Study on Risk Assessment and Early Warning Platform for Voltage Sag

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Study on Risk Assessment and Early Warning Platform for Voltage Sag

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Abstract. Voltage sag, as an unavoidable power quality problem, has been attracted wide attention. Voltage sag risk assessment and early warning technology research have great significance for power supply companies and power users. This paper conducts the quantitative assessment of voltage sag risk based on the fault intensity and probability distribution of each component in power grids. In addition, a voltage sag automatic assessment and early warning platform is developed, which can visualize the failure probability of power grid components.

1. Introduction

At present, researchers have carried out fruitful research in voltage sag risk assessment and formed theoretical results. Specifically, it can be divided into two categories, grid node and industrial process voltage sag risk assessment. The former mainly uses stochastic estimation method to simulate the short circuit fault of the power grid to obtain the corresponding voltage sags, and then calculate the related indicators to quantify the risk of node voltage sags . The latter mainly considers the uncertainty of the voltage sags response events in the sensitive process. The risk of industrial voltage sags is evaluated by the relationship between voltage sags and the voltage tolerance of the equipment[1-8].

This paper conducts the assessment of voltage sag risk and designs the early warning platform. First, based on the component reliability index, the stochastic estimation method is used to evaluate the distribution characteristics of the bus voltage sags, then the sensitive load fault risk is evaluated with the tolerance of the typical sensitive equipment. Finally, a voltage sag automatic assessment and early warning platform is developed to visualize the failure probability of power grid components.

2. Research on quantitative technology of voltage sags risk index

The risk assessment of bus voltage sags uses components reliability index to make stochastic estimation on bus voltage sags. On this basis, a risk quantitative evaluation index system is built.

2.1 Stochastic Estimation of bus voltage sags

The voltage sags suffered by the selected bus can be described as followed:

$$F(u,t)_i = \sum_f^n \sum_x (\lambda_{f,x} \mid u_i \le u, \Delta t_{f,x} > t) \tag{1}$$

where $\lambda_{f,x}$ is the failure rate of fault type x at fault location f, u_i is the voltage at bus i after the sag. $\Delta t_{f,x}$ is the voltage sag duration determined by protective action time. The short circuit failure rate

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λ_f at certain location *f* represents the failure rate of all fault types, and the failure probability of each type of fault should satisfy the formula (2) and (3):

$$\lambda_f = \sum_x \lambda_{f,x} = \sum_{ft} \frac{p_{f,x}}{100} \lambda_f \tag{2}$$

$$\begin{cases} 0 \le p_{f,x} \le 100\% \\ \sum_x p_{f,x} = 100\% \end{cases} \tag{3}$$

2.1.1 voltage sags evaluation model

Figure 1 is the system voltage sags assessment model, *r* is the estimated bus, point *r* and *f* are the cases of short circuit faults on the bus and line, respectively.

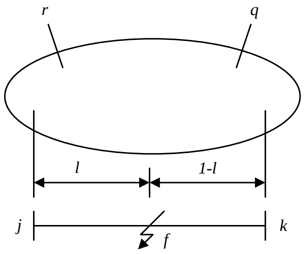

Figure 1. Voltage sags evaluation model

When the fault occurs on the bus *q*, the voltage amplitude of *r* is:

$$U_r^c = U_{r0}^c - Z_{rq}^c I_q^c \tag{4}$$

where *c*=0,1,2 represents zero, positive and negative sequence, respectively. U_{r0}^c is the voltage before the fault on bus *r*, Z_{rq}^c is the mutual impedance between bus *r* and *q*, and I_q^c is the short-circuit current on bus *q*.

When any line *j*-*k* fails in the system, assuming that the distance between the fault point *f* to the bus *j* is *l*, $0 \le l \le 1$(per-unit value), the mutual impedance and self-impedance of point *f* to bus *r is:*

$$Z_{rf}^c = (1-l) Z_{rj}^c + l Z_{rk}^c \tag{5}$$

$$Z_{ff}^c = (1-l)^2 Z_{jj}^c + l^2 Z_{kk}^c + 2l(1-l) Z_{jk}^c + l(1-l) z_{jk}^c \tag{6}$$

where $Z_{jj}^c, Z_{kk}^c, Z_{rr}^c$ are the self-impedance of bus *j,k,r*, respectively. $Z_{rj}^c, Z_{rk}^c, Z_{jk}^c$ are the mutual impedance between each bus, and z_{jk}^c is the impedance of line *j*-*k*. The voltage amplitude on bus *r* is:

$$U_r^c = U_{r0}^c - Z_{rf}^c I_f^c \tag{7}$$

where I_f^c is the short-circuit current at the fault point *f*.

