Comprehensive Evaluation of Two-side Voltage Sag based on Local State Variable Weight and Complex Correlation Coefficient Method

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Abstract. The severity assessment of voltage sag is one of the important bases to measure power quality. At present, voltage sag assessment is mostly based on system or load, lacking of unity on both sides. The evaluation indexes of the voltage sag on the side of the system are divided into the first level and the second level. The load-side evaluation adopts the equipment failure rate based on the comprehensive tolerance curve of sensitive equipment, and the failure probability model is based on the energy function. The complex correlation coefficient method is used to synthesize the indexes of system side and load side to avoid the excessive evaluation caused by the repetition of information in the evaluation. At last, an example analysis is carried out on the proposed method based on the measured data, which verifies the correctness and superiority of the method.

1. Introduction
With more and more sensitive loads connected to the power grid, voltage sag has become the most important problem of power quality in recent years\([1]\). Compared with the traditional load only affected by power failure, these new loads are easily affected by voltage sag and the sensitive equipment will be in abnormal operation state or even out of service, which will cause huge economic losses\([2,3]\). Therefore, it is of great theoretical value and practical significance to conduct comprehensive evaluation on both the system side and the load side, and establish a complete evaluation system.

Different reasons may cause different types of sags, among which the majority of sags in the power grid are caused by short-circuit faults\([4]\). Literature \([5]\) studied the time and amplitude variation of voltage sag under different protection types in short circuit fault. Literature \([6]\) introduced the method of multi-threshold analysis to evaluate the sag event with non-rectangular wave. Literature \([7]\) established the voltage sag influence function of the comprehensive load based on the comprehensive tolerance curve of sensitive equipment. Literature \([8]\) indicates that it is more practical to evaluate the sensitivity with the severity index of voltage sag. The maximum entropy principle was introduced in literature \([9]\). By solving the maximum entropy model, the probability density function of the severity index of voltage sag was obtained to evaluate the severity degree of load affected by the sag. Starting from the energy index, literature \([10]\) evaluated the system side and the load side respectively, and
then multiplied the two to obtain the severity of voltage sag. In literature [11], the improved AHP analysis method was used to evaluate the voltage sag on the system side, and the entropy weight method was used on calculating the comprehensive degree of voltage sag.

Aiming at the defect and low accuracy of the above assessment methods, this paper firstly uses the local state variable weight method to classify and evaluate the voltage sag on system side, among which the non-rectangular wave sag is analyzed by the multi-threshold method. Secondly, the Voltage Tolerance Curve (VTC) of the load side is used to calculate the failure rate of the sensitive equipment. After obtained the results of both sides, the multiple correlation coefficient method is used to synthesize the comprehensive degree of voltage sag, so as to avoid the excessive evaluation caused by the redundant information. Finally, based on the measured data in literature [12], this paper carries out the example calculation to prove the high accuracy and superiority of the method proposed.

2. System voltage sag analysis using the local state variable weight method

2.1. Local state variable weight

Local state variable weight method is a kind of objective weighting method which can effectively distinguish the different index intervals of evaluation targets. The basic principle is as follows:

Given the index set \( U=\{A_1, A_2, \ldots, A_m\} \), the normal weight distribution of each indicator is \( W=\{w_1^{(0)}, w_2^{(0)}, \ldots, w_m^{(0)}\} \). The value of each index of the assessed object is:

\[
X=(x_1, x_2, \ldots, x_m), \quad x_i \in [0, 1]
\]

Specifically, the variable weight vector of fixed local state is set as follows:

\[
S(X) = (S_1(X), S_2(X), \ldots, S_m(X))
\]

Thus, the local variable weight vector can be obtained:

\[
W(X) = \frac{W_0 \cdot S(X)}{\sum_{j=1}^m w_j^{(0)} S_j(X)} = \left[ \frac{w_1^{(0)} S_1(X)}{\sum_{j=1}^m w_j^{(0)} S_j(X)}, \frac{w_2^{(0)} S_2(X)}{\sum_{j=1}^m w_j^{(0)} S_j(X)}, \ldots, \frac{w_m^{(0)} S_m(X)}{\sum_{j=1}^m w_j^{(0)} S_j(X)} \right]
\]

Therefore, the comprehensive weight is:

\[
V(X) = \sum_{i=1}^m w_i(X) \cdot x_i = \sum_{i=1}^m \frac{w_i^{(0)} S_i(X)}{\sum_{j=1}^m w_j^{(0)} S_j(X)} \cdot x_i
\]

