The study on the influence on sensitive equipment to the voltage sag characteristics based on process immunity time

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Abstract:

It is clear that the influence of different voltage sag characteristics on equipment performance is a very concerned problem for manufacturers and users, and also the precondition of choosing a scheme to control the influence of voltage sag on sensitive equipment, so it is necessary to know the effect of voltage sag on equipment. This paper present a method to study the influence of sag characteristics on sensitive devices by using process immunity time. By using the change rule of process parameters which can be observed directly, combined with the acceptable consequence of the user, the influence of different sag characteristics on the sensitive equipment is quantified by the process immunity time. By using Matlab/simulink to model, simulate and analyze the adjustable speed drive, the correctness and feasibility of the method are verified.

Keywords: sag characteristics; sensitive equipment; process immunity time; adjustable speed drive

1. Introduction

Voltage sag refers to the instantaneous decrease of voltage magnitude (root mean square), then automatically restore to the normal voltage level, it is a very prominent power quality problem in the power system, mainly caused by the short-circuit fault in the system, the large motor starting and the excitation inrush of the transformer [1]. In recent years, with the development of science and technology, more and more devices are sensitive to voltage sags in power systems, such as speed control devices, personal computers, PLCs, photovoltaic inverter and so on. When these devices suffer a voltage sag, the equipment may fail or be damaged, also means that the continuous production process controlled by the device may be interrupted, resulting in economic loss to the users. According to statistics, in the complaint of power quality problems, the voltage sag problem occupies a large proportion [2], so the users and scholars of great concern. These sensitive loads are affected by the voltage sag because they are not able to resist it. Therefore, understanding the influence of voltage sag characteristics on sensitive devices is very important for system voltage sag control and equipment development.

Some scholars have done a lot of research on personal computers [3], adjustable speed drivers [4], AC contactors [5-6] and programmable logic controllers [7] and other sensitive devices, their voltage tolerance curves (VTC) are obtained respectively. However, these studies only consider the magnitude and duration, but equipment performance will be affected by other characteristics, such as phase angle jump, point on wave and three phase asymmetry. Domestic scholars have studied the influence of the AC contactor on the phase angle jump and the point on wave through the test, and obtained its sensitivity to the point on wave [6], but VTC can be plotted by several tests, and the critical point of the device failure is not easy to obtain. In reality, it has been recognized that different types of equipment, and even different brands or model of the same type of equipment, may present important differences with respect to their sensitivity to voltage sag characteristics. Therefore, studying the impact of voltage sag characteristics on sensitive devices is of great significance for mitigate voltage sag and equipment development.

Based on the concept of process immunity time and the acceptable consequence state of users [9], this paper present a new method to study the influence of sag characteristics on sensitive equipment, and in the Matlab/simulink, ASD is modeled and simulated, and the correctness and feasibility of the proposed method are validated.

2. The sag characteristics

Although the definition of voltage sag are different between IEEE and IEC, it is mentioned that other characteristics of sag will affect the operation of the equipment. In the literature [9], the influence of point-on-wave, voltage dip unbalance and phase shift on the equipment is mentioned. For example, electro-mechanical contactor drop-outs, the phase angle at which a voltage dip begins is an important characteristic, dip unbalance can damage 3-phase rectified loads, or cause over-current devices to trip, 3-phase rectifiers, the phase shift of the voltage dip can be important[9]. In the literature [10], the three phase unbalance, phase angle jump, and point on wave can also influence the performance of the equipment. Therefore, other characteristics should be fully considered when studying the impact of voltage sag on equipment.

Magnitude (M): The minimum value of $V_{rms(1/2)}$ recorded during a voltage sag. The magnitude is expressed as a value in volts or as a percentage or per-unit value of the declared voltage or sliding-reference voltage[11].

Duration (D): The length of the interval between the time when the root-mean-square (rms) voltage drops below the sag threshold and the time it subsequently rises above the sag threshold[11].

Phase angle jump (PJ): it is caused by the change of system impedance, the change of the instantaneous voltage zero point, which may have an effect on the power electronic devices triggered by phase angle [10] [12].

Point on wave (PW): It is the phase angle of the fundamental voltage waveform at the beginning of the voltage sag, which corresponds to the angle of the instantaneous short-circuit fault [10].