2.1.2 Evaluation of duration of voltage sags

After the fault occurs, the protection device moves out the fault components, so the sag duration is mainly determined by the time of fault clearing.

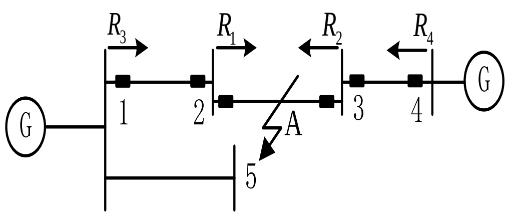

Figure 2. A power system with a protective device

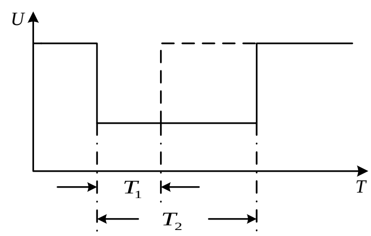

Figure 3. Voltage sags characteristics of bus 5

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System components are usually equipped with main and backup protection which cooperates with each other and have different effects on the duration of voltage sags. Figure 2 is a power system with protective devices and Figure 3 is the voltage sag characteristic curve of bus 5 in Figure 2. Assuming there is an instantaneous short-circuit fault at point A on line 2-3. When the major protects R1 and R2 take action, the voltage sag duration equal to the fault clearing time of main protection. That is, T1 in Figure 3. While R1 and R2 fail to move, R3 and R4 act and remove faults. The voltage sag duration is backup protection fault clearing time which is T2 in Figure 3.

2.1.3 Frequency calculation of voltage sags

Based on the fault point method, we divide lines into 5 segments and take piecewise analysis to determine the voltage sag frequency of a given bus voltage sag depth and duration. Let f_{Bi} and f_{Lj} represent the failure rate of bus i and line j, respectively. When the failure rate of each line is incomplete, f_{Lj} can be calculated by:

$$f_{Lj} = l_j \cdot f_{l\text{-}v} \tag{8}$$

where l_j is the length of line j, $f_{l\text{-}v}$ is the line failure rate for voltage level of v.

Assuming r is the selected bus and every sag event can be defined as [U_{BrSm}, f_{BrSm}], in which U_{BrSm} is the sag amplitude of m voltage sag event. For asymmetrical fault, Taking the lowest amplitude of a, b and c voltage as the sag amplitude. f_{BrSm} is the frequency of the event, equal to the failure rate of the fault point. If the sag at the selected bus is caused by bus i fault, f_{BrSm} is calculated by:

$$f_{BrSm} = f_{Bi} \cdot P_{i-x} \tag{9}$$

where $P_{i\text{-}x}$ is the failure rate of bus i with x type short-circuit fault. While a certain type of fault of a fault point occurs on line j, f_{BrSm} is determined by:

$$f_{BrSm} = \frac{f_{Lj}}{n} \cdot P_{j-x} \tag{10}$$

In which n is the number of segments divided by the line, $P_{j\text{-}x}$ is failure probability of line j with x type short circuit fault. After getting the voltage sag duration, every sag event at bus r can be defined as [U_{BrSm}, f_{BrSm}, t_{BrSm}] , where t_{BrSm} is the duration of the sag event.

2.2 Quantitative index system for voltage sags risk assessment

2.2.1 Evaluation index of bus voltage sags

(1) System Average root mean square value change frequency index

A statistical index $SARFI_X$ for a threshold voltage can be described as

$$SARFI_X = \frac{N \times D}{D_T} \tag{11}$$

where X is the root mean square value of voltage whose value may be 90, 80, 70, 50 or 10, etc. And it is expressed in terms of the percentage of the nominal voltage which is X%. N is the number of voltage sags or short interruptions with a voltage sag less than X% during the monitoring period. D_T is the total number of days in the monitoring period, and D is the period days of index calculation, which can be set as 30 days or 365 days, which indicates the average times of voltage sags or short-time interruption with sag amplitude less than X% in a month and a year, respectively.

