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Evaluation Method of Voltage Sag Severity in Distribution Networks

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Abstract: Recently voltage sags have gradually become one of the most important power quality problems with the large scale use of sensitive electrical equipment. Analysis of varied attributes causing voltage sags can not only guide the planning, equipment selection, operation and maintenance of power supply engineering, but also can provide a theoretical basis for effectively assessing the risks and severity of the power quality incidents. It is meaningful to combine the existing problems of technology and management level to get the assessment results of the voltage sags. In this paper, clustering analysis and evaluation method are proposed for multi-cause attributes that affect voltage sags. The calculation method of the voltage on the multiple fault location parameters in the power grid is derived. The evaluation method of the voltage sags considering the user's tolerance level is given. The characteristic properties of causes are used as parameters to describe disturbances which provide a basis for voltage sag evaluation. Then the equipment compatibility index is introduced, the analytic hierarchy process is used to determine the weight of the voltage sag evaluation index, and the severity of the voltage sag of each node of the distribution network is calculated to realize the distribution network voltage sag severity assessment. Finally, the voltage sag under multi causal attributes is analyzed using the equipment compatibility index as the standard, and the sag severity of the equipment is analyzed. The multi-factor attributes contribution degree proposed in this paper takes the equipment compatibility as the index, and can accurately reflect the impact of various attributes on equipment after voltage sags.

Keywords: Voltage Sags, Evaluation, Analytic Hierarchy Process, Equipment Compatibility Index

1. Introduction

In recent years, with the large-scale application of voltage sensitive electrical equipment such as variable frequency speed control equipment, various automatic production lines and computer systems in industrial production, the problem of voltage sags has attracted more and more attention [1]. Voltage sags have become one of the most important power quality problems affecting the normal operation of electrical equipment, and will lead to huge economic losses [2-4].

At present, a number of the researchers have focused on the voltage sag assessment method [5-11]. The analysis and management methods of the voltage sags at the Point of Common Coupling (PCC) are studied, but it is difficult to support the demand for the utilization of distribution network equipment, the economics of investment and the overall optimal management. Therefore, it is necessary to study the evaluation method of the weak point of the distribution network easy to emerge the voltage sag. The effective analysis basis for the global optimization management of the voltage sag of the distribution network is provided. From another point of view, it is necessary to provide a reference for enterprises with sensitive loads to investigate the quality of power supply and reduce the local investment. The evaluation of the weak point of the voltage sag of the distribution network involves three contents: (1) The multi-factor of the voltage sag clustering analysis; (2) Voltage calculation of the distribution network node under the condition of full operating conditions; (3) Study on the evaluation of the weak point of the distribution network voltage sag from point of the user's tolerance level. Multi-factor refers to a variety of causes to result in the voltage sag in the power system, such as single or multiple short-circuit faults, induction motor start-up, lightning strikes, switching operations of the transformers and capacitor banks. These causes also possess different characteristic properties, such as short-circuit fault characteristic properties, short-circuit fault location, fault point ground impedance, fault duration, etc. These properties affect the evaluation results after considering the tolerance level of node users to varying degrees, so it is the key factors that must be considered in the evaluation of weak points. In this paper, the clustering method is introduced to comb the numerous voltage sag causes in the distribution network into a category with clear characteristic properties. At the same time, the characteristic properties of causes are used as parameters to describe disturbances which provide a basis for subsequent sag evaluation.

In the research on the assessment of the voltage sag severity in the distribution network considering the user tolerance level, some scholars and researchers have proposed and recommended evaluation method of the voltage sag severity considering the compatibility of the voltage sag characteristics and the equipment withstand capability [5-8]. In addition, there are also the severity indicators expressed in MSI and DSI, fuzzy indicators [9, 10], and the system average outage time index ASIDI proposed in literature [11] that can be used to characterize the voltage sag after appropriate modification. Zhang Bingjiang proposes two degrees of compatibility: one is the standard compatibility, which refers to the voltage sag event and the standard tolerance curve provided by the industry (such as ITIC curve, SEMI curve, etc.) or the deviation degree of agreement curve signed between user and power supply department; the other is the device compatibility, which refers to the degree of deviation between the voltage sag event and the actual tolerance range of the sensitive device [12]. Yan Lin proposes voltage sag severity analysis based on improved FP-Growth algorithm and AHP algorithm [13]. Standard compatibility can be used to measure the quality of power supply in the power supply department, and equipment compatibility can better reflect the actual situation of equipment affected by voltage sags. These studies are all focused on the analysis and evaluation of specific PCC points, and cannot reflect the global distribution and weak points of sags in the distribution network. Then it is difficult to effectively support the planning and design requirements of the global optimal control of voltage sags.

