Evaluation Method and Probabilistic Index of Voltage Sag Severity Considering Point-on-wave

Guopei Wu, Qing Zhong, Qizhang He, and Zhong Xu

***Abstract*—The impact of voltage sag on sensitive devices is related to the time when the sag occurs. However, the point-on-wave of a sag is uncertain. Therefore, this paper presents a novel approach to evaluate the voltage sag severity considering a random point-on-wave. First, the uncertainty of equipment malfunction is revealed. Second, under a given residual voltage, the relationship between the point-on-wave and the duration that the device can withstand is described with a fitting curve. Third, a voltage sag probabilistic index is proposed to describe the severity. The evaluation procedure is also presented. Finally, three types of releasers are tested and analyzed to determine the effectiveness of the proposed method. The evaluation method can help instruct electrical engineers establish more well-grounded sag mitigation proposals.**

***Index Terms*—Voltage sag, evaluation method, severity index, probabilistic index.**

I. Introduction

VOLTAGE sag is defined as a decrease of between 0.1 and 0.9 p.u. in root mean square (RMS) voltage or current at the power frequency for a duration of 0.5 cycle to 1 min [1]. Voltage sag often leads to equipment malfunction, substantial economic losses, and even casualties, causing increasing concern [2], [3]. In order to assure optimal operation of production lines, it is critical to evaluate the voltage sag severity of a supply system so that specific mitigation proposals can be designed. The severity of voltage sag is determined by characteristics such as residual voltage, duration, and point-on-wave [4]-[6]. Moreover, the performance during a voltage sag varies as the sag characteristics change, which poses a problem for sag mitigation. The equipment may also have different sensitivities to voltage sag. Thus, it is crucial to establish an evaluation method of voltage sag severity.

The voltage sag severity is co-determined by factors including the sag type, residual voltage amplitude, duration, reclosing time, and sensitivity of the electrical equipment. Existing studies on voltage sag severity indices mainly focus on residual voltage and duration. Other voltage sag characteristics are seldom mentioned in most of the literature. A few studies consider the existing standards and define a voltage severity index by comparing the residual voltage or duration value with a reference value, considering equipment sensitivity. In [7], the relationship among multiple voltage sag magnitudes and cumulative durations is demonstrated by establishing a voltage duration curve. The researcher put forward a voltage sag severity index by superposing the sensitivity of multiple voltage sag duration intervals. In [8], the IEEE Std 1564-2014 Guide for voltage sag indices is used to assess voltage sag severity. In [9], voltage sags are identified by using a stochastic approach based on simulation results. An index is proposed considering sag frequency, residual voltage, and duration, which is used to identify the weak areas of the network that are exposed to disruptive voltage sags. Some studies have proposed a comprehensive index considering the power system and consumer equipment [10]-[12]. However, the behavior of certain equipment is affected by the point-on-wave in addition to the residual voltage sag magnitude and duration [13]. The assessment will be more precise if more influential sag characteristics are considered. Moreover, the equipment performs differently under various voltage sags, which leads to uncertainty in equipment malfunction [14]. To account for this uncertainty, various methods have been used to evaluate equipment sensitivity to voltage sag, including probabilistic methods [15], [16] and fuzzy logic [17]. Probabilistic methods possess the advantages of less computation and straightforward results and are exploited to evaluate voltage sag severity.

This paper first analyzes the uncertainty of equipment malfunction under voltage sag. The relationship between the point-on-wave and duration is revealed and fitted as a function based on an abundance of test data. With the fitting function, a probabilistic index for voltage sag severity is proposed to evaluate the effect of voltage sag on sensitive devices. Three kinds of ABB releasers are tested and analyzed to verify the effectiveness of the evaluation method. The method contributes to assessing voltage sag severity considering the point-on-wave and can be applied to design reasonable sag mitigation schemes.

II. Uncertainty of Equipment Malfunction

The point-on-wave refers to the phase angle where instantaneous voltage begins to experience voltage sag. The point-on-wave of voltage sag initiation is the primary characteristic of voltage sag. It exerts considerable influence on the sen-

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sitivity of certain equipment, especially the operation of equipment that relies on the influence of timing [18]. When the point-on-wave is fixed, the dip immunity of equipment can be characterized by the voltage tolerance curve (VTC) [19], [20]. The VTC changes when the point-on-wave varies. A cluster of VTCs can be obtained based on experimental data. In general, the sensitivity of equipment can be described by three regions: operation, malfunction, and uncertainty, as shown in Fig. 1. U_{max} and U_{min} are the residual voltage magnitude thresholds, and T_{max} and T_{min} are the duration thresholds. The equipment performs well in the operation region and trips in the malfunction region. However, equipment performance is unclear in the region of uncertainty, because the VTCs may appear anywhere in the region [19].

