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Identification of Weak Areas of Power Network based on Exposure to Voltage Sags — Part I: Development of Sag Severity Index for Single-event Characterization

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Abstract—This paper presents new single-event characteristic, sag severity index (SSI) derived with respect to equipment sensitivity to voltage sags. It is more inclusive of associated uncertainties/variation in equipment response to voltage sags than existing sag severity indices. By changing parameter settings the index appropriately accounts for sag duration and adequately addresses the variation in equipment sensitivity. The value of the index changes continuously at the joining regions of different sag severity levels and reflects realistically the sensitivity trend of equipment embedded in voltage tolerance curves. The properties of the SSI are analysed and discussed through comparison with characteristics of five previously reported single-event indices including four numerical indices and one fuzzy voltage sag index.

Index Terms—Voltage sags, equipment susceptibility, voltage tolerance curves, sag severity index.

I. INTRODUCTION

Voltage sags result in substantial financial losses to many utilities and industries, due to the frequent disruptions to industrial processes and malfunction of electronic equipment [1]. This issue is one of the most critical power quality problems, and sag severity assessment has been a focal point for many researchers in the area of Power Quality in the past. As a critical step of mitigation planning, it is necessary to assess the severity of voltage sags accurately.

The severity of voltage sags is strongly related to the response of equipment to voltage sags. Therefore, in order to accurately evaluate the impact of voltage sags, the sensitivity of equipment and ultimately industrial processes to voltage sags must be known. The sensitivity curves of specific equipment have been intensively investigated [2-4], and a number of international standards have been set up to provide guidelines for system/tool design in terms of ride-through capability to voltage sags, such as the voltage tolerance curves recommended in IEEE 1346 [5]. From the customers' and equipment manufacturers' perspective, step-shaped ITIC curve [6], a successor of CBEMA curve, was proposed and

recommended for use after extensive research in computer power supplies. More recently proposed SEMI F47 curve/standard with similar step-shaped curve was proposed to specify the design requirements of minimum voltage sag ride-through capability for equipment used in semiconductor industry [7]. This standard provides a target for the facility and utility systems, and it has been used to strictly guide the design of semiconductor processing, metrology, and automated test equipment. In IEEE Standard 1564, ITIC and SEMI F47 are recommended as reference curves to calculate voltage sag severity [8]. In the absence of accurate, specific equipment and process sensitivity curves to voltage sags, standards ITIC and SEMI can be, and generally are used to approximate the response of equipment and industrial processes to voltage sags from the perspective of utility side, equipment manufactures and customers in distribution networks [8-11].

A number of single-event characteristics have been proposed to assess the severity of voltage sags in literature. Voltage sag energy was proposed based on retained voltage and duration by calculating energy during voltage sags [12, 13]. Lost energy is used to evaluate the severity of voltage sags by calculating the energy that was not delivered by the system to the load during a voltage sag [14]. Voltage sag severity is defined based on residual voltage and duration of a voltage sag by comparing their values with a reference curve [15-17]. More recently in [18], two indices Magnitude Severity Index (MSI) and Duration Severity Index (DSI) were proposed to represent the magnitude and duration severity respectively, and served as input parameters for different assessment approaches. Magnitude-Duration Severity Index (MDSI) uses single numerical value, by combining MSI and DSI, to represent the failure risk of equipment when subjected to voltage sags. The efficiency of MDSI has been demonstrated in [19]. In [20], a sag severity index was introduced based on calculating the missing voltage-time area of a sag. The numerical indices mentioned above were derived using mathematical formulae, which are straightforward and easy to apply. Apart from these numerical indices, voltage sag indices based on fuzzy logic approaches were also proposed [10, 21, 22]. The membership functions in these indices are designed based on the information embedded in voltage

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tolerance curve/standard. In [23], fuzzy methods are used to assess sag severity while taking MSI and DSI as input parameters. It is shown that fuzzy logic methods require significant computational power and they might not be suitable for large scale assessments, i.e. network level assessment. Most recently, a sag detection and assessment in terms of magnitude and duration was proposed based on spectral energy of phase voltages instead of rms-based methods [24]. Although many indices were proposed to assess the severity of voltage sag events, only a few of them take the sensitivity of equipment to sag events into account. Incorporation of voltage tolerance curves (especially the step-shaped curves/standards that are widely-used in computer and semiconductor industry) into sag severity assessment still needs more research, considering that multiple interconnected equipment is typically exposed to sags occurring at a bus and more importantly having in mind that the ultimate measure of sag severity is not electrical equipment but industrial process failure due to a sag.