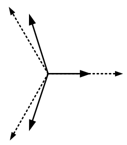
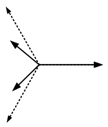
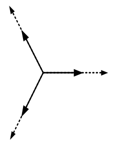
Three-phase asymmetry is for three-phase systems or equipment. Based on the different types of faults which may occur in three-phase power system, voltage sag can be divided into three types, namely type Ⅰ, type Ⅱ and typeⅢ, as is shown table 1. In which type Ⅰ and Ⅱ are the asymmetric voltage sag, and type Ⅲ is symmetrical voltage sag.

Type Ⅰ: Mainly the amplitude of a relative voltage decreases.

Type Ⅱ: The amplitude of a first-line voltage drops.

TypeⅢ: The amplitude of the three-phase voltage is reduced together.

Table 1 voltage sag type

Type	I	II	III
Expression	$\overline{U_a}=\overline{V}$ $\overline{U_b}=-\frac{1}{2}\overline{V}-\frac{\sqrt{3}}{2}j\overline{E}$ $\overline{U_c}=-\frac{1}{2}\overline{V}+\frac{\sqrt{3}}{2}j\overline{E}$	$\overline{U_a}=\overline{E}$ $\overline{U_b}=-\frac{1}{2}\overline{E}-\frac{\sqrt{3}}{2}j\overline{V}$ $\overline{U_c}=-\frac{1}{2}\overline{E}+\frac{\sqrt{3}}{2}j\overline{V}$	$\overline{U_a}=\overline{E}$ $\overline{U_b}=-\frac{1}{2}\overline{E}-\frac{\sqrt{3}}{2}j\overline{V}$ $\overline{U_c}=-\frac{1}{2}\overline{E}+\frac{\sqrt{3}}{2}j\overline{V}$
Phasor diagrams			

Note: $\overline{E}$ is the pre-event voltage; $\overline{V}$ is the "characteristic voltage"of the dip. The dotted line indicates the three-phase voltage before the sag, and the solid lines indicate the three-phase voltage.

For type Ⅰ, when V_A=50%, V_B=95%, V_C=95%; D_A=D_B=D_C=0.05s; PJ_A=0°, PJ_B=30°, PJ_C=45°; PW_A=0°, PW_B=-120°, PW_C=120°, the waveform is shown in Figure 1.

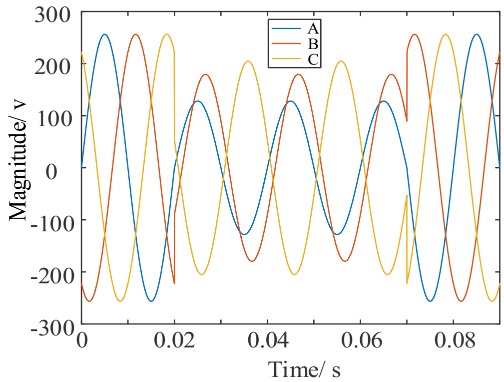


Figure 1 waveform of type I

3. Study on the influence of sag characteristics

3.1 Process immunity time

When the voltage sags occur, the voltage tolerance curve of the equipment can be used to determine whether the equipment is invalid, as shown in Figure 1, but the failure of the device does not necessarily cause the interruption of the process [13], as long as the interruption of the process is not caused during the voltage sag, it is considered that the process has immunity.

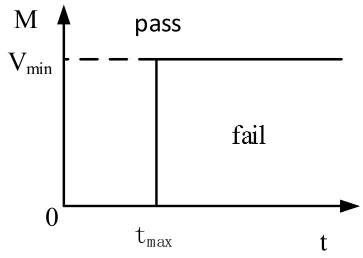


Figure 2 voltage tolerance curve

Thus, in 2006, CIGRE/CIRED/UIE established a joint working group and presented in the research report the concept of process immunity time (PIT) [1], which is temporarily lowered at a given amplitude, the time that a process parameter crosses an acceptable limit reflects the rule of process parameters changing over time [7]. It can be judged whether the device is immune to the sags by the relationship between the process immunity time and the duration of the sag. As shown in Figure 3.