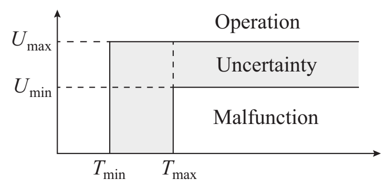

Fig. 1. Diagram of VTCs.

The equipment malfunction probability, which reflects the voltage sag severity, is determined by voltage sag immunity. The voltage sag immunity of equipment can be described by the residual voltage magnitude thresholds and duration thresholds under a fixed point-on-wave. However, under-estimation or over-estimation may occur if the region of uncertainty is too small or too large, as shown by shaded areas in Fig. 2.

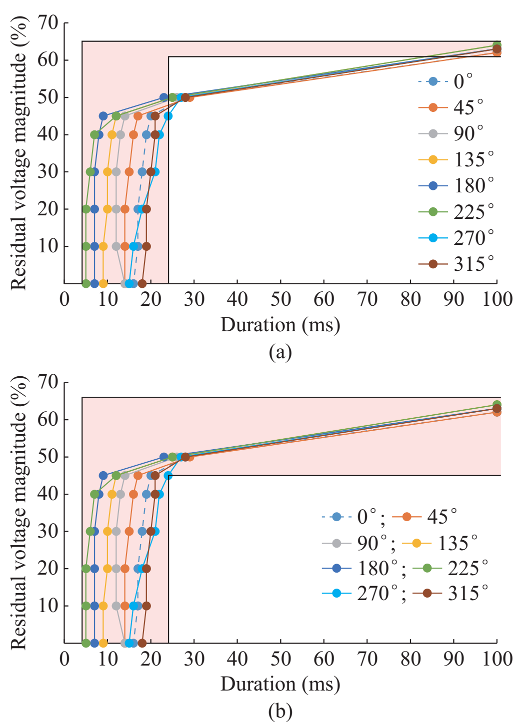

Fig. 2. Estimation of uncertainty region. (a) Under-estimation of uncertainty region. (b) Over-estimation of uncertainty region.

Moreover, the point-on-wave ranges from 0° to 360°, and the point-on-wave where the sag occurs is uncertain. These uncertainties make it difficult to evaluate voltage sag severity. Therefore, this paper puts forward an evaluation method and index considering the uncertainty of equipment voltage sag immunity and point-on-wave. The point-on-wave is difficult to acquire directly in most cases when the duration is recorded by monitoring devices. By means of fitting experimental test results, the relationship between the point-on-wave and duration under a fixed residual voltage can be obtained. Assuming that the point-on-wave is a random variable, the equipment malfunction probability can be described by the integral of the probability density function of the point-on-wave under a fixed residual voltage when the duration is known. The equipment malfunction probability contributes to assess the voltage sag severity.

III. Voltage Sag Severity Evaluation

A. Probabilistic Index of Voltage Sag Severity

Previous research [21] has found that the relationship between the duration threshold and point-on-wave of initiation under a fixed residual voltage exhibits a periodic characteristic. The relationship between point-on-wave θ and duration threshold T can be expressed by a continuous function $T=g(\theta)$. When the point-on-wave varies between 0° and 360°, most duration threshold values will repeat twice. Therefore, two points-on-wave of initiation θ_1 and θ_2 can be calculated when the duration threshold is known under a fixed residual voltage. When the residual voltage and sag duration are given, if the point-on-wave is between θ_1 and θ_2, the device will malfunction. Thus, a probabilistic index I_P is proposed to evaluate the voltage sag severity. I_P is defined as the probability that the point-on-wave is between θ_1 and θ_2, as expressed in (1).

$$I_P=\int_{\theta_1}^{\theta_2} f(\theta)\mathrm{d}\theta\times 100\% \tag{1}$$

where $f(\theta)$ is the probability density function of the point-on-wave derived from statistical analysis on the grid side. θ_1 and θ_2 ($\theta_1<\theta_2$) can be obtained when the duration threshold and $T=g(\theta)$ are given. Thus, the I_P can represent the probability of equipment malfunction under a fixed residual voltage and duration.

B. Evaluation Procedure of Voltage Sag Severity

The evaluation procedure of the voltage sag severity is illustrated in Fig. 3, which can be described as follows.