Individual susceptibility curve cannot represent all cases of equipment sensitivity [5], as the equipment/process sensitivity to voltage sags is influenced by a number of factors, e.g. the equipment involved, its composition ratio, the interconnections of equipment involved, and the process operating regime. Even equipment of the same type would respond to voltage sags differently [19]. As stated in IEEE Standard 1346 [5], there is a threshold range for equipment where its response to voltage sags varies. Further studies have confirmed that the range of variation cannot be neglected when referring to equipment susceptibility [3, 4]. In literature, probabilistic theory has been applied to represent the variation in equipment sensitivity in the past [25-27]. However, for the aforementioned sag severity indices, the variation of equipment sensitivity is not taken into account for assessment.

This paper proposes a new Sag Severity Index (SSI) based on generally accepted and widely used voltage sag tolerance curves of equipment. It reflects the sensitivity trend of equipment response to voltage sags and allows gradual transition from one severity level to another with adjustable steepness of contour lines at the joint region of the two severity levels. The properties of the proposed SSI are analysed through comparison with several numerical and fuzzy sag indices proposed in the past. In this paper, the variation of equipment sensitivity is taken into account by introducing a set of voltage sag tolerance curves which are normally distributed around the standard voltage sag tolerance curve. The mean of the SSI obtained by the set of tolerance curves is used to represent the final sag severity index. The paper introduces two new concepts: i) New single-event characteristic SSI derived based on equipment sensitivity, i.e. voltage sag tolerance curves; ii) probabilistic assessment of sag severity by taking into account the variation of the voltage sag tolerance curves.

The paper is organised as follows: The Sag Severity Index is introduced in Section II. The properties of SSI are analysed and compared with four numerical single-event characteristics [19] and one fuzzy voltage sag index [10, 22] in Section III.

Section IV presents major conclusions of the paper.

II. SAG SEVERITY INDEX

A. Derivation of SSI

The standard voltage tolerance curve SEMI F47 (marked by red solid line) adopted from [7] is shown in Fig. 1. Since the clearing time by protection relays is less than 1s, and the majority of sags are caused by faults and cleared by protection relays, the sag duration within the range of [0, 1] only is considered in the study. In Fig. 1, the area covered by the voltage tolerance curve (i.e. the area in grey) represents sag susceptibility area. T_x represents the x -th duration range. In Fig. 1, there are three duration ranges along the t -axis beginning from 0.02s to 1s.

Fig. 1. Illustration of sag susceptibility area.

The proposed SSI represents the severity of voltage sags in terms of magnitude and duration based on equipment sensitivity. A voltage sag event is defined as a triplet $\langle f_{Bij}, v_{Bij}, t_{Bij} \rangle$, where the subscripts j and i denote the j -th sub-sag occurring at bus i ; f_{Bij} denotes the sag occurrence frequency (to be used in assessment of single-site index regarding voltage sags); v_{Bij} denotes sag magnitude; and t_{Bij} denotes duration of sag, i.e., the duration the voltage sag magnitude stays below a threshold assuming rectangular voltage sag with constant sag magnitude. Voltage sag magnitude and duration are obtained from conventional short circuit simulations carried out in DigSILENT/PowerFactory. In case of non-rectangular voltage sags the rms sag envelope can be decomposed into a series of magnitude and duration pairs sampled from the envelope using multiple magnitude-duration function [11]. Each pair would then be evaluated individually and the one with highest SSI used as the final SSI. This, however, will increase computational burden if a high frequency of sampling is applied. Measurement/detection of sags using PQ monitors [28-31], i.e., calculation of sag magnitude and duration based on measurements, is not in the scope of this study. SSI is developed for sag simulation studies rather than sag measurement/monitoring, and a single representative pair of sag characteristics, i.e., sag magnitude and duration, is used to represent a voltage sag in the study.