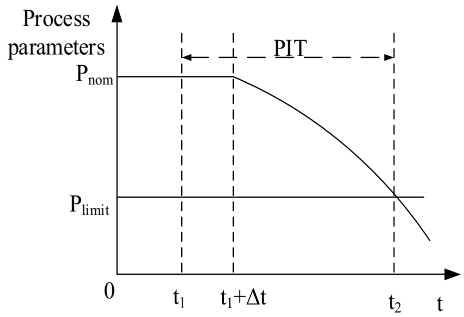


Figure 2 process immunity time

In Figure 3, P_{nom} is the normal operation value of process parameter, P_{limit} is acceptable limit value of process parameter, t_1 is the beginning of the voltage sag, t_2 is the time when the parameter changes to the acceptable limit value, so the PIT is determined by the formula (1); When the process suffers a voltage sag, if the PIT>D, the equipment is immune to the voltage sag.

$$PIT = t_2 - t_1 \quad (1)$$

3.2 The research principle of the influence of sag characteristics

The existing research shows that the effects of different sag characteristics on sensitive devices are different. For example, the AC contactor is very sensitive to the point on wave, under the same magnitude, the tolerance time of the point on wave at 90°is shorter than 0°[6], and the phase angle jump will affect the operating state and performance of the photovoltaic inverter [12]. For the sensitive equipment, the performance of the device may be different when the size of the sag characteristics is different, and this difference can be shown by the change of the process parameters. Therefore, we can use process immunity time to study the impact of voltage sags on sensitive devices. As shown in Figure 4, V1, V2, V3 and V4 respectively represent the sag events with different of the sag characteristic size, and the process parameter curves are different under different sag events, when the acceptable value of the process parameters is determined, the size of PIT1, PIT2, PIT3,and PIT4 can be obtained, the influence of sag characteristic on sensitive equipment is quantified by using formula (2).

$$\delta = \frac{PIT_{max} - PIT_{min}}{PIT_{max}} \tag{2}$$

Where: PIT_{max} and PIT_{min} are the maximum and minimum values in PIT1, PIT2, PIT3 and PIT4 respectively.

When $\delta > 30\%$, the effect of the voltage sag on the equipment is considered to be large, whereas the effect on the device can be ignored.

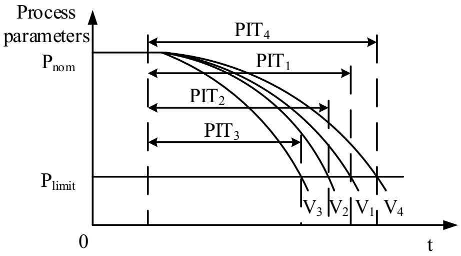


Figure 4 PIT curve with different sag event

The research on the effect of sag characteristics on sensitive equipment involves the following steps:

1) the voltage sag events Vi (i=1,2,3,...) are composed of different characteristics.
2) the power supply parameter of ASD is set to Vi, and the change rule of process parameter with time is obtained through experiment or simulation.
3) According to the user's acceptable consequence state, the acceptable value of the process parameter is obtained, and get $PITi$ (i=1,2,3,...) through formula (1).
4) The PIT_{max} and PIT_{min} are found from the $PITi$, and determine the influence degree of the sags on sensitive devices by formula (2).

4. Case study

Because the adjustable speed drive (ASD) is widely used in modern industrial production, this paper using Matlab/Simulink to modelling of ASD, and select the speed of asynchronous motor as the process parameter, the correctness and feasibility of the proposed method are verified by simulation.

4.1 Simulation principle

The structure of ASD is shown in Figure 5, and the circuit consists of a front-end active or passive diode rectifier, dc link and a PWM inverter [14]. Rectifier links are usually composed of three-phase rectifier diodes, convert the AC into DC; the DC link is composed of capacitance, so that the DC port output voltage waveform is more smooth, in some circuits there is also a series of inductance, so that the filter effect is better; the inverter is usually composed of voltage source type inverter, according to the user's need and under the controller's function, AC voltage with variable amplitude and frequency is output.

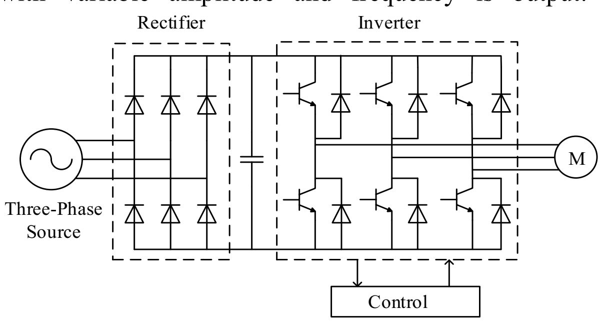


Figure 5 typical topological structure of ASD

ASD is more sensitive to voltage sags. Generally, there are undervoltage and overcurrent protection systems [14], once the protective action value is reached, the protection will act, thereby to protecting the equipment. ASD is modeled in Matlab/Simulink and the resulting model is shown in Figure 6, and the model parameter setting is shown in Table 2.