At present, the calculation and analysis methods of voltage sag mainly include real-time monitoring method and random estimation method. Real-time monitoring has the advantages of convenient, intuitive and reliable data sources, but in order to obtain accurate voltage staging analysis of complex networks extensive and long-term monitoring is often required, and the high equipment costs limit the scope of application of this method [14-17]. The method of random estimation mainly includes the method of critical distance, the method of point of failure and the analytics method. The critical distance method is based on a simple divider model to calculate the critical distance of the fault point when the voltage of a bus node is equal to the set voltage sag threshold at the time of the system failure. The principle of this algorithm is simple and clear, but it is only suitable for voltage sag analysis in the event of symmetrical failure of the simple radiant network. The point-of-failure method [18-24] is based on operating experience in the system to select a certain number of possible points of failure, and set various faults at these possible fault points in turn, and directly the voltage amplitude of each node is obtained through short-circuit calculation or simulation methods. This method can be applied to various network topologies, and the influence of various fault types and fault distribution characteristics can be taken into account. However, due to the need for a large number of simulation calculations of system failures, in order to improve the accuracy of analysis, the number of points of failure needs to be increased, and the location and number of points of failure are based on operational experience and lack of clear theoretical guidance. The analytics method obtains the analysis results by calculating the fault residual pressure of the node, which has the characteristics of high precision and mature theory, but the influence of fault resistance is ignored [25, 26]. The above voltage sag analysis methods assume that only a single point of failure occurs in the power grid, and Wang Dongxu proposes the analysis method of voltage sag when the system has multiple points of failure at the same time, while the study of voltage sag under the influence of complex multi-factor is rarely involved [27]. The voltage sag analysis method under multiple fault conditions is proposed [27]. Under the condition that the system has multiple sources (including faulty and non-faulty causes), all disturbance points are regarded as newly added virtual nodes, and use the characteristic attribute of the cause as a parameter to describe the disturbance. The node impedance matrix is expanded by deriving the self-impedance of the virtual node, the mutual impedance between the virtual node and the non-faulty node, and the virtual node, and the fault system is described by the extended node impedance equation. Combining the boundary conditions of each disturbance point, the phasor of each fault current is calculated, and then the disturbance voltage phasor of any node is derived, which provides analysis conditions for the evaluation of the weak point of the voltage sag of the distribution network considering the user's tolerance level.

Starting from the characteristic attribute analysis of voltage sag, we constructs a typical disturbance source model of voltage sag, and the global node voltage calculation results of the distribution network through the analytical method of preset disturbance nodes is obtained. Then the equipment compatibility index is introduced, the analytic hierarchy process is used to determine the weight of the voltage sag evaluation index, and the severity of the sag of each node of the distribution network under the condition of multi-factor is calculated to realize the voltage sag assessment.

2. Voltage Sag Analysis

2.1. Multi-cause and the Characteristic Properties

When short-circuit faults, induction motor starting, lightning strikes, switching operations, switching of transformers and capacitor banks occur in the power transmission and distribution system, voltage sags can all be appearing. Recorded field data and research show that short-circuit faults, induction motor starting and lightning strikes are the main causes of voltage sags [4]. Therefore, we mainly consider the analysis of the short circuit fault and the non-faulty cause by the induction motor starting and lightning strike.

Short-circuit faults are one of the main causes of voltage sags in the power system. Transmission lines and distribution feeders are mostly exposed to the natural environment. Therefore, weather factors such as strong wind, rain or snow overlapping lines and engineering transportation activities, etc. will also cause line short-circuit faults. Since the protection device of the system cannot remove the fault without delay, the propagation of the short-circuit current in the system will inevitably cause the voltage sag of the adjacent lines. When such a voltage sag occurs at a certain point in the system, its sag amplitude mainly depends on the type of short-circuit, the location of the fault point, the wiring method of the transformer and the short-circuit impedance. The fault may be symmetrical (three-phase short-circuit) or asymmetrical (single-phase ground fault or two-phase short-circuit or two-phase short-circuit to ground). Therefore, the voltage sag amplitude of each phase may be same (symmetrical fault) or different (asymmetrical fault). A short-circuit fault may cause a severe sag in the remote power supply voltage of the system, affecting the normal operation of voltage-sensitive electrical equipment in the industrial production process.