2.2. System voltage sag analysis using the local state variable weight method

In the assessment of voltage sags, the amplitude index and the duration index of the sag show a trend of slow change at both ends and sharp change in the middle. When the voltage sag is relatively light, the severity index in this range should be stimulated; while when the voltage sag is more serious, the severity index in this range should be punished. As shown in figure 1 and figure 2:

![Figure 1](changing_curve_magnitude.png)  ![Figure 2](changing_curve_duration.png)
Using the proposed method, the assessment index on system side is firstly divided into first-level index and second-level index according to the reasons causing the sag events. Here, this paper uses DSI (Duration Severity Index) and MSI (Magnitude Severity Index) for the secondary index of voltage sag, which is described as follows:

\[
DSI(T) = \begin{cases} 
0 & , \ T < T_{\text{min}} \\
(T - T_{\text{min}}) \times \left( \frac{100}{T_{\text{max}} - T_{\text{min}}} \right) , \ T_{\text{min}} \leq T \leq T_{\text{max}} \\
100 & , \ T > T_{\text{max}}
\end{cases}
\]  

\[
MSI(U) = \begin{cases} 
0 & , \ U > U_{\text{max}} \\
(U_{\text{max}} - U) \times \left( \frac{100}{U_{\text{max}} - U_{\text{min}}} \right) , \ U_{\text{min}} \leq U \leq U_{\text{max}} \\
100 & , \ U < U_{\text{min}}
\end{cases}
\]  

Where \( U_{\text{max}} \) and \( U_{\text{min}} \) are respectively the maximum and minimum magnitude values defined in the voltage sag study, and \( T_{\text{max}} \) and \( T_{\text{min}} \) are the maximum and minimum values of duration. The values of MSI and DSI range from 0 to 100, and the bigger the DSI and MSI are, the more serious the sag events tend to be.

Moreover, the multi-threshold analysis method is introduced to describe the voltage sag with non-rectangular waves, which transform the DSI as a series of durations \( T(0.9), T(0.9-h), T(0.9-2h), \ldots, T(0.1) \). Thus, the comprehensive severity index of multi-threshold voltage sag is obtained:

\[
MMDSI = \max\{MDSI(0.9, T(0.9)), MDSI(0.9 - h, T(0.9 - h)), MDSI(0.9 - 2h, T(0.9 - 2h)), \ldots, MDSI(0.1, T(0.1))\}
\]  

3. Load side sag assessment based on energy index

Voltage sag may cause abnormal operation state or even out of service for sensitive equipment on the load side, which is manifested with the failure rate of sensitive equipment. In this paper, the voltage sag assessment on load side is mainly based on the voltage tolerance curve of sensitive equipment. In practice, there are uncertain areas in the VTC curve, as shown in figure 3.

![Figure 3: Uncertainty region of voltage tolerance curve](image)

The comprehensive tolerance curve of sensitive equipment proposed by SEMI curve, ITIC curve and C4.110 working group was used to divide the middle uncertain area between curve 1 and curve 2 into three blocks A/B/C for probability analysis. The failure rate of region A is a one-dimensional function of the duration time \( T \), and is proportional to \( T \). The failure rate of region B is a one-dimensional function of \( U \), and is inversely proportional to \( U \). The failure rate of region C is a two-dimensional function of \( U \) and \( T \). Therefore, the failure probability model of region A/B/C can be obtained:
\[ p_A = \frac{T - T_{\min}}{T_{\max} - T_{\min}}, (U, T) \in A \]  
\[ p_B = \frac{U^2_{\max} - U^2_{\min}}{U^2_{\max} - U^2_{\min}}, (U, T) \in B \]  
\[ p_C = p_A p_B = \frac{T - T_{\min}}{T_{\max} - T_{\min}} \times \frac{U^2_{\max} - U^2_{\min}}{U^2_{\max} - U^2_{\min}}, (U, T) \in C \]  

Thus, the sag severity on load side, namely the equipment failure rate, can be obtained:

\[ E_2 = \sum p_i \alpha_i \]  

Where \( \alpha_i \) is the proportion of sensitive equipment \( i \) in the load side.

4. Comprehensive evaluation based on complex correlation coefficient method

In this paper, the complex correlation coefficient method is used to synthesize the weight of the voltage sag index on the system side and the load side.