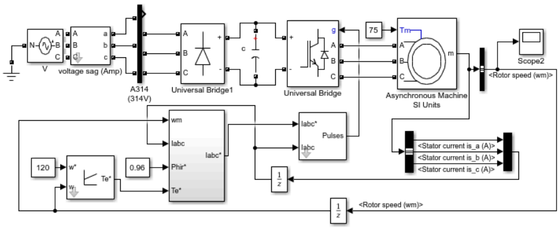


Figure 6 Simulation model of ASD

Table 2 Model parameter settings

Power supply Amplitude (v)	220	Expected speed (rpm)	120
Power frequency (Hz)	50	Given magnetic linkage (Wb)	0.96
Capacitance (F)	0.0047	Load (N.m)	75

4.2 Simulation Results

First of all, when only the magnitude changes are considered, this paper simulates the voltage sag of type Ⅰ, Ⅱ and Ⅲ, and studies their effects on equipment. Secondly, under the precondition of three phase symmetric voltage sag, the influence of phase angle jump and point on wave on the equipment are considered.

1) Type Ⅰ

The main reason for the type Ⅰ is that the single-phase grounding fault causes a certain phase voltage to change obviously, and the probability of occurrence is the most in the system. Therefore, the phase voltage of A and B is maintained, and the amplitude of the C phase voltage decreases by 10%, which forms a different voltage sag event, and the magnitude of the phase voltage is shown in table 3.

Table 3 Type Ⅰ

Sag event / Phase voltage	V1	V2	V3	V4
A（pu）	1	1	1	1
B（pu）	1	1	1	1
C（pu）	0.2	0.3	0.4	0.5

The power supply parameters in the model are setting according to table 3, and are simulated under different voltage sag events to get the change of motor speed with time. As shown in Figure 7.

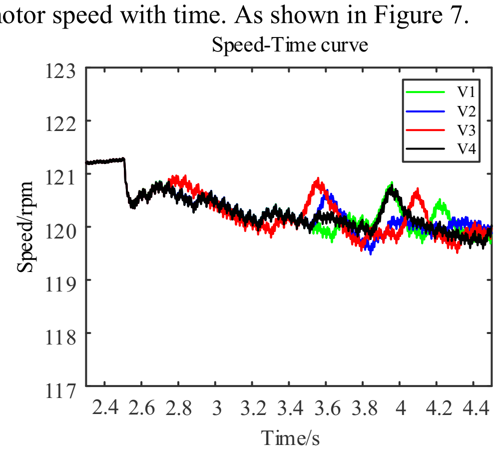


Figure 7 PIT curve of type Ⅰ

The occurrence time of the sags is Time=2.5s, and the acceptable value of the rotational speed is Speed=100rpm; from Figure 7, when ASD is subject to type I, the speed of the asynchronous motor has only a slight change, and then it is stable at the desired speed, and there is no intersection with the acceptable speed value; therefore, the influence of the type Ⅰ on ASD is very small and can be ignored

2) Type II

For type II, it is usually caused by interphase short circuit, which leads to a significant change in a line voltage. Therefore, it is considered that the voltage of A phase is constant, and the amplitude of B and C phase voltage are reduced by 10%, which constitutes different voltage sag events, and its magnitude is shown in table 4.

Table 4 Type II

Sag event / Phase voltage	V1	V2	V3	V4	V5
A (pu)	1	1	1	1	1
B (pu)	0.2	0.3	0.4	0.5	0.6
C (pu)	0.2	0.3	0.4	0.5	0.6

The voltage sag events in table 4 are simulated and the results are shown in Figure 8.

