A Load Outage Judgement Method Considering Voltage Sags

Abstract: Whether the load equipments of the power system will be outage considering voltage sags is analyzed in this paper. Reclassifying the load equipments because of the great impact on the sensitive loads due to the voltage sags. This paper has proposed a new Power Consumers Integrated Voltage Sensitive Curve and the Electrical Nodes Integrated Voltage Sensitive Curve based on the CBEMA and ITIC curves in order to characterize the sensitivity of the power consumers to voltage sags. The outage criterion for the sensitive loads is proposed based on the curves which has been described previously and can be used to get the probability curves of both amplitudes and durations of the voltage sags for different power users.

Keywords: Voltage sags; Power Quality; Load outage; Sensitive curves; Probability curves

1 Introduction

The electrical equipments and precision instruments which are based on the microprocessors are quite sensitive to the voltage sags and power outages. The economic losses caused by the voltage sags and other transient power quality problems has been growing all the time, so it’s very necessary to put the voltage dips and other transient power quality problems into the power system reliability evaluation [1-4].

Whether the load equipments will be outage when the voltage sag occurs will be a key link considering the voltage sag in power system reliability analysis, then a correct load outage criterion will be particularly important. The literature [5] and [6] propose a load outage criterion method based on the SCBEMA curve, which put forward an average outage criterion contains amplitude and downtime. However, the curve cannot fully reflect the different important levels between the sensitive and non-sensitive loads as the load outage happens. The different levels of sensitive loads should also be taken into account. This paper proposes the IVSC and ENIVSC curve which are more comprehensive than any other curves, in order to determine whether the load equipment will be outage based on the IVSC curve.

*Corresponding author: Xue ZHENG, Wuhan Electric Power Technical College, Wuhan, China, E-mail: dreamy_zx@qq.com
Dong-xu WANG, Wei CAI, State Grid Wuhan Power Supply Company, Wuhan, China
Xi YE, School of Electrical Engineering, Wuhan University, Wuhan, China
Zhi-chun YANG, Electric Power Research Institute of Hubei Electric Power Company, Wuhan, China
2 Classification of load equipments for electric users

Because the sensitive loads have a very short tolerance time to the voltage sags, these loads may tend to be affected from different levels or even outage when the power system have the voltage sag problems. Generally speaking, the electric power users can be divided as the resident users, the commercial office users, the general industrial users and the major industrial users. The type and the percentage of the load equipments that each power user contains are not the same as well, they can be divided into the following four categories [7]:

1. General loads (non-sensitive loads). The general loads will not be significantly affected by the voltage sags, they will be affected only by the circumstances such as the longtime blackouts or a wide range of voltage fluctuations.
2. Little sensitive loads. This kind of loads will be influenced by a certain degree when faced with the power quality problems such as the voltage sags. It may also cause certain damage to the load equipments.
3. Sensitive loads. The sensitive loads will have more serious effects when faced with the power quality problems such as the voltages sags, we should take certain measures to ensure the quality of electric energy to avoid the load equipments damage.
4. The core loads. They are often in the central position of the load equipments, and they are very sensitive to the voltage sags and other power quality problems that may cause the outage of the power system directly, which can cause huge economic loss and negative social impact.

The above four kinds of loads will be of different types and in different proportions in each electric power user, the sensitive loads mentioned in this paper will refer to the three kinds of sensitive loads above.

3 Voltage sensitive curve

3.1 Definition of voltage sensitive curve

The voltage sensitivity curve generally has two branches---the up branch and down branch, which separately define the limit value of high voltage and low voltage that the equipments can bear. The voltage sensitivity of the equipments can be reflected intuitively in the curve. The abscissa of the curve is generally defined as the duration of the voltage disturbance, the ordinate is generally defined as the voltage amplitude or the percentage that the voltage deviates from the nominal value.
3.2 Traditional voltage sensitive curves

(1) CBEMA curve. As is shown in Figure 1, the curve was determined by the Computer Business Equipment Manufacturing Association because of the power quality requirements based on the mainframe computers, in order to prevent the maloperation and damage of the computers and control equipments cause by the voltage disturbance. The curve is a kind of the statistical curve, most CBEMA curves of the sensitive loads can be formulated according to the experimental data and historical data [8].

![Figure 1. The CBEMA sensitive curve](image)

This paper mainly discusses the influence on the power system reliability caused by voltage sags. Both the amplitude and the duration of voltage sags have to be taken into account. So we make the curve become to the polyline. Then the following typical load equipment CBEMA curve is obtained in Figure 2 by collecting the historical statistics [9].