For given sag magnitude and duration SSI=0 if the corresponding sub-sag is in the non-susceptibility area, i.e., the area above the voltage tolerance curve; if the sag is in the susceptibility area, SSI is calculated as:

$$SSI_{Bij}^{C_w} = \left(\sum_{x=1}^{y-1} a x \times \frac{v_{\max}(T_x) - v_{Bij}}{v_{\max}(T_x) - v_{\min}(T_x)} \right) + a y \times \frac{v_{\max}(T_y) - v_{Bij}}{v_{\max}(T_y) - v_{\min}(T_y)} \times \left(\frac{t_{Bij} - T_{\min}(T_y)}{T_{\max}(T_y) - T_{\min}(T_y)} \right)^{b y - 1} \quad (1)$$

where $a=3$ and $b=\frac{1}{2}$; C_w refers to the sag tolerance curve used for assessment. Variable y denotes the index of duration range

the sag belongs to, and x denotes the indices of duration ranges which are less than y . For example, voltage sag with magnitude 0.6 p.u. and duration 0.6 s will be in the third duration range (T_3) of the duration-magnitude space in Fig. 1. In this case, $y=3$, while x ranges from 1 to 2. $V_{\max}(T_x)$ and $V_{\min}(T_x)$ denote the maximum and minimum voltage of the susceptible region within duration range T_x , respectively. $T_{\max}(T_x)$ and $T_{\min}(T_x)$ denote maximum and minimum duration (boundaries) of the range T_x , respectively. Coefficient a is used to control the difference between the SSI values estimated from sags located in different duration ranges. The larger the coefficient a is, the larger the difference between SSI estimated from different duration ranges is. The first term of (1) adjusts the difference between SSI values estimated from different duration ranges and ensures that for a given sag magnitude SSI gradually increases as sag duration increases. Coefficient b adjusts the rate of increase of SSI as sag duration increases within duration range T_y . For a given y , the smaller the coefficient b ($b < 1$) is, the smaller b^{y-1} ($b^{y-1} < 1$) is. With $\frac{t_{Bij}-T_{\min}(T_y)}{T_{\max}(T_y)-T_{\min}(T_y)} \leq 1$ and $b^{y-1} < 1$, smaller b^{y-1} , i.e., smaller exponent for $\left(\frac{t_{Bij}-T_{\min}(T_y)}{T_{\max}(T_y)-T_{\min}(T_y)}\right)$, results in larger increasing rate of SSI at the beginning of a duration range and smaller increasing rate of SSI at the end of a duration range. This will be further discussed in Section III. B. Furthermore, even with a fixed b , the increasing rate of SSI in different duration ranges varies due to the use of b^{y-1} . As y ($y \geq 1$) increases, b^{y-1} ($b^{y-1} < 1$) decreases. With smaller b^{y-1} , the increasing rate of SSI at the beginning of duration range T_3 is larger than that of T_1 and T_2 , and is smaller at the end of the duration ranges compared to that of T_1 and T_2 .

The contour colour map of SSI estimated using (1) is presented in Fig. 2, where the more affected areas are marked in red, and the areas which are not subject to potential voltage sag interference are marked in light blue. In this figure, the standard voltage tolerance curve can still be observed vaguely. This representation accounts for the variation associated with equipment sensitivity to voltage sags defined by a single tolerance curve. In reality the boundary between an equipment trip and ride through cannot be defined by a crisp line due to many factors influencing equipment sensitivity to voltage sags [21]. SSI accurately describes gradual transition from one severity level to another, which will be further discussed and illustrated in Section III. A. The joint regions between two neighbouring duration ranges can be easily identified. The colour enhancement around the joint regions suggests that another duration range having higher severity level is present.

SSI is suitable for reflecting the severity of voltage sags based on voltage tolerance curves which have step-shaped characteristics. It approximates the sensitivity trend embedded in existing standards/curves. It can be used to calculate single-event characteristics in distribution networks from the perspective of utilities, equipment manufactures and customers, as a part of the five-step procedure proposed in IEEE Standard 1564 [8, 17]. If voltage tolerance curves are not in step-shaped formats (e.g., the typical ride through curves given in [32], including CBEMA, ASDs and Contactors), SSI works equally well by treating the whole

curve as one duration range.

Fig. 2. Colour contour map of SSI using (1) with $a=3$ and $b=\frac{1}{2}$.