1) Set up the voltage tolerance test platform and obtain test results for various points-on-wave of initiation under a fixed residual voltage.

2) Fit experiment data to approximate the relationship between the point-on-wave and duration threshold with a mathematical function $T=g(\theta)$ by means of the least squares method.

3) Calculate the I_P according to (1), assuming that the point-on-wave is subjected to a certain probability distribution.

IV. Case Study

A. Voltage Tolerance Test

A voltage tolerance test platform is established in this paper. An Ametek MXII-45, which can generate three-phase symmetric and asymmetric voltage, is adopted as the sag generator.

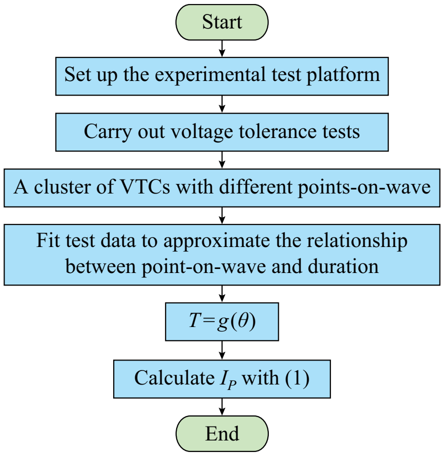

Fig. 3. Evaluation procedure of voltage sag severity.

Its rated capacity is 45 kVA, and its voltage output ranges from 0 V to 300 V. When the equipment trips, it is considered to be disturbed by the voltage sag. When the RMS value of input current decreases to 0.1 A and cannot recover in 1 min, the equipment fails in the test.

Three types of releasers C20, C32, and C50 are tested with the experimental platform for more than 4000 times, whose parameters are given in Table I. The voltage tolerance test data of these releasers are presented in Appendix A Tables AI-AIII, where M and D represent the magnitude and duration, respectively. The releaser is a component of a low-voltage breaker that can make the breaker trip if the input voltage drops below a certain value.

TABLE I
General Information of Tested Releasers

Type	Rated current (A)	Operation voltage (V)		Rated frequency (Hz)		Actuator type
		AC	DC	AC	DC	
C20	20	72-253	12-72	50	60	Insulation group II, black, sealable
C32	32	12-440	12-440	50	60	Insulation group II, black, sealable
C50	50	12-440		50	60	Toggle

The test procedure is described as follows.

Step 1: the initial residual voltage magnitude is set to be 0.9 p.u., and the initial point-on-wave is 0°.

Step 2: the moment when the equipment failed to pass the test is recorded. If the equipment passes the test, the recorded value is 1 s.

Step 3: the point-on-wave is changed from 0° to 315° with steps of 45° . *Step 2* is repeated.

Step 4: the residual voltage magnitude is changed from 0 to 0.9 p.u. with steps of 0.05 p.u.. *Step 2* and *Step 3* are repeated. To achieve greater detail, the step of the residual voltage magnitude change can be reduced.

More than 800 pieces of data are obtained. VTCs of the three types of releasers at different points-on-wave are shown in Fig. 4.

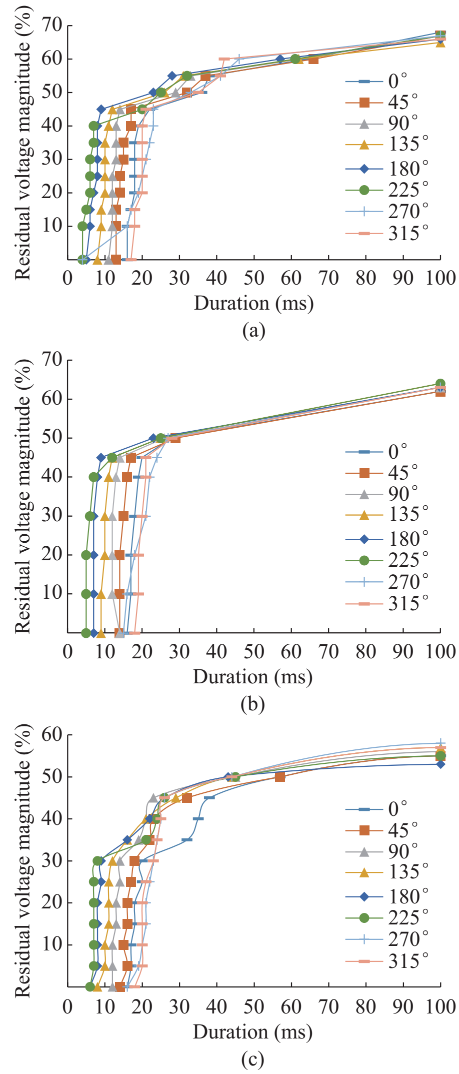

Fig. 4. VTCs of tested releasers at different points-on-wave. (a) VTCs of C20. (b) VTCs of C32. (c) VTCs of C50.