![Figure 2. The CBEMA curve of the typical loads](image)
(2) ITIC curve. The ITIC curve is formulated by the Information Technology Industry Council, it is based on the CBEMA curve, in order to characterize the disturbance rejection capability of the computers and other information industrial equipments under the voltage sag circumstance (Figure 3). The ITIC curve becomes polyline compared with the CBEMA curve, while the up and low tolerance value was changed to 110% and 90% and the starting time is changed from 8.33ms to 20ms.

![Figure 3. The ITIC curve](image)

### 4 Load outage criterion

#### 4.1 The integrated voltage sensitive curve of the power users

We get the traditional CBEMA curve by measuring the individual sensitive load, it can only reflect the effect that the individual load has under the voltage sags [10], and it can't be used to analyze the voltage sags’ impact on the overall loads. So it's difficult to react the influence on the overall loads under the voltage sag circumstance. What’s more, the same loads will not in the same position when they are in different electric users. For example, when voltage sag happens in the resident users, we always focus on the little sensitive loads, but we will focus on the core loads when the same thing happens in the major industrial users. If we use CBEMA curve to analyze the electric users’ sensitivity, then we can't know the difference between them.

In order to get the overall power outage criterion for amplitude and downtime of the power users, part of the literatures propose a SCBEMA curve (Specified Computer Business Equipment Manufacturer Association). To strike a SCBEMA curve we may first set she composition ratio of the load equipments in each power user, then we will
multiply the tolerance limit value from the CBEMA curve and the composition ratio, after having done this we accumulate the result to get the SCBEMA tolerance limit values for each user type [5]. Here is the formulas:

\[
\begin{align*}
X &= \sum_{i=1}^{j} (X_i + K_i) + X_0 \times K_0 \\
Y &= \sum_{i=1}^{j} (Y_i + K_i) + Y_0 \times K_0
\end{align*}
\]

(1)

The \(X\) and \(Y\) represent the voltage sag duration and voltage sag amplitude in the SCBEMA curve; The \(X_0\) and \(Y_0\) represent the voltage sag duration and voltage sag amplitude of the non-sensitive loads in a certain power user; The \(K_i\) represents the composition ratio of the \(i\) type of sensitive loads in a certain power user; The \(K_0\) represents the composition ratio of non-sensitive loads.

Although the SCBEMA curve can describe the voltage sag outage probability more comprehensively compared with the CBEMA curve, we can still find some defects from the corresponding formulas: (1) The formula only considers the number ratio of the load equipments, the capacity ratio isn’t mentioned. If a core load exists in the certain user, when it comes to be outage then the whole load equipments of the user will be outage, if we still use the above formula to calculate then the voltage sensitive curve we get will be quite different to the actual circumstances; (2) In the formula we can see that the importance of all load equipments are the same, but we can find that the non-sensitive loads have little effect on the outage of the power users when the voltage sag is happening, while the sensitive loads and the core loads can often play a decisive role.

For these reasons, this paper presents a Power Consumers Integrated Voltage Sensitive Curve, which referred to as the IVSC curve. The IVSC curve reflects a comprehensive concept, It will get a comprehensive criterion of outage amplitude and outage time by making statistical analysis of all kinds of load equipments for power users and considering the ratio of capacity and number for load equipments, at the same time we will create different weighting factors which will depend on the sensitivity level of the load equipments in the synthesis of the IVSC curve. When a voltage sag reaches a certain amplitude or duration, then we can believe that all the load equipments in this class of users will have power outage.

Here we will introduce the steps to calculate the IVSC curve: (1) To classify the load equipments according to the classification method which is mentioned previously and make sure the capacity and number of each kind of load equipment; (2) To determine the weighting factor of each load equipment and the weighting coefficients of the capacity ratio and number ratio according to the load equipments’ sensitivity level; (3) We will multiply the different tolerance values by the corresponding ratios and weighting factors of each load equipments, and then accumulate them to get the tolerance values of the IVSC curve for the certain kind of power users.
The tolerance values of IVSC curve can be calculated by the following formula:

\[
\begin{align*}
T &= \sum_{i=0}^{j} W_i X_i \left( \alpha \frac{N_i}{N} + \beta \frac{S_i}{S} \right), \\
U &= \sum_{i=0}^{j} W_i Y_i \left( \alpha \frac{N_i}{N} + \beta \frac{S_i}{S} \right)
\end{align*}
\]