The other is a statistical index $SARFI_{CURVE}$ for tolerance curves of a sensitive device, calculated by formula (12). The index indicates the sag frequency of nodes falling below the sensitive equipment tolerance curve, such as $SARFI_{CBEMA}$, $SARFI_{ITIC}$ and $SARFI_{SEMI}$

$$SARFI_{curve} = N_{undercurve} \tag{12}$$

Selecting $SARFI_{90\%}$, $SARFI_{SEMI}$ and $SARFI_{ITIC}$ into the bus risk assessment index system, where $SARFI_{90\%}$ is the number of annual expectations for bus voltage sags or short-time interruption events, and $SARFI_{SEMI}$ and $SARFI_{ITIC}$ are the annual expectations of the bus voltage sags, which lead to semiconductor process equipment and information industry equipment failures, respectively.

(2) Statistical table of voltage sags events

The voltage sag time table can be divided into voltage sag density and cumulative table, which can directly reflect the stochastic estimation results of voltage sag on the selected bus. The elements in the sags cumulative table are calculated by:

$$F_{MD}=\sum_{m=0}^{M}\sum_{d=D}^{d_{\max}} f_{md} \tag{13}$$

where f_{md} is the element in the density table, d is the number of voltage sag times with the duration range , F_{md} is the element in the cumulative table.

2.2.2 Calculation of sensitive equipment failure rate

The voltage tolerance of sensitive equipment can be described by the uncertainty area of the voltage tolerance curve of the device, as shown in Figure 4. Where U_{max},U_{min}, T_{max} and T_{min} are voltage and time threshold of the voltage tolerance curve for a sensitive device, respectively. The area between curve 1 and curve 2 represents the uncertain area of equipment outage.

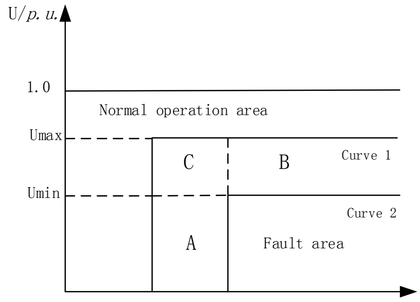

Figure 4. The uncertainty area of the voltage tolerance curve of the equipment

When the sags fall into the normal operation area, the fault probability of the sensitive load is 0, while in the fault area, the probability is 1. The probability of the outage is calculated basic on the energy loss when the sags fall into the uncertain area. It's obvious that T and U are independent random variables and satisfy the cumulative distribution probability function. So the equipment failure rate in each area can be calculated by:

$$P_1=\frac{T-T_{\min}}{T_{\max}-T_{\min}},(U,T)\in A \qquad P_2=\frac{U_{\max}^2-U^2}{U_{\max}^2-U_{\min}^2},(U,T)\in B \qquad P_3=\frac{T-T_{\min}}{T_{\max}-T_{\min}}\frac{U_{\max}^2-U^2}{U_{\max}^2-U_{\min}^2},(U,T)\in C \tag{14}$$

The number of sag events in each area is recorded as N_{normal}, $N_{uncertain}$, N_{fault}, the failure rate of sensitive equipment caused by sags every year is calculated by：

$$N=\sum_{N_{uncertain}} P_i + N_{fault} \tag{15}$$

where P_i is the sensitive equipment failure rate caused by i^{th} sag event. Bus sag risk assessment algorithm flow chart is shown in Figure 5.

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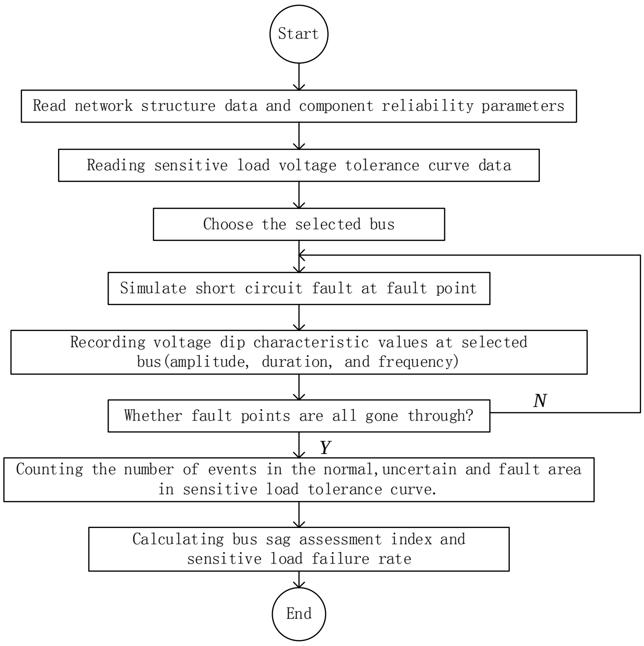