1) SSI with Smooth Joint Borders

To present the flexibility and capability of SSI, (1) is modified to:

$$SSI_{Bij}^{Cw} = \left(\sum_{x=1}^{y-1} ax \times \frac{V_{\max}(T_x) - v_{Bij}}{V_{\max}(T_x) - V_{\min}(T_x)} \right) + ay \times \frac{V_{\max}(T_y) - v_{Bij}}{V_{\max}(T_y) - V_{\min}(T_y)} \times \left(\frac{t_{Bij} - T_{\min}(T_y)}{T_{\max}(T_y) - T_{\min}(T_y)} \right)^{\frac{1}{1+0.2(y-1)}} \quad (2)$$

which is almost the same as (1), except that a is set to 2 and the term $\left(\frac{1}{2}\right)^{y-1}$ in (1) is replaced with $\frac{1}{1+0.2(y-1)}$. Using smaller setting for coefficient a , (2) reduces the difference between the estimated SSI values for sags located in different duration ranges. When $y=1$, $\frac{1}{1+0.2(y-1)} = \left(\frac{1}{2}\right)^{y-1}$, which means that the increasing rate in T_1 would be the same for (1) and (2) if the same a is used. If $y > 1$, $\frac{1}{1+0.2(y-1)} > \left(\frac{1}{2}\right)^{y-1}$ therefore, unlike the rapid growth at increasing rate at the beginning of T_2 and T_3 in case of (1), equation (2) reduces the increasing rate of estimated SSI values at the beginning of a duration range and has a relatively steady increasing rate within a duration range, due to the use of larger exponent for $\left(\frac{t_{Bij}-T_{\min}(T_y)}{T_{\max}(T_y)-T_{\min}(T_y)}\right)$. The colour contour map obtained from (2) is presented in Fig. 3. Compared to Fig. 2, it can be seen from Fig. 3 that the steep slope at the joint region between two neighbouring duration ranges is softened in this case, and the increasing rate of SSI is relatively steady. In Fig. 3, the standard voltage tolerance curve can also be observed vaguely. Given the flexibility of SSI, the coefficients can be adjusted according to specific cases in practical applications.

Fig. 3. Colour contour map of SSI using (2) with $a=2$.

B. Accounting for Uncertainty/Variation of Voltage Tolerance Curve

The single voltage tolerance curve cannot represent the susceptibility of all equipment [5], as it could be affected by a number of variables. To model this variation, a probabilistic model of voltage sag tolerance curves is given, as shown in

Fig. 4, where the solid line marked in red represents the standard voltage tolerance curve SEMI F47. The three red solid dots, (t_1, v_1) , (t_2, v_2) and (t_3, v_3) in Fig. 4, represent the main characteristic of the voltage tolerance curve. Their location determines the characteristic knee points of the voltage tolerance curve. To account for uncertainty/variation in equipment tolerance to voltage sags the knee points of voltage tolerance curve are randomly located by varying their t -axis and v -axis values according to preset normal distributions whose means and coefficients of variation are given. In this way, a number (denoted by W) of normally distributed voltage tolerance curves are generated within the variation area (i.e. the green shaded area in Fig. 4) with the mean values corresponding to standard voltage tolerance curve (i.e. the red solid line in Fig. 4). Since the sag duration within the range of $[0, 1]$ only is considered in the study, the variation area whose duration is less than 1 is highlighted in Fig. 4. In a specific application, the curves can be selected according to actual equipment sensitivity curve depending on the voltage tolerance of equipment connected to the bus.

With W voltage tolerance curves, W values of SSI_{Bij} are obtained for each sag event $\langle f_{Bij}, v_{Bij}, t_{Bij} \rangle$ based on (1) or (2). The mean of the W values is taken as the final single-event characteristic, denoted as SSI_{Bij}^M :

$$SSI_{Bij}^M = \frac{1}{W} \sum_{w=1}^W SSI_{Bij}^{C_w} \quad (3)$$

This index represents the severity of the sag while taking into account the variation of voltage tolerance curves. The reasons for using mean values for defining SSI_{Bij}^M , rather than the most probable values, are discussed in Section III. C.

Fig. 4. Probabilistic model of voltage tolerance curves.

III. CASE STUDIES

A. SSI Compared to MDSI [12]

Given a voltage tolerance curve, the severity of voltage sags can be assessed with respect to their magnitude and duration. Considering the purpose of sag severity assessment, SSI is expected to meet the following requirements:

1. According to if-else rule applied to represent the severity of sag events [10, 21-23], the sags which have long duration and small voltage magnitude are classified as severe sags, i.e., the SSI of this type of sags is high; for the sags which have short duration or high voltage magnitude, SSI is low; otherwise, the SSI is medium. Based on these rules, the severity index should reflect approximately the sensitivity trend of equipment to sags, i.e. the distribution of severity levels shown in Fig. 5.

2. For any straight line selected in the magnitude-duration space of Fig. 5, the SSI value should vary continuously along the line and ensure gradual transition from one severity level

to another in order to appropriately reflect disturbance severity [10]. In other words, when infinitely approaching a point from different directions, the obtained SSI values should be equal. This is to ensure the continuity of SSI index in the magnitude-duration space.