(2)

The \( T \) and \( U \) respectively represent the coordinate values of the corresponding duration and amplitude of the voltage sags; The \( X_i \) and \( Y_i \) represent the abscissa and ordinate values of the CBEMA curve which is belong to the certain kind of load equipment for an electric power use; The \( X_0 \) and \( Y_0 \) represent the coordinate values of the non-sensitive loads; The \( \alpha \) and \( \beta \) represent the weighting coefficients considering the number and capacity, which is determined by the actual composition of the load equipments; The \( W_i \) represents the weighting factor considering the load equipments’ sensitivity; The \( N_i \) and \( S_i \) represent the number and capacity of the certain kind of load equipment; The \( N \) and \( S \) represent the total numbers and capacities of load equipments in the certain power user.

According to the types of users and the composition ratio of load equipments in Table 1 and the calculation from formula (2), we can get the IVSC curves for different types of power users which are shown in Figure 4.

### Table 1. Different types of power users and composition ratio of load equipments

<table>
<thead>
<tr>
<th>Loads</th>
<th>resident users</th>
<th>commercial office users</th>
<th>general industrial users</th>
<th>major industrial users</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number ratio</td>
<td>Capacity ratio</td>
<td>Number ratio</td>
<td>Capacity ratio</td>
</tr>
<tr>
<td>DC motor controllers</td>
<td>0</td>
<td>0.05</td>
<td>0.1</td>
<td>0.15</td>
</tr>
<tr>
<td>Electromagnetic contactors</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.15</td>
</tr>
<tr>
<td>Lights</td>
<td>0.1</td>
<td>0.1</td>
<td>0.15</td>
<td>0.2</td>
</tr>
<tr>
<td>Computer and communications equipment</td>
<td>0.15</td>
<td>0.2</td>
<td>0.3</td>
<td>0.15</td>
</tr>
<tr>
<td>Automatic voltage regulator</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.1</td>
</tr>
</tbody>
</table>
| Non-sensitive loads           | 0.75           | 0.7                     | 0.55                     | 0.6                    | 0.2                    | 0.2                    | 0.15                    | 0.1
4.2 The integrated voltage-sensitive curve for electrical nodes

Meanwhile, we should also think that there are many power users and load equipments in the power system, it’s very difficult to collect the relevant data. Secondly, sometimes we don’t need to know the voltage-sensitive situations for each power user for the viewpoint of power system, the only thing we need to do is to know the voltage-sensitive situation for one electrical node. Then the Electrical Nodes Integrated Voltage Sensitive Curve (ENIVSC curve) will be a good choice which can reflect the whole voltage-sensitive situation of the load equipments in one electrical node. The ENIVSC curve is a curve which is based on the IVSC curve, it can reflect the sensitivity of all power users in one node, the following formula will explain how we get it:

$$\begin{align*}
T' &= \sum_{m=1}^{n} W'_m T_m (\alpha' \frac{N'_m}{N'} + \beta' \frac{S'_m}{S'}) \\
U' &= \sum_{m=1}^{n} W'_m U_m (\alpha' \frac{N'_m}{N'} + \beta' \frac{S'_m}{S'})
\end{align*}$$

(3)

The $T'$ and $U'$ represent the Abscissa and ordinate value of the curve; The $T_m$ and $U_m$ represent the Abscissa and ordinate value of the IVSC curve; The $\alpha'$ and $\beta'$ represent the weighting coefficients that considering the number and capacity ratio of electric power users in the electrical node; The $W'_m$ represent the weighting coefficient that considering the importance of the power users; The $N_m$ and $S_m$ represent the number and capacity of the certain kind of power users; The $N'$ and $S'$ represent the total number of load equipments and the total capacities.
4.3 The load outage probability curve of the voltage sags

The CBEMA curve we discussed earlier is essentially a kind of probability and statistics curve, the load equipments may be outage if the duration and amplitude value exceed the critical value of the curve. The IVSC curve is the curve which is obtained from the CBEMA curve, it also has the features of probability and statistics: When the voltage sag occurs inside the IVSC curve, part of the load equipments may be outage. what’s more, different durations and amplitudes will have different effects on the power users, these two factors are interrelated in general. In order to get better smoothing feature, this paper will select a similar S-shaped curve as the outage probability curve of the load equipments under the voltage sag circumstance.