Figure 5. The flow chart for the risk assessment of the bus sags

2.3 Effect of compensation device on voltage sags

Adding voltage compensation equipment to the system or load side is an effective measure to suppress voltage sag and interruption. There are parallel voltage controller (STATCOM), series dynamic voltage restorer (DVR), or uninterruptible power supply (UPS), etc. This paper mainly discusses the compensation effect of DVR on voltage sag.

DVR is connected in series between the power supply and the sensitive load. When the system voltage is normal, DVR is by-pass while the system voltage is sags, DVR can act quickly, effectively compensate the sags, and protect the sensitive load from the effect of voltage sags. The rated voltage of DVR determines which range of amplitude and phase jump angle can be suppressed. Active demand and storage capacity determine the longest duration of the sag that can be suppressed.

Ignoring the phase jump angle, the required energy is to traverse the V with a duration of T is：

$$E = [1 - V]TP_{load} \tag{16}$$

For the sag with duration of T, the minimum amplitude of V_{min}, the available energy is:

$$E_{avail} = [1 - V_{min}]TP_{load} \tag{17}$$

For voltage tolerance curves, the following formula can be obtained:

$$V_{min} = 1 - (1 - V_0)\frac{T_0}{T} \tag{18}$$

3. Design of risk index evaluation platform for voltage sags

The function of the voltage sags risk assessment platform is evaluate the risk of bus voltage sags risk based on the reliability data of power grid elements and historical fault data, and combining with the indicators proposed by the national standard and international standard. The user needs to establish the corresponding model before the risk assessment of voltage sags, including the selection of parameters of the system topology, generators and the zero-sequence network and the drawing of the corresponding geographic wiring diagram.

3.1 Risk assessment of voltage sags - evaluation results interface

Figure 6 is a voltage sag risk assessment interface. The lower part of it shows the calculation results of the bus and related evaluation indexes selected by the user. The upper part of the interface is the ranking method of bus evaluation results based on calculation results of each index so that users can compare the evaluation indexes of multiple buses. For the selected bus, there are three options, "sag characteristic value table", "SARFI related index" and "DVR compensation capability".

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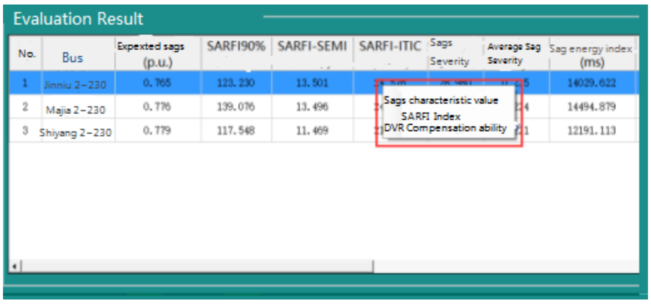
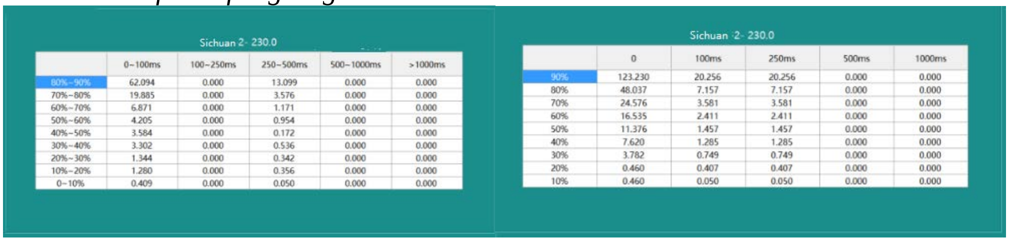