Magnitude duration severity index (MDSI) [19] and SSI are therefore analysed based on the two aforementioned requirements.

Fig. 5. Illustration of severity levels in susceptible area.

Assuming a sag event is within the susceptible area, MDSI can be obtained by:

$$MDSI = 100 \times \frac{(t - t_{\min})}{(t_{\max} - t_{\min})} \times \frac{(v_{\max} - v)}{(v_{\max} - v_{\min})} \quad (4)$$

where $t \in [t_{\min}, t_{\max}]$ and $v \in [v_{\min}, v_{\max}]$. When MDSI is applied to the voltage tolerance curves as given in Fig. 1, there are two possible cases regarding parameter settings:

- Case 1: The setting of $t_{\min}$ and $t_{\max}$ varies when duration t locates in different duration ranges as shown in Fig. 1. For instance, if t is within T_1 , the parameters of (4) are set to $t_{\min} = 0.02$, $t_{\max} = 0.2$, $v_{\min} = 0.1$ and $v_{\max} = 0.5$; if t is within the duration range of T_2 , parameters are set to $t_{\min} = 0.2$, $t_{\max} = 0.5$, $v_{\min} = 0.5$ and $v_{\max} = 0.7$; the same rule applies to t located in T_3 .
- Case 2: The setting of $t_{\min}$ and $t_{\max}$ remains the same no matter which duration range the duration t is within. For instance, if t is within T_1 , parameters are set to $t_{\min} = 0.02$, $t_{\max} = 1$, $v_{\min} = 0.1$ and $v_{\max} = 0.5$; if t is within T_2 , parameters of (4) are set to: $t_{\min} = 0.02$, $t_{\max} = 1$, $v_{\min} = 0.5$ and $v_{\max} = 0.7$; the same rule applies to t located in T_3 .

Three dot-dashed blue lines ($v=0.4$, $v=0.6$ and $v=0.75$) are selected from the magnitude-duration space of Fig. 5. MDSI is calculated along the three lines, using the parameter settings of cases 1 and 2 respectively. The results are plotted in Fig. 6. MDSI is expected to increase gradually along any line selected. However, in Fig. 6(a), MDSI drops to zero at the beginning of each duration range. Taking point $(t=0.5, v=0.75)$ of Fig. 5 as an example, it is obvious that both values, $\lim_{v=0.75, t \rightarrow 0.5^+} MDSI$ and $\lim_{v=0.75, t \rightarrow 0.5^-} MDSI$, are expected to be zero. However, in Fig. 6(b), $\lim_{v=0.75, t \rightarrow 0.5^+} MDSI$ is not equal to zero. It can be seen that the MDSI derived from case 1 cannot meet either of the two aforementioned requirements, and the MDSI derived from case 2 cannot meet the second requirement.

It can be seen from the contour colour map of SSI, as shown in Fig. 2, that SSI is in line with the sensitivity trend and severity distribution shown in Fig. 5. In Fig. 2, although the joint region of two neighbouring duration ranges is distinguished, SSI is continuous at any point of the magnitude-

duration space. To observe the continuity of SSI, the contour lines of SSI in the local area around a critical point, (0.5, 0.5) in Fig. 2, are shown in Fig. 7. The continuity around this point can be proved by the fact that $\lim_{v \rightarrow 0.5^+, t=0.5} \text{SSI} = \lim_{v \rightarrow 0.5^-, t=0.5} \text{SSI} = \lim_{v \rightarrow 0.5^+, t=0.5} \text{SSI} = \lim_{v \rightarrow 0.5^-, t=0.5} \text{SSI}$, which shows that SSI values calculated from four directions are equal. This fact demonstrates that SSI changes continuously across this point, and the contour lines of SSI change gradually between neighboring duration ranges. The steep slope around $t=0.5$ of Fig. 7 suggests that when t reaches 0.5, another duration range having higher severity level is entered, as discussed in Section II. The steepness of the slope can be adjusted by modifying coefficients, as mentioned in Section II.

Fig. 6. Variation of MDSI with respect to the magnitude and duration of voltage sags.

Fig. 7. Contour lines of SSI in an area around (0.5, 0.5).

Through the analysis above, it can be seen that MDSI does not meet the two requirements specified before, while SSI meets both of them. The SSI reflects the severity distribution of equipment sensitivity and ensures continuous transition at the joint region of two neighbouring duration ranges. The properties of SSI will be further discussed in the following subsection.