The basic principle of the complex correlation coefficient method is: the more repeated information a certain index has with others, the smaller the role it plays in the evaluation. The complex correlation coefficient of the index is used to measure the amount of repeated information with other indexes. The specific implementation steps applied in the comprehensive assessment of voltage sag are as follows:

1) Build the correlation coefficient matrix \( R \) of each evaluation index by using the obtained evaluation results of system side and load side. Suppose the number of evaluation indicators is \( m \), then the correlation coefficient matrix is:

\[
R = \begin{bmatrix}
r_{11} & r_{12} & \cdots & r_{1m} \\
r_{21} & r_{22} & \cdots & r_{2m} \\
\vdots & \vdots & \ddots & \vdots \\
r_{m1} & r_{m2} & \cdots & r_{mm}
\end{bmatrix}
\]

2) Calculate complex correlation coefficient. Taking the complex correlation coefficients of the \( m \)-th index \( E_m \) and other \( m-1 \) indexes as an example, the matrix \( R \) is transformed as follows:

\[
R = \begin{bmatrix}
R_{m-1} & r_{m} \\
r'_{m} & 1
\end{bmatrix}
\]

Where, \( R_{m-1} \) is the correlation coefficient matrix of other \( m-1 \) indexes, and \( R_m \) is an \( m-1 \) order column vector. The complex correlation coefficient of index \( E_m \) to other indexes can be obtained as follows:

\[
\rho_m = r'_m \sum_{i=1}^{m-1} \frac{1}{\rho_i}
\]

3) According to the calculated complex correlation coefficient, take the inverse and normalization to get the index weight:

\[
\omega_j = \frac{1}{\rho_j} \left( \sum_{j=1}^{m} \frac{1}{\rho_j} \right)^{-1}
\]

5. Analysis of examples

5.1. Introduction of examples

The power quality monitoring system of a power network in four large cities in China has detected a total of 155 voltage sag events in 10kv distribution network in five years, which are classified
according to the causes of the voltage sag. The average magnitude and duration of each type of voltage sag are taken to obtain the voltage sag situation as shown in Table 1.

### Table 1. Voltage sag event statistics

| Voltage sag reasons | frequency | percentage(%) | magnitude(pu) | duration(s) |
|---------------------|-----------|---------------|---------------|-------------|
| SLGF                | 81        | 52.26         | 0.85          | 0.025       |
| LLF+DLGF            | 44        | 28.39         | 0.4           | 0.09        |
| TPF                 | 17        | 10.97         | 0.85          | 0.12        |
| T/M Start           | 13        | 8.38          | 0.75          | 0.35        |

#### 5.2. Comprehensive calculation of the voltage sag severity

The local state variable weight method is used to evaluate the degree of voltage sag on the system side. From the perspective of feasibility, the following mode is the best:

$$S_j (X) = \begin{cases} 
1, & x_j \in [0, T] \\
\frac{C-1}{U-T} x_j + \left(1 - \frac{C-1}{U-T} \right) T, & x_j \in (T, U] \\
C, & x_j \in (U, V] \\
\frac{1-C}{1-V} x_j + \left(1 - \frac{1-C}{1-V} \right) V, & x_j \in (V, 1]
\end{cases} \quad (16)$$

Where $T, U, V, C$ are the parameters in $[0,1]$, and $T$ is the negative level, $U$ is the passing level, $V$ is the incentive level, and $C$ is the adjustment level. After the assignment, it is set as follows:

$$S_j (X) = \begin{cases} 
1, & x_j \in [0.0, 0.3] \\
1.8-2.67 x_j, & x_j \in (0.3, 0.6] \\
0.2, & x_j \in (0.6-0.9] \\
8 x_j - 7, & x_j \in (0.9-1]
\end{cases} \quad (17)$$

Thus, the constant weight and variable weight of the system side are calculated, as shown in Table 2.