Evaluation Result

No.	Bus	Expexted sags (p.u.)	SARFI90%	SARFI-SEMI	SARFI-ITIC	Sags Severity	Average Sag Severity	Sag energy index (ms)
1	Jinniu 2-230	0.765	123.230	13.501	[illegible]	[illegible]	[illegible]	14029.622
2	Majia 2-230	0.776	139.076	13.496	[illegible]	[illegible]	[illegible]	14494.879
3	Shiyang 2-230	0.779	117.548	11.469	[illegible]	[illegible]	[illegible]	12191.113

Figure 6. Evaluation result interface

3.2 Statistical table interface of sags eigenvalue



Sichuan 2- 230.0

	0~100ms	100~250ms	250~500ms	500~1000ms	>1000ms
80%~90%	62.094	0.000	13.099	0.000	0.000
70%~80%	19.885	0.000	3.576	0.000	0.000
60%~70%	6.871	0.000	1.171	0.000	0.000
50%~60%	4.205	0.000	0.954	0.000	0.000
40%~50%	3.584	0.000	0.172	0.000	0.000
30%~40%	3.302	0.000	0.536	0.000	0.000
20%~30%	1.344	0.000	0.342	0.000	0.000
10%~20%	1.280	0.000	0.356	0.000	0.000
0~10%	0.409	0.000	0.050	0.000	0.000

Sichuan 2- 230.0

	0	100ms	250ms	500ms	1000ms
90%	123.230	20.256	20.256	0.000	0.000
80%	48.037	7.157	7.157	0.000	0.000
70%	24.576	3.581	3.581	0.000	0.000
60%	16.535	2.411	2.411	0.000	0.000
50%	11.376	1.457	1.457	0.000	0.000
40%	7.620	1.285	1.285	0.000	0.000
30%	3.782	0.749	0.749	0.000	0.000
20%	0.460	0.407	0.407	0.000	0.000
10%	0.460	0.050	0.050	0.000	0.000

Figure 7. Sags density and transient accumulative table

In left sag density table, the cell corresponding to the amplitude 70%~80% and duration 0~100ms is shown to the density of the sag within this amplitude and duration range. In right sag cumulative table, if the equipment can only withstand the sags of 80% and 250ms, the equipment will drop out average 1.47 times per year.

3.3 Voltage sags risk assessment-SARFI index interface

SARFI index include SARFI-X and SARFI-CURVE. In the “SARFI-X” statistical figure, the bar chart represents the density function of the sags amplitude and duration, each blue column represents the sags frequency of corresponding sags amplitude range. The broken line chart represents the distribution function of the sag amplitude and frequency. Each inflection point represents the sag time with the upper limit of the current amplitude range is 0. In the "SARFI-ITIC" statistics table, the red curve represents the sags part of the ITIC curve. If the sag event is inside of the ITIC curve, it means that this voltage sage will cause the fault of information industry equipment.

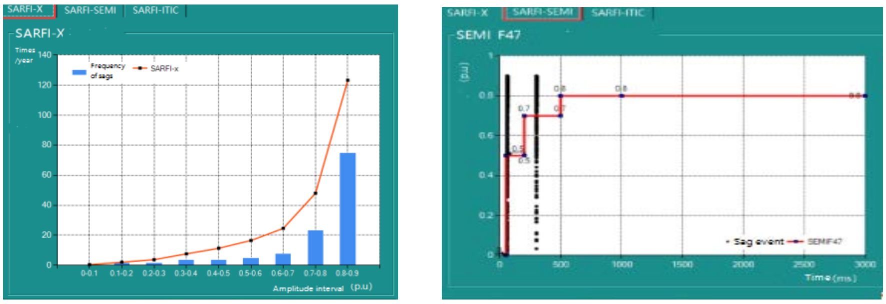


Figure 8. SARFI index interface about SARFI-X and SARFI-ITIC

4. Conclusion

In this paper, based on the reliability index of components, the bus voltage sags are estimated randomly, and the risk quantitative evaluation index system is set up based on the national standard and international standard, so as to realize the quantitative evaluation of the risk of the bus sags. The voltage tolerance curve of typical sensitive equipment is used to calculate the failure rate of the typical sensitive equipment connected to the bus due to voltage sags, which provides the basis for the access of sensitive equipment. At the same time, the compensation capability of compensation equipment is analyzed, and the measures to improve bus voltage sag are provided. The simulation platform is used to edit the failure probability of the power grid components to achieve targeted evaluation of different targets and indexes.

Acknowledgments

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