After the lightning strikes on the transmission line, if the lightning current exceeds the lightning withstand level of the line, the line insulation will have an impact flashover, and the lightning current will enter the ground along the flashover channel. Since the time is only tens of microseconds, it is not enough to operate the line switches. The short circuit current continues to flow through the flashover channel and establish a stable arc for continuous combustion, forming a grounding fault, and the line will trip. After the grounding fault is caused by the insulator flashover, the short-circuit current will cause the voltage sag to spread in the system, and the node voltage will fall again after rising and fluctuating. Insulator flashover or ground discharge caused by the lightning strike will make the protection device act, resulting in power supply voltage sag. This sag has a wide influence range and generally lasts for more than 100ms.

Induction motors are widely used in industrial and agricultural production and daily work. In the total load of the power grid, the electricity consumption of induction motors accounts for more than 60%, which is an important load in the power grid. When the motor starts at full voltage, the large current value needs to be drawn from the power supply. When this large current flows through the system impedance, it will cause the voltage sag suddenly. The duration of this sag is longer, but the degree of sag is smaller.

2.2. Multi-cause Clustering Analysis

Clustering is an important research method in data mining, which distinguishes and classifies things with similar properties or trends. Clustering is based on the similar characteristics between things. If you cluster them into one category, so the similarities within them are relatively obvious. Cluster analysis in the traditional sense usually starts from limited feature attributes and strictly delimits objects into a certain class.

The characteristic attributes of short circuit fault include three-phase, two-phase or single phase to ground short circuit; short circuit fault location; grounding impedance at fault point; fault duration. The characteristic properties of induction motor starting are also divided into three-phase, phase to phase and single-phase power supply; access node; equivalent impedance and start-up time. Flashover caused by the lightning stroke is similar to the fault, and the characteristic attributes are treated as short circuit.

3. Voltage Calculation of the Distribution Network

Wang Dongxu proposes a voltage sag analysis method under multiple fault conditions [27]. When the system has multi-cause, all disturbance points are regarded as newly added virtual nodes, and the characteristic attributes of the cause are used as parameters to describe the disturbance. Combined with the boundary conditions of each disturbance point to calculate each fault current phasor, and then deduce the disturbance voltage phasor of any node. In an n-node complex power grid, k is the number of simultaneous faults, f_i (i=1,...,k) is the fault point. When multiple faults occur, all fault points are regarded as newly-added virtual nodes, and the node impedance matrix is extended to obtain the fault voltage of each node [27]:

$$\begin{bmatrix} \dot{U}_1 \\ \dot{U}_2 \\ \vdots \\ \dot{U}_n \\ \dot{U}_{f_1} \\ \vdots \\ \dot{U}_{f_k} \end{bmatrix} = \begin{bmatrix} \dot{U}_1^{(0)} \\ \dot{U}_2^{(0)} \\ \vdots \\ \dot{U}_n^{(0)} \\ \dot{U}_{f1}^{(0)} \\ \vdots \\ \dot{U}_{f_k}^{(0)} \end{bmatrix} - \begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1n} & Z_{1f_1} & \cdots & Z_{1f_k} \\ Z_{21} & Z_{22} & \cdots & Z_{2n} & Z_{2f_1} & \cdots & Z_{2f_k} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ Z_{n1} & Z_{n2} & \dots & Z_{nn} & Z_{nf_1} & \cdots & Z_{nf_k} \\ Z_{f_1 1} & Z_{f_1 2} & \dots & Z_{f_1 n} & Z_{f_1 f_1} & \cdots & Z_{f_1 f_k} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ Z_{f_k 1} & Z_{f_k 2} & \dots & Z_{f_k n} & Z_{f_k f_1} & \cdots & Z_{f_k f_k} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ \dot{I}_{f_1} \\ \vdots \\ \dot{I}_{f_k} \end{bmatrix} \quad (1)$$

where: $\dot{U}_j^{(0)}$ is the voltage phasor of normal system operation before the effect of voltage sag, $\dot{U}_j$ is the voltage phasor when node j under the influence of voltage sag, $\dot{I}_{f_i}$ is the fault current phasor at fault point f_i. Compared with the original system node impedance matrix, due to the increase of virtual nodes, the node impedance matrix increases k rows and k columns. The corresponding newly added elements in the impedance matrix can be calculated by using the known system element parameters and the introduced multiple fault location parameters. Z_{jfi} is the mutual impedance between system node j and virtual node fi and Z_{fifi} is the self impedance of the virtual node fi. Taking the multi-source cause characteristic attribute as the calculation boundary condition, the fault current phasor of the fault point is obtained, and then the fault voltage phasor of any node is obtained.