B. SSI Compared to Other Single-event Characteristics

SSI is compared with five single-event characteristics, including voltage sag energy [12, 13], lost energy [14], missing voltage time area index [20], voltage sag severity [15-17], and a fuzzy voltage sag index [10, 22]. The contour lines of these indices are given in Fig. 8. Among the five single-event characteristics, the first three indices do not take the equipment sensitivity into account. Fig. 8 (a) has an even contour distribution, Figs. 8 (b) and (c) lean towards CBEMA curve. Unlike these three indices, voltage sag severity takes standard SEMI F47 as reference curve, and the fuzzy voltage sag index is obtained based on the membership functions which are derived from standard/curves. Therefore it can be

seen that the shape and distribution of contours in Figs. 8 (d) and (e) lean towards standard/curves in comparison with those in Figs. 8 (a), (b) and (c).

Fig. 8. Contour lines of other single-event characteristics.

Due to the similarity among voltage sag severity, fuzzy voltage sag index and SSI, which all aim to reflect the severity of sags based on reference curves (i.e. equipment sensitivity), the following analysis focuses on these three indices.

1) Voltage sag severity (VSS)

Using the same notation as that in (1), VSS can be defined as $\frac{1-v_{Bij}}{1-v_{\max}(T_x)}$, which calculates the ratio between the depth of the voltage sag and the depth of the reference voltage (SEMI F47). In SSI, the sag magnitude is included by calculating the normalized distance between sag magnitude and the reference voltage, as shown in (1). For VSS, sag duration is not taken into account within one duration range. And it can be seen from Fig. 8 that under the reference curve, VSS remains the same as sag duration varies within one duration range for a given sag magnitude, i.e. the contours are parallel to the SEMI F47 curve. The transition from one severity level to another appears abrupt and discontinuous, as shown by the factor that $\lim_{v \rightarrow 0.5^+, t \rightarrow 0.5^+} \text{VSS} \neq \lim_{v \rightarrow 0.5^-, t \rightarrow 0.5^-} \text{VSS}$. In Fig. 8 (d), the contour lines overlap at the joint region of two neighboring duration ranges. For SSI, its contour lines are continuous at the joint regions, and all contour lines do not overlap, as shown in Fig. 7.

2) Fuzzy voltage sag index

In Fig. 8 (e), SEMI F47 curve is marked by the red dotted line, and ITIC curve is marked by the pink dotted line. Fuzzy voltage sag index models the vagueness between different severity levels. The transition from one severity level to another appears gradual in this case, and the sharp boundary of different duration ranges is eliminated. It can be seen that both SSI and fuzzy voltage sag index presents gradual transition between different duration ranges. With respect to the representation of fundamental statements specified in standard, it can be seen from Fig. 8 (e) that most of the contours lines cross the reference curves, which means that the estimated index values of sags located in susceptibility area could be the same as those of sags located in the non-susceptibility area, which is against the fundamental statement of standard specification, i.e., equipment must continue to operate without interrupt during conditions identified in the area above the defined line, which suggests that the index values of sags located in non-susceptibility area should be smaller than those in susceptibility area. For instance, along the contour line labeled with 1.6, it can be seen that the index values estimated when $v \in [0, 0.5]$ p.u. and $t > 0.02$ (i.e., in susceptibility area) are the same as the index values estimated when $v > 0.9$ p.u. (i.e., in non-susceptibility area). However, from the perspective of standard/reference curves, the risk when $v > 0.9$ should be much less than in the case that $v \in [0, 0.5]$ p.u. and $t > 0.02$.

3) SSI

For the convenience of comparison, the range of the estimated SSI values is adjusted based on that of the fuzzy logic based index given in Fig. 8 (e). In this way, the two sag severity indices can have the same ranges. The contour lines obtained using (1) and (2) are presented in Figs. 9 and 10 respectively. It can be seen that the contour line marked with zero SSI is the same as the standard voltage tolerance curve. The severity index of any point located on/above the standard voltage tolerance curve is zero. Different from the contours of fuzzy voltage sag index, the contour lines do not cross the reference curve, and they stay well under the reference curve. For those sags located in the susceptible area (below the voltage tolerance curve), the estimated index values vary based on both magnitude and duration. The contour line marked with zero SSI in Fig. 9 divides the areas of zero and non-zero SSI. In other words, the contour line marked with zero SSI strictly distinguishes between the sag susceptibility and non-susceptibility areas as defined by the voltage tolerance curve. The contour lines follow the shape of the sensitivity curve and the severity distribution given in Fig. 5. In Fig. 9, SSI presents a clear division between different duration ranges, which suggests that the severity levels among different duration ranges are distinguished. To illustrate the impact of coefficient b on SSI, the contour lines of SSI obtained with smaller setting of b in (1) is given in Fig. 9 (b). The figure shows that the increasing rate of contour lines of SSI at the beginning of duration range T_2 (or T_3) is larger than that given in Fig. 9 (a), and the contour lines become flatter at the end of the duration ranges in Fig. 9 (b), which is in line with the discussion in Section II. A. In Fig. 10, the division of