### Table 2. Calculation of the severity of voltage sag at system side using local state variable weight method

| First indicators | SLGF | LLF+DLGF | TPF | T/M Start |
|------------------|------|----------|-----|-----------|
| Second indicators | MSI (0.5) | DSI (0.5) | MSI (0.5) | DSI (0.5) |
| Second indicators status value | 6.25 | 0.86 | 62.5 | 12.07 | 6.25 | 17.24 | 18.75 | 56.9 |
| First indicators status value $A_j$ | 3.5556 | 37.2850 | 11.7451 | 37.8253 |
| First indicators evaluation value $x_j (=A_j/100)$ | 0.0356 | 0.3729 | 0.1175 | 0.3783 |
| Constant weight value $\sum_{j=1}^4 w_j^{(0)} x_j$ | 0.1689 |
| $S_j (X)$ | 1 | 0.8044 | 1 | 0.7900 |
| $w_j^{(0)} S_j (X)$ | 0.5226 | 0.2283 | 0.1090 | 0.0662 |
\[
\sum_{j=1}^{4} \sum_{i=1}^{4} |j| |j| = 0
\]

By comparison, it can be seen that the evaluation of voltage sag on system side obtained by using local state variable weight method takes into account the changing trend of the severity, which is smaller than the other weight evaluation and more in line with the actual situation in this region.

Table 3 and table 4 show the proportion of typical sensitive devices on the load side and their tolerance to voltage sag.

**Table 3. Proportion of load at distribution network**

| Equipment | PC | ASD | PLC | Normal sensitive |
|-----------|----|-----|-----|------------------|
| Proportion| 1/15 | 1/5 | 1/5 | 8/15 |

**Table 4. Voltage tolerance of typical sensitive equipment**

| Equipment | Magnitude/pu | Duration/s |
|-----------|--------------|------------|
|           | U_{min} | U_{max} | T_{min} | T_{max} |
| PC        | 0.46      | 0.63      | 0.04    | 0.205   |
| ASD       | 0.59      | 0.71      | 0.015   | 0.175   |
| PLC       | 0.30      | 0.90      | 0.02    | 0.4     |

Using the voltage tolerance curve of sensitive equipment, the failure rate \( E_2 \) caused by voltage sag on the load side was obtained by evaluating the load side, as shown in table 5.

**Table 5. Fault rate of sensitive equipment affected by voltage sag at load side**

| Equipment | PC | ASD | PLC |
|-----------|----|-----|-----|
| Failure rate | 0.30 | 0.4 | 0.4984 |
| 30 | 688 |
| Voltage sag degree on load side \( E_2 \) | 0.2137 |

The complex correlation coefficient method was used to comprehensively evaluate the weight of the system side sag severity \( E_1 \) and the load side sag severity \( E_2 \). The system side sag index weight \( w_1 \) and load side sag index weight \( w_2 \) are obtained: \( w=(w_1, w_2)=(0.5717, 0.4283) \).

Thus, the severity of the voltage sag events at monitoring points can be obtained:

\[
E = w_1 E_1 + w_2 E_2
\]  

In view of the above calculation results, this paper compares the combined evaluation results of the constant weight evaluation method and the entropy weight method, and analyzes the correlation coefficient with the original voltage sag information, and the results are shown in table 6.
Table 6. Comparison of weights and correlation coefficients of different combinations of weights

| Combination weighting method                          | Combination weight | Coefficient correlation |
|-------------------------------------------------------|--------------------|-------------------------|
| Constant weight method + Entropy weight method        | 0.1931             | 0.67                    |
| Local state variable weight method + Entropy weight method | 0.1833             | 0.74                    |
| Local state variable weight method + Complex correlation coefficient method | 0.1789             | 0.79                    |

The larger the correlation coefficient in table 6 is, the more practical the calculation results are. It can be seen that the evaluation method adopted in this paper can more accurately reflect the severity of actual voltage sag events, and avoid the problem of excessive evaluation caused by the inaccuracy of unilateral sag evaluation and other combined evaluation methods.

6. Conclusion
In this paper, we firstly assessed the voltage sag on the system side. After combining the failure rate of equipment on the load side, both sides voltage sag assessment was unified. The measured sag events in the 10kv distribution network were analyzed and calculated. After compared the results, we effectively verified the accuracy of the algorithm adopted in this paper. The specific performance is as follows:

1) The local state variable weight method not only reflects the data information of various indexes in the voltage sag assessment, but also reflects the influence of different value ranges of its indexes on the severity of voltage sag. Therefore, compared with the normal weight assessment method, it can reflect the actual situation of voltage sag much more precise.

2) The complex correlation coefficient method is used to comprehensively evaluate the severity index of voltage sag on the system side and the load side, so as to avoid excessive evaluation caused by redundant information and have higher accuracy.

3) Using the measured data of 10kv distribution network for example calculation, the results are consistent with the actual situation of voltage sag. Through comparative analysis with other methods, the correctness and rationality of the method adopted in this paper is verified.

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