate the initial power flow of the power grid, and calculate the voltage of each node at normal operation;
(2) According to the topological structure and line parameters of the network, the node impedance matrix is formed; The mutual impedance and self impedance of fault point f and sensitive load access node j are formed according to line parameters and fault location parameters \( \lambda \);

(3) Set the corresponding voltage sag amplitude range \([U_{\text{low}}, U_{\text{high}}]\), and calculate the corresponding fault interval \([\lambda_{\text{low}}, \lambda_{\text{high}}]\);

(4) The fault voltage is calculated, then a year voltage sag frequency of sensitive node caused by p-q line fault is calculated by combining the fault frequency \( N_{pq} \) and fault probability distribution function \( \mu(\lambda) \);

(5) Cycle until all lines are calculated.

3.2. Evaluation of voltage sag region

Voltage sag region is defined as the voltage of sensitive node j drops below the acceptable voltage range when the power grid fails. The voltage drop threshold \( U_{\text{threshold}} \) is used for explanation.

The analysis steps are as follows:

(1) It is the same as the 1 ~ 2 steps of voltage sag frequency evaluation

(2) According to the characteristics of the sensitive node, the appropriate threshold voltage \( U_{\text{threshold}} \) is set. The fault voltage is calculated;

(3) Compare the magnitude between the fault voltage amplitude of each node and the set threshold voltage \( U_{\text{threshold}} \), list the table, and draw the voltage sag region of threshold voltage \( U_{\text{threshold}} \) in the circuit network structure diagram according to the table data;

(4) Cycle until all lines are calculated.

3.3. Evaluation of voltage sag in IEEE-33 bus distribution network

Suppose two-phase short circuit fault occurs on line 2-3, 19-20, 26-27, j=5. The relationship between fault voltage of node j and fault location parameter \( \lambda \) is obtained as shown in Fig. 3.

![Figure 3. Relationship between fault voltage of j and fault location parameter \( \lambda \) under two-phase fault](image)

It can be seen from Figure 3 that the voltage and fault location parameter \( \lambda \) of the sensitive node are not all monotonic functions, so there may be multiple sag intervals in the same line.

3.3.1. Frequency evaluation of voltage sag in IEEE-33 bus distribution network

Set the voltage range in \([0, 0.2], [0.2, 0.4], [0.4, 0.6], [0.6, 0.8]\) and \([0.8, 0.9]\), and calculate the voltage drop frequency of node 5 when two-phase fault occurs in the power grid within the above range by MATLAB programming. Assuming that the probability of two-phase short circuit is 15%, the probability of line fault occurrence is 0.085 times / km / year. The frequency of two-phase short-circuit voltage drop is obtained, as shown in Table 1.

| phase     | \( U_{\text{threshold}} \) |
|-----------|-----------------------------|
|           | \([0--0.2]\)     | \([0.2--0.4]\)     | \([0.4--0.6]\)     | \([0.6--0.8]\)     | \([0.8--0.9]\)     |
| A (times/km) | /   | /   | /   | 2.72   |
| B (times/km) | /   | /   | 0.709444 | 0.7104215 | 1.3000665   |
| C (times/km) | /   | /   | 0.486438 | 0.6890865 | 1.544416   |
| Totalt times (times/km) | 0 | 0 | 1.195882 | 1.399508 | 2.8444825 |
It can be seen from the above table that the voltage sag of two-phase short circuit is mainly concentrated between [0.4, 0.9], and there is almost no voltage sag between [0, 0.4]. In the same way, the voltage sag frequency range of other faults can be deduced.

3.3.2. Evaluation of voltage sag region in IEEE-33 bus distribution network

According to the definition of sag region and the calculated data, the voltage sag region of node 5 with threshold voltage $U_{\text{threshold}} = 0.75\text{pu}$ can be drawn, as shown in Fig. 4. It can be seen that when bus nodes 1, 2, 3, 4, 5, 6, 7, 8, 19, 23, 26, 27, 28 have two-phase short circuit, the B-phase voltage of node 5 will drop below 0.75pu. In addition to the above nodes, the B-phase voltage of node 5 will drop below 0.75pu when two-phase grounding faults occur at nodes 9, 24 and 29. The voltage sag region of two-phase short-circuit grounding fault is larger than that of two-phase short-circuit fault [5].