When the system has multiple attributes at the same time under the influence of voltage sag, the fault voltage of any node j is [27].

$$\dot{U}_j = \dot{U}_j^{(0)} - Z_{jf_1}\dot{I}_{f_1} - Z_{jf_2}\dot{I}_{f_2} - \ldots - Z_{jf_k}\dot{I}_{f_k} \quad (2)$$

The calculated results of the node voltage can be used for further voltage sag evaluation.

4. Voltage Sag Multi-cause Attribution Analysis

With the construction of smart grid, the rapid development of system capacity, scale, voltage level, etc., the complexity and diversity of the system, the enhancement of user production efficiency and equipment sensitivity, the factors that affect voltage sags are gradually becoming more complicated. They mainly include: system fault type, system grid structure, load anti-interference ability, fault location, etc. The various factors that affect voltage sags are divided into two categories: external attributes and internal attributes in this paper.

The external attributes are the main factors affecting sag, which can be divided into four types: system fault type, location of fault point, relay protection configuration, and grid structure.

1) The types of system faults mainly include: single-phase grounding, two-phase grounding, three-phase grounding, and two-phase interphase faults.
2) The location of the fault point can be divided into: power supply, power grid of the same level, and the load equipment.
3) The relay protection configuration is divided into: automatic reclosing, automatic switching device and PLC, frequency converter, contactor.
4) The grid structure can be divided into the radial network structure, the ring network structure, and the grid structure.

The internal attributes are determined by the characteristics of the load equipment, which can be divided into two categories: load anti-interference ability and load equipment operating status.

1) Through load anti-interference ability, it is divided into sensitive load and general load.
2) The operating status of load equipment is divided into: high-load operation, normal operation, and low-load operation.

For the calculation of the indicator of a single event, IEEE P1564 Draft 1 provides the indicator to describe the sag event. It can be the amplitude and duration of the sag or the loss of voltage (LV), loss of energy (LE). Although a single indicator is simple and direct, it cannot reflect the sensitivity of the device to sag.

According to the actual situation of the equipment of a single event, we consider the amplitude and duration of the sag event together, and use the device compatibility as the evaluation index of the voltage sag of the multi-factor attributes. Before calculating this index, it is necessary to define the sensitivity curve of the device. Typical sensitivity curves include CBEMA, ITIC and SEMI curves.

Consider three aspects to construct a compatibility model: the farther the voltage sag event deviates from the tolerance curve, the smaller the compatibility; when the sag voltage value is on the tolerance curve, the compatibility is 1; For voltage sag events equidistant from the tolerance curve boundary, the compatibility shall be smaller in the area with low tolerance value. The calculation method of compatibility is shown in equation (3):

$$D_C = \frac{1 - U_{curve}(t)}{U_{curve}(t) - U} \quad (3)$$

where: U is the voltage sag amplitude per unit value; $U_{curve}(t)$ is the unit value of voltage amplitude on the withstand curve when the sag duration is time t; D_C is the equipment compatibility.

The contribution degree proposed in this paper refers to the ratio of the number of voltage sags to the total number of failures under one or more attributes after the system has sags. On this basis, the device compatibility is used as the index to calculate the severity of the sag under this attribute. We define a multi-factor attributes contribution degree λ_i, as shown in equation (4).

$$\lambda_i = \frac{n_i}{N} \Big/ \frac{\sum D_{ci}}{n_i} \quad (4)$$

where: n_i is the number of voltage sags caused by the ith cause attribute; N is the total number of voltage sag faults; $\sum D_{ci}$ is the sum of compatibility of n failures of the equipment.

5. Contribution Degree Evaluation Method

5.1. Construction of Multi-cause Attributes Weight System

At present, there are many weight calculation methods, of which the most extensive application field of analytic hierarchy process (AHP), the main idea of AHP is to make a comparative judgment on the importance between the two indicators by breaking down complex problems into several levels and several factors, to establish a judgment matrix, and to calculate and judge the maximum characteristic value of the matrix and the corresponding feature vector. Then we can obtain the weight of different scheme importance, and provide the basis for the selection of the best scheme [13].