The time probability function of load outage:

\[
P_{T_x} = \begin{cases} 
\frac{1}{2} \times \left( \frac{x}{a} \right)^2 & 0 < x < a \\
1 - \frac{1}{2} \times \left( \frac{b-x}{b-a} \right)^2 & a \leq x < b \\
1 & b \leq x
\end{cases}
\] (4)

The \(P_{T_x}\) represent the time probability function value of load outage for voltage sags; The \(x\) represents the sag duration; The \(a\) and \(b\) represent the corresponding curve value when the probability value is 0.5 and 1. Generally, the value of \(a\) is often the tolerance value of the curve. The value of \(b\) will be 500ms, which represents most of the loads will be outage.

The amplitude probability function of load outage:

\[
P_{U_y} = \begin{cases} 
1 & y < 100 - b' \\
1 - \frac{1}{2} \times \left( \frac{b' + y - 100}{b' - a'} \right)^2 & 100 - b' < y < 100 - a' \\
\frac{1}{2} \times \left( \frac{100 - y}{a'} \right)^2 & 100 - a' < y < 100
\end{cases}
\] (5)

The \(P_{U_y}\) represents the amplitude probability function value of load outage for voltage sags; The \(y\) represents the residual amplitude value after the voltage sag (in percent); The \(a'\) and \(b'\) represent the corresponding curve value when the probability value is 0.5 and 1. Generally, the value of \(a'\) is often the tolerance value of the curve; The value of \(b'\) will be 100%, when most of the loads will be outage.

After getting the two probability curves, we should taking two curves into account to determine the probability of load outage under voltage sag circumstance, that is: \(P = (P_{T_x} + P_{U_y}) / 2\)
Taking example for the data of Figure 4 and referring the general industrial users’ data of IVSC curve, we can calculate the time probability curve (as is shown in Figure 5) of load outage when voltage sag happens by using the formula (4):

![Time probability curve of load outage for general industrial users](image)

**Figure 5.** The time probability curve of load outage for general industrial users

We can calculate the amplitude probability curve (as is shown in Figure 6) of load outage when voltage sag happens.

![Amplitude probability curve of load outage for general industrial users](image)

**Figure 6.** The amplitude probability curve of load outage for general industrial users

Similarly, by referring the tolerance value of IVSC curve for the resident users, we can respectively get the time and amplitude probability curve which is shown in Figure 7 and Figure 8.
When a voltage sag happens in the power system, we can calculate the amplitude and duration data of the voltage sag by several ways, then we can know the load outage probability by comparing with the corresponding $P_{Tx}$ and $P_{Uy}$ curves, when it is greater than a set value, we can consider that the load will be outage. The same method can also be applied to determine whether the electrical nodes will be outage under the voltage sag circumstance. The flow chart of load outage judgment is as follows:

Taking the fifth bus of the RTS-6 bus test system for example, the load composition in the fifth bus has already be given in Table 1. Assuming that a voltage sag happens because of the three phase short circuit somewhere in this bus, for a certain power user, such as the general industrial user on the 14th node, we first set an outage...
probability threshold $P_0 = 45.6\%$, according to the short circuit flow calculation and protection device operating time we can calculate the drop amplitude and duration are 24% and 153ms when the voltage sag happens. Compared with Figure 5 and Figure 6 we can know the amplitude probability and time probability value are $P_1 = 10.8\%$ and $P_2 = 75.3\%$. The power user’s comprehensive outage probability value is $P = (P_1 + P_2)/2 = 43.05\%$, it is obvious that $P < P_0$, so we believe that the loads of the power user can still work in the period of three phase short circuit. If we find $P > P_0$ in practice, it shows that the loads of the power user will be outage in the period of three phase short circuit.

**Figure 9.** The flow chart of load outage judgment
6 Conclusion

This paper has re-classified the load equipments as the different sensitivities of loads; analyzing the CBEMA curve which was mentioned in part of the articles and pointing out its shortcomings; Proposing the IVSC and ENIVSC curves based on the CBEMA curve; Proposing a sensitive load outage criterion based on the IVSC curve considering the voltage sags; Using the ambiguity function to get the outage amplitude and duration probability curves, when the voltage sag happens, we can get the load outage probability value by using the voltage sag amplitude and duration values. Comparing the calculated outage probability value with the outage probability threshold, if the calculated value is greater than the set value, it can be judged that the load equipments will be outage.

References