the joint region of two neighbouring duration ranges is not so obvious compared to that in Fig. 9. Both contour plots given in Figs. 9 and 10 are in agreement with the requirement of sensitivity trend and distribution of sag severity introduced in Section III. A.

Fig. 9. Contour lines of SSI using different coefficients in (1).

Fig. 10. Contour lines of SSI using coefficient $a=2$ in (2).

C. The Influence of Voltage Tolerance Curve Variation on SSI

To observe the effect of modelling variation of voltage tolerance curves on SSI, sub-sag ($v=0.146$, $t=0.0551$) is used as an example. The number of selected voltage tolerance curves, W , within the area of variation (green shaded area in Fig. 4) is set to 10, 50, 500 and 1000, respectively, and the corresponding histograms of SSI are shown in Fig. 11. It can be seen that, as the number of curves in the area of variation increases, the distribution of SSI approaches a normal distribution, i.e. the distribution of SSI is closer to the distribution of the voltage tolerance curves for larger number of randomly selected voltage tolerance curves.

For previous analysis, the parameters of variation/uncertainty range of voltage tolerance curves, i.e., the standard deviations of t_1 , t_2 , t_3 , v_1 , v_2 and v_3 , are set to 0.000667, 0.00967, 0.01667, 0.0233, 0.0267 and 0.03 respectively. To observe the effect of variation/uncertainty of voltage tolerance curves on SSI, the variation/uncertainty range is increased by setting the standard deviations of t_1 , t_2 , t_3 , v_1 , v_2 and v_3 to 0.010667, 0.01967, 0.02667, 0.07333, 0.07667 and 0.08 respectively. The obtained histogram of SSI when $W=1000$ is given in Fig. 12. It can be seen that the distribution is also normal, similar to that in Fig. 11(d). The mean of SSI in Fig. 11(d) is almost the same as that in Fig. 12. However, the range of SSI in Fig. 12 is wider than that in Fig. 11(d), which suggests that the variation of SSI increases with the increase in variation/uncertainty range of voltage tolerance curve.

The relationship between the variation/uncertainty range of voltage tolerance curve and SSI can be observed by the following analysis. It is noticed that sub-sag ($v=0.146$,

$t=0.0551$) is only affected by the settings of t_1 and v_1 . The standard deviation of t_1 is changed from 0.000667 to 0.010667, i.e., the variation range of t_1 is increased by ≈ 16 times. The standard deviation of v_1 is changed from 0.02333 to 0.07333, i.e., the variation range of v_1 is increased by ≈ 3 times. The standard deviation of 1000 SSI values in Fig. 11(d) is 0.0295, and that of Fig. 12 is 0.1456, suggesting that the variation of SSI is increased by ≈ 5 times. It can be seen that in this case the variation of SSI is more affected by the variation of v_1 , comparing with that of t_1 .

Fig. 11. Histogram of SSI when the number of voltage tolerance curves is set to different values.

Fig. 12. Histogram of SSI when the variation level of voltage tolerance curves is increased.

Another sub-sag ($v=0.2$, $t=0.02$) located within the variation area of voltage tolerance curve is selected as example. As introduced in Section II. B, the value of t_1 is selected around 0.02 based on a normal distribution. For sub-sag ($v=0.2$, $t=0.02$), if $t_1 \geq 0.02$ (i.e. the selected voltage tolerance curve is on the right side of the sub-sag), the obtained SSI is zero. Since the SSI values obtained when $t_1 = 0.02$ are also zero, the probability of obtaining zero SSI is slightly larger than 50%. If the selected t_1 is on the left side of the sub-sag, the further away from the sub-sag the value of t_1 is, the larger the obtained SSI is.