![Figure 4. Sag Voltage of Node 5 in Two-Phase Short-Circuit and Two-Phase Short-Circuit Grounding Faults.](image)

![Figure 5. Fault location identification based on particle swarm optimization.](image)

**Figure 4.** Sag Voltage of Node 5 in Two-Phase Short-Circuit and Two-Phase Short-Circuit Grounding Faults.

**Figure 5.** Fault location identification based on particle swarm optimization

4. Fault location method based on PQMS monitoring data

The constraint conditions and objective function of fault location identification based on particle swarm optimization algorithm are as follows:

$$0 \leq \lambda \leq 1$$

$$U(\lambda) = [\hat{U}_{m1}(\lambda), \hat{U}_{m2}(\lambda), \hat{U}_{m3}(\lambda), ..., \hat{U}_{mq}(\lambda), \hat{U}_{m1}(\lambda), \hat{U}_{m2}(\lambda)] - U_d$$

(10)

Where $q$ is the number of monitoring points; $U_i$ is the measured value of monitoring point $i$; $U_d$ is the measured value of sensitive monitoring point.

The calculation formula of inertia weight is as follows:

$$\omega = \omega_{\text{max}} \times \left( \frac{\omega_{\text{max}} - \omega_{\text{min}}}{i/T} \right)$$

(11)

In the above formula, $i$ is the $i$-th iteration; $T$ is the total number of iterations; the maximum inertia weight is set to 0.9, and the minimum inertia weight is set to 0.4 [8].
\[ v_{\lambda,i}^{k+1} = \omega v_{\lambda,i}^{k} + c_1 r_1 (J_i^{\lambda} - \lambda_i^{k}) + c_2 r_2 (J_i^{\lambda} - \lambda_i^{k}) \]
\[ \lambda_i^{k+1} = \lambda_i^{k} + r v_{\lambda,i}^{k+1} \] (12)

Set the number of particle swarm \( N = 100 \); particle dimension \( D = 2 \); the maximum number of iterations \( T = 100 \). It is known that two-phase short-circuit fault occurs on line 23-24, and the B-phase fault voltage of node 5 is 0.55pu. According to particle swarm optimization algorithm, the fault location parameter \( \lambda \) is obtained and marked, as shown in Fig. 5 (a). When the same method is applied to the other three kinds of faults, the corresponding fault location parameter \( \lambda \) can also be obtained.

It can be seen from Fig. 5 (b) that the minimum value of the objective function has been found after the 7th iteration, that is, the fault location \( \lambda = 0.3985 \) is found. At the same time, when two-phase fault is set at \( \lambda = 0.3985 \) of line 23-24, the fault drop voltage of node 5 is 0.55pu, which verifies the accuracy.

5. Conclusion

The analysis of voltage sag for specific nodes can assist sensitive users to select suitable grid access points, avoid economic losses caused by voltage sag, and improve the overall economic benefits of industrial enterprises. The main contents and conclusions of this paper are as follows:

1. A voltage sag evaluation method based on virtual node is used to calculate the function of fault location parameters \( \lambda \). According to the fault boundary conditions, the fault voltage of any node in the power grid is calculated by using the symmetrical partition method. The voltage sag amplitude obtained is a function of fault location parameters \( \lambda \).

2. The IEEE-33 bus distribution network system is modeled by Simulink, and the programming data is listed statistically. Set the threshold voltage, draw the voltage sag area of the node concerned according to the data, and calculate the voltage sag frequency.

3. Without considering the fault resistance, the fault type is determined by PQMS, the fault line route is determined by PDR, and the fault location parameters are obtained by particle swarm optimization algorithm, that is, the location of the fault line.

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