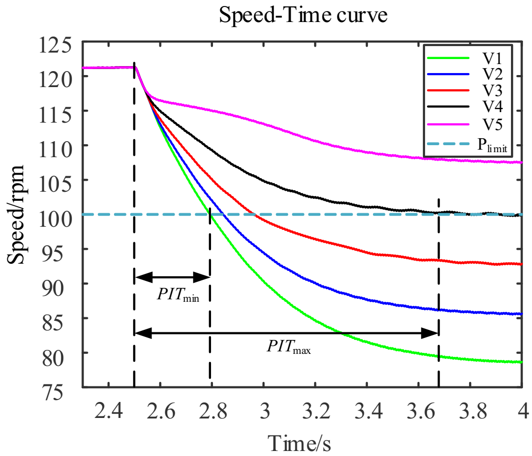


Figure 8 the PIT curve of type II

The starting time of the sag is Time=2.5s, the acceptable limit value of the rotational speed is Speed=100rpm; When V1 occurs, the speed fall out of the acceptable limit value at Time=2.793s, at this time PIT=0.293s; when V6 happens, the speed exceeds the limit value at Time=3.676s, then PIT=1.176s; so:

PIT_{min}=0.293s

PIT_{max}=1.176s

From the formula (2): δ=75.1%>30%

Therefore, when ASD suffers from type II, the speed of the asynchronous motor will change obviously, the lower the magnitude of voltage sag, the smaller the rate of change of the motor speed (rate of change is negative), and the smaller the corresponding PIT, the greater the impact on ASD, the under-voltage protection of ASD is more likely to trigger. If the DC side capacitor voltage does not trigger the protection system, then in the closed-loop vector control, the rotational speed will stabilize at a certain value.

3) TypeIII

For type III, it may be caused by the large motor start-up or three-phase short circuit, and the minimum probability occurs in the system. The voltage magnitude of A, B and C reduced by 10% at the same time, forming different sag events. The magnitude as shown in Table 5.

Table 5 TypeIII

Sag source / Three phase	V1	V2	V3	V4	V5	V6
A(pu)	0.2	0.3	0.4	0.5	0.6	0.7
B(pu)	0.2	0.3	0.4	0.5	0.6	0.7
C(pu)	0.2	0.3	0.4	0.5	0.6	0.7

The different sag events in table 5 are simulated and the curves of the speed change with time are obtained, as shown in Figure 9.

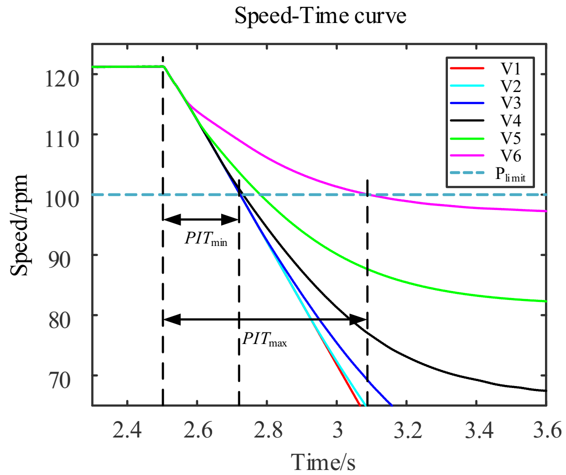


Figure 9 TypeIII PIT curve

The start time of the sags event is Time=2.5s, the acceptable limit value of the rotation speed is Speed=100rpm; for the sag event V1, the speed falls out of the acceptable limit value at Time=2.724s, at this time PIT=0.224s; for the sag event V6, the speed exceeds the limit value at Time=3.092s, then PIT=0.592s; so:

PIT_{min}=0.224s

PIT_{max}=0.592s

From the formula (2): δ=62.3%>30%

Therefore, when ASD suffers from type III, the speed of asynchronous motor changes obviously. The lower the magnitude of voltage sag, the smaller the rate of change of the motor speed (rate of change is negative), and the smaller the corresponding PIT. Similar to the type II, when the under-voltage protection is not triggered, the speed is stable at a certain value. ASD stops running when the protection is triggered.

From Figure 7, we can see that when type I occurs, the speed does not change significantly. Therefore, the paper sums up the tendency of type Ⅱ and Ⅲ to change with time, and get the PIT with different sag events through acceptable minimum speed. With the voltage sag magnitude as the horizontal axis and the PIT as the vertical axis, the change trend of the PIT corresponding to different magnitude under different types of sag, as shown in Figure 10.