To illustrate this, the variation of the voltage tolerance curve is set to two different levels, as in the previous comparison performed for sub-sag ($v=0.146$, $t=0.0551$). The obtained histograms are given in Fig. 13, for $W=1000$. It can be seen from Fig. 13 that the probability of obtaining zero SSI is slightly larger than 500/1000, which is in line with previous analysis. The mean of SSI in Fig. 13(a) is 0.0031, and that of Fig. 13(b) is 0.0458. For sub-sag ($v=0.2$, $t=0.02$), the larger the variation/uncertainty range of the voltage tolerance curves is,

the larger the mean of SSI (i.e., SSI^M) is. This is different from the case of sub-sag ($v=0.146$, $t=0.0551$), in which the variation/uncertainty of voltage tolerance curve does not affect the mean of SSI.

It can be concluded, therefore, that if the sub-sag locates outside of the variation/uncertainty area (i.e. outside of the green shaded area in Fig. 4) of the voltage tolerance curves, the distribution of SSI is approximately normally distributed, and the mean of SSI is not appreciably affected by the level of the variation/uncertainty of the voltage tolerance curves; otherwise, the mean of SSI is greatly related to the variation/uncertainty level of the applied voltage tolerance curves.

Fig. 13. Histogram of SSI derived from sub-sag ($v=0.2$, $t=0.02$) when changing the variation/uncertainty level of voltage tolerance curves.

The mean of SSI values derived from a set of voltage tolerance curves is used as the final severity index, SSI^M in (3), as it takes into account the variation/uncertainty of voltage tolerance curves for sags located within the variation/uncertainty area of voltage tolerance curve. In this way, the values which occur more frequently will have larger influence on the final severity index, SSI^M . The mean value of SSI is used in the study rather than the most probable value. If the most probable value is used it would be likely derived from the standard voltage tolerance curve which eliminates the effect of variation/uncertainty in voltage tolerance curve if sags locate within the variation/uncertainty area of voltage tolerance curve. For example, if the most probable value is used, the SSI of the sub-sag ($v=0.2$, $t=0.02$) which locates on the reference curve will remain zero no matter what variation level of the tolerance curves is, as shown by Figs. 13 (a) and (b).

IV. CONCLUSIONS

This paper presents a novel index SSI to assess the severity of voltage sags. This new index is able to translate physical sag parameters (sag magnitude and duration) into voltage sag severity levels. Based on equipment sensitivity, SSI generates the contour lines which approximate the sensitivity trend of equipment embedded in the voltage tolerance curve. Two sets of coefficients are introduced for SSI assessment in Section II: the former enables a clear division of severity levels between two neighbouring duration ranges; the latter enables smooth transition of severity levels between two neighbouring duration ranges. The contour maps derived using the two coefficient sets demonstrate that the steepness of contour lines at the joint region of two neighbouring duration ranges and the increasing rate of SSI within one duration range can be adjusted by modifying corresponding coefficients. The SSI is then compared with previously reported MDSI based on two

requirements that are derived from the definition of sag severity index and its assessment purpose. SSI is able to ensure the continuity of the estimated index values at any point of the magnitude-duration space. Further comparison is made against five single-event indices, in particular voltage sag severity and fuzzy voltage sag index which use step-shaped standard/curves as reference curves. Compared with voltage sag severity, the contour lines of SSI are continuous and do not overlap at the joint region of two neighboring duration ranges. Compared with fuzzy voltage sag index, SSI demonstrates full compliance with fundamental statements specified in standard and its representation of sensitivity trend and sag severity distribution embedded in voltage tolerance curve by: i) SSI is zero when sags are within non-susceptibility area; ii) in the sag susceptibility area, the contour lines do not cross the voltage tolerance curve and remain well under it, and they reflect the severity of sag events in terms of magnitude and duration based on equipment sensitivity. Finally, the variation/uncertainty of equipment sensitivity to voltage sags is taken into account by adopting a set of normally distributed voltage tolerance curves, within predefined range of variation/uncertainty, instead of a single curve. The mean value of the SSI obtained from the set of voltage tolerance curves is used as the final severity index, SSI^M . The sensitivity of the SSI to the variation of voltage tolerance curve is investigated by analysing two sub-sags located inside and outside of the variation/uncertainty area respectively. It was found that SSI^M is only affected by the variation in voltage tolerance curve if the sags are within the area of variation/uncertainty of voltage tolerance curve. In this case the SSI^M is strongly related to the variation level of the applied voltage tolerance curve.

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