B. Calculation of I_P

A C32 releaser is taken as an example, and its test result under 30% residual voltage is shown in Fig. 5. In order to simplify the mathematical expression, the data from 285° to 360° are shifted to 0°, and the corresponding starting angle is subtracted by 360°.

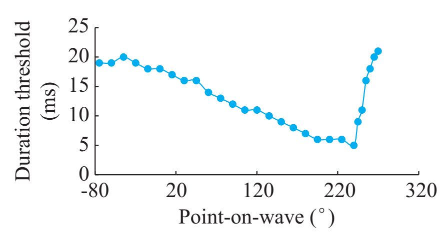

Fig. 5. Point-on-wave and duration threshold curve under 30% residual voltage.

Taking 225° as the dividing point, the left and right curves are linearly fitted by the least square method. The piecewise function $T=g(\theta)$ is defined as (2).

$$T=\begin{cases}-0.0519\theta+16.85 & -75°\le\theta<225° \\ 0.382\theta-82.44 & 225°\le\theta\le 285°\end{cases} \tag{2}$$

Assuming that the point-on-wave is subjected to a uniform distribution between −75° and 285°, the probability density function of the point-on-wave could be calculated as $f(\theta)=1/360$. Therefore, I_P should be calculated with (3).

$$I_P=\frac{\theta_2-\theta_1}{360}\times 100\% \tag{3}$$

For example, θ_1 is 131.98° and θ_2 is 268.17° when T = 10 ms under 30% residual voltage. The corresponding I_P can be calculated and is equal to 37.83%. The I_P with 30% residual voltage (uniform distribution) is shown in Fig. 6.

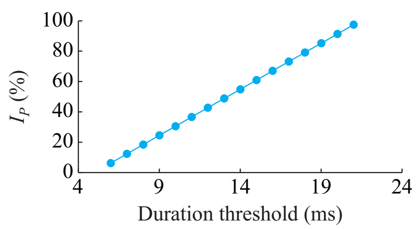

Fig. 6. I_P with 30% residual voltage (uniform distribution).

Assuming that the point-on-wave is subjected to a normal distribution, both the median and standard deviations are 90. I_P should be calculated as (4).

$$I_P=\int_{\theta_1}^{\theta_2}\frac{1}{90\times\sqrt{2\pi}}\mathrm{e}^{-\frac{(\theta-90)^2}{2}\times 8100}\mathrm{d}\theta\times 100\% \tag{4}$$

I_P with 30% residual voltage (normal distribution) is shown in Fig. 7. I_P varies when the point-on-wave is subjected to different distributions. If the residual voltage and duration threshold are known and the probability distribution of the point-on-wave is given, I_P can describe the probability of device malfunction. The larger the I_P, the higher the probability of device malfunction.

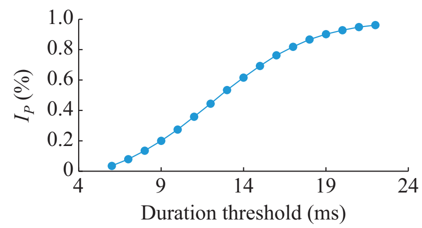

Fig. 7. I_P with 30% residual voltage (normal distribution).

In reality, only residual voltage data and duration data are recorded, whereas the information about the point-on-wave is typically unavailable. The sensitivity of equipment can be fully and precisely assessed when the point-on-wave is included in the analysis.

V. Conclusion

A probabilistic index calculation method of voltage sag severity is proposed to evaluate the effect of voltage sag on sensitive equipment. The relationship between the point-on-wave and duration threshold is determined by a mathematical function based on test results. The voltage sag I_P is then calculated using the probabilistic density function of the point-on-wave. Three types of releasers are chosen to verify the effectiveness of the method. The evaluation results are beneficial for further analyzing the seriousness of voltage sag and putting forward schemes for voltage sag mitigation.

The evaluation method is based on voltage tolerance tests. Therefore, considerable field/laboratory tests should be performed to support the application of the method. Furthermore, more sag characteristics should be considered to accurately assess the voltage sag severity.