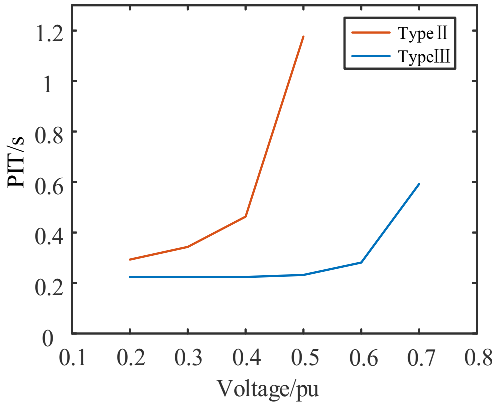


Figure 10 The trend of PIT change

From Figure 10, the PIT change curve of type Ⅱ is above the type Ⅲ, and the influence of type Ⅱ and Ⅲ on ASD can not be ignored; the more serious the voltage sag, the greater the rate of change of PIT. The effect of type Ⅰ、 Ⅱ and Ⅲ on the equipment is: Ⅰ < Ⅱ <Ⅲ

4) phase angle jump

In the present research, it is shown that phase angle jump may have an impact on power electronic devices, so it is necessary to study the effect of phase angle jump on equipment. The jump range in the system is usually between +60°and -60°, which is negative in most cases. ASD is a power electronic device which is sensitive to voltage sag, it can be used to study the effect of phase angle jump, so as to verify the correctness of the proposed method. The parameters are shown in Table 5.

Table 5 change of phase

Characteristics / Sag events	M(pu)	D(s)	
V1	0.7		0
V2	0.7		
V3			
V4	0.7	1.5	
V5	0.7	1.5	

The speed change with time under different voltage sag events, as shown in Figure 11.

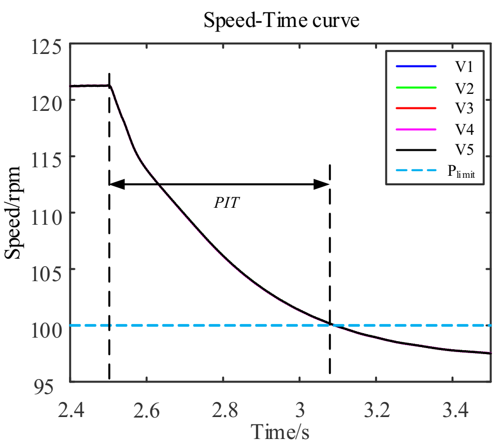


Figure 11 the change of speed with time

From Figure 11, we can see that the change trend of speed with time is same under different sag events, and the PIT are equal at different angles. By formulae (2) to quantify the impact on equipment, we can get that phase angle jump has no significant effect on ASD.

5) point on wave

This characteristic usually affect the devices which are operated by electromagnetic force, such as AC contactor. By setting different angles, the model is simulated, and the angle size is shown in table 6.

Table 6 Change of point on wave

Characteristics / Sag events	M(v)		PW_A(°)
V1	0.7	1.5	
V2	0.7		45
V3	0.7	1.5	
V4	0.7	1.5	135
V5	0.7	1.5	

The simulation results under different sag events are shown in Figure 12

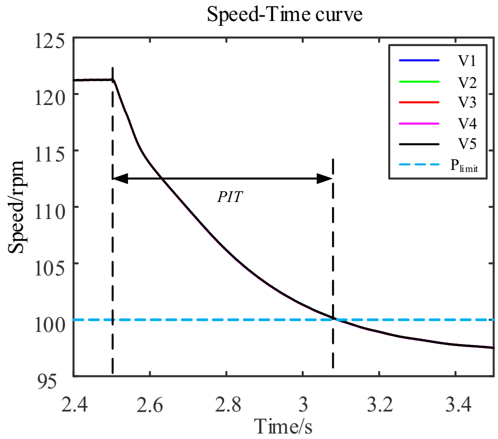


Figure 12 PIT curves considering phase angle jump

From Figure 12, we can see that change trend of speed with time is same under different angles, and the PIT is equal at different events. By formulae (2) to quantify, the influence of point on wave on ASD can be ignored.

5. Conclusion

Based on the process parameters and acceptability of the sensitive equipment, this paper quantifies the influence of the characteristics of the voltage sag on the sensitive equipment by the difference between PIT_{max} and PIT_{min} is divided by PIT_{max}. Through the modeling and Simulation of ASD, we get the sensitive characteristics of ASD, and prove the correctness and feasibility of the method.

In order to apply this method to practical engineering, we need further research on the way to get PIT that is close to the actual situation. Because on-the-spot survey of PIT can cause economic losses, in many cases, the method of measurement is not allowed. How to get PIT that is close to the real situation is worth studying.

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