Based on the multi-factor attributes of voltage sag, the principle of AHP is used to analyze its hierarchical and hierarchical levels, O layer ={multi-factor attributes that cause voltage sag}; A layer ={external attributes, internal attributes}; B layer ={fault type, fault point location, relay protection configuration, grid structure, load anti-interference ability, equipment operating status}, and P layer containing each single factor attribute. For each attribute of layer A, layer B, and layer P, the faulty device has a corresponding fault severity index: compatibility, and the greater the compatibility of the device, the greater the impact of the causal attribute on the voltage sag of the device, that is, this causal attribute has a high "contribution" to the system voltage sag.

5.2. Multi-cause Weight Calculation

For any layer attribute $T=[T_1, T_2,..., T_i,..., T_j,...]$, use the scale of 1 ~ 9 to compare the importance of any two specific attributes T_i and T_j to the upper layer attribute, that is, between 1 ~ 9 and its reciprocal, and its meaning is shown in Table 1.

Table 1. *The scale of analytic hierarchy process.*

F_{ij} Value	Meaning
1	T_i and T_j are equally important
3	T_i is slightly more important than T_j
5	T_i is significantly more important than T_j
7	T_i is more important than T_j
9	T_i is more important than T_j
2, 4, 6, 8	The median between the two adjacent judgments above
Reciprocal	$F_{ji}$is $1/F_{ij,}$ which indicates how important property T_j is to T_i

Based on Table 1, the discriminant matrix F can be constructed. In this paper, the calculation of value F_{ij} takes the lead in classifying the importance of the B layer attributes, and then further considering the P layer attributes, and comprehensively obtaining the discriminant matrix F, and using the geometric average method to calculate the weight. Then solve the eigenvalue of the judgment matrix, use its maximum eigenvalue λ_{max} for consistency check, and calculate the consistency ratio CR=CI/RI, where $CI=(\lambda_{max}-n)/(n-1)$ and $RI=\sum CI_i/n$ (i=1,…,n). If CR<0.1, it meets the requirements of the AHP for the judgment matrix; otherwise, it needs to be modified.

Suppose the weight of P layer causal attribute obtained by AHP is Q, $Q=[q_1,q_2,...,q_n]$, and $P=[p_1,p_2,...,p_n]^T$, introduce the weight of each attribute, equation (4) is amended. It can be concluded that the calculation method of the contribution degree of the *i* attribute of the P layer is:

$$\lambda_i = \frac{q_i p_i}{\sum_{i=1}^{n} q_i p_i} \times 100\% \tag{5}$$

In this way, the contribution degree of the multi-cause attributes that affect the voltage sag in a certain area can be intuitively sorted. Then the improvement of various areas is promoted and the overall voltage sag protection measures are improved. In practical applications, based on the characteristic parameters after the voltage sag occurs, the contribution degree ranking of multi-cause attributes can be obtained, so that effective management and preventive measures can be taken. It can provide a theoretical basis for effectively evaluating the severity of power quality events encountered by users and combing the existing problems at the technical and management levels.

The multi-factor attributes contribution degree proposed in this paper and the equipment compatibility as the index is derived. We comprehensively considers the probability and weight of different attributes after voltage sag, and the evaluation results can accurately reflect the impact of various attributes on equipment after voltage sag compared with only calculating the compatibility index.

6. Conclusion

In this paper, the cluster analysis method is used to uniformly cluster the multi-cause attributes of voltage sag, such as circuit fault, induction motor start-up and lightning impact, to the short-circuit fault analysis. We further construct the typical disturbance source model of voltage sag, and obtain the global node voltage calculation results of distribution grid through the analytical method of preset disturbance nodes. Finally, the equipment compatibility index is introduced, the weight of the new voltage sag evaluation index is determined by the analytic hierarchy process, and the sag severity of each node of the distribution network under the condition of multi-factor is calculated to realize the evaluation of voltage sag severity of the distribution network. By calculating the contribution degree of various cause attributes of voltage sag, we can find out the multi-factor attributes and weak links that are relatively sensitive to voltage sag in the system, so as to take targeted precautions. The feasibility of the proposed evaluation method can be verified by simulation. The evaluation value of the voltage sag of transmission and distribution network can be obtained based on the method in the paper. The analysis result may have significance to choose the proper scheme to improve the power quality through assessing the risks and severity of the power quality incidents and to analyze the existing problems at the technical and management levels.

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