Appendix A

TABLE AI
Voltage Tolerance Test Data of C20 Releaser

$\theta=0°$		$\theta=45°$		$\theta=90°$		$\theta=135°$		$\theta=180°$		$\theta=225°$		$\theta=270°$		$\theta=315°$	
M (%)	D (ms)	M (%)	D (ms)	M (%)	D (ms)	M (%)	D (ms)	M (%)	D (ms)	M (%)	D (ms)	M (%)	D (ms)	M (%)	D (ms)
70	1000	68	1000	68	1000	66	1000	66	1000	68	1000	68	1000	66	1000
68	100	67	100	67	100	65	100	66	100	67	100	67	100	66	100
60	64	60	66	60	62	60	62	60	57	60	61	60	46	60	42
55	38	55	37	55	33	55	31	55	28	55	32	55	41	55	41
50	36	50	32	50	29	50	26	50	23	50	25	50	33	50	35
45	22	45	17	45	14	45	12	45	9	45	20	45	23	45	21
40	19	40	17	40	13	40	11	40	8	40	7	40	23	40	20
35	18	35	15	35	13	35	10	35	8	35	7	35	22	35	20
30	18	30	15	30	13	30	10	30	8	30	6	30	21	30	20
25	18	25	14	25	12	25	10	25	8	25	6	25	20	25	20
20	18	20	14	20	12	20	10	20	7	20	6	20	19	20	20
15	17	15	13	15	12	15	9	15	6	15	5	15	17	15	18
10	16	10	13	10	12	10	9	10	6	10	4	10	16	10	18
0	16	0	13	0	11	0	8	0	5	0	4	0	4	0	17

TABLE AII
VOLTAGE TOLERANCE TEST DATA OF C32 RELEASER

$\theta=0°$		$\theta=45°$		$\theta=90°$		$\theta=135°$		$\theta=180°$		$\theta=225°$		$\theta=270°$		$\theta=315°$	
M (%)	D (ms)	M (%)	D (ms)	M (%)	D (ms)	M (%)	D (ms)	M (%)	D (ms)	M (%)	D (ms)	M (%)	D (ms)	M (%)	D (ms)
63	1000	63	1000	65	1000	65	1000	64	1000	64	1000	63	1000	63	1000
62	100	62	100	63	100	64	100	63	100	64	100	63	100	63	100
50	28	50	29	50	26	50	25	50	23	50	25	50	27	50	28
45	20	45	17	45	14	45	12	45	9	45	12	45	24	45	21
40	19	40	16	40	13	40	11	40	8	40	7	40	22	40	21
30	18	30	15	30	12	30	10	30	7	30	6	30	21	30	20
20	17	20	14	20	12	20	10	20	7	20	5	20	18	20	19
10	17	10	14	10	12	10	9	10	7	10	5	10	16	10	19
0	16	0	14	0	14	0	9	0	7	0	5	0	15	0	18

TABLE AIII
VOLTAGE TOLERANCE TEST DATA OF C50 RELEASER

$\theta=0°$		$\theta=45°$		$\theta=90°$		$\theta=135°$		$\theta=180°$		$\theta=225°$		$\theta=270°$		$\theta=315°$	
M (%)	D (ms)	M (%)	D (ms)	M (%)	D (ms)	M (%)	D (ms)	M (%)	D (ms)	M (%)	D (ms)	M (%)	D (ms)	M (%)	D (ms)
55	1000	55	1000	57	1000	57	1000	55	1000	55	1000	58	1000	57	1000
55	100	55	100	56	100	57	100	53	100	55	100	58	100	57	100
50	57	50	57	50	45	50	44	50	43	50	45	50	44	50	44
45	38	45	32	45	23	45	29	45	26	45	26	45	26	45	26
40	35	40	23	40	21	40	21	40	22	40	24	40	25	40	25
35	32	35	22	35	19	35	16	35	16	35	21	35	24	35	24
30	20	30	18	30	14	30	12	30	9	30	8	30	23	30	23
25	20	25	17	25	14	25	11	25	9	25	7	25	22	25	21
20	18	20	16	20	13	20	11	20	8	20	7	20	21	20	20
15	18	15	16	15	13	15	11	15	8	15	7	15	21	15	20
10	17	10	15	10	12	10	10	10	8	10	7	10	20	10	20
5	17	5	16	5	12	5	10	5	8	5	7	5	19	5	20
0	16	0	14	0	12	0	8	0	6	0	6	0	16	0	18

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