Research on uncertainty evaluation measure and method of voltage sag severity

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Abstract. Voltage sag is an inevitable serious problem of power quality in power system. This paper focuses on a general summarization and reviews on the concepts, indices and evaluation methods about voltage sag severity. Considering the complexity and uncertainty of influencing factors, damage degree, the characteristics and requirements of voltage sag severity in the power source-network-load sides, the measure concepts and their existing conditions, evaluation indices and methods of voltage sag severity have been analyzed. Current evaluation techniques, such as stochastic theory, fuzzy logic, as well as their fusion, are reviewed in detail. An index system about voltage sag severity is provided for comprehensive study. The main aim of this paper is to propose thought and method of severity research based on advanced uncertainty theory and uncertainty measure. This study may be considered as a valuable guide for researchers who are interested in the domain of voltage sag severity.

1. Introduction

Voltage sag even is one inevitable problem of short duration power quality disturbances in power system [1]-[2]. Nevertheless, voltage sag severity is a new concept and proposition proposed recently [3]-[4]. The cognition of voltage sag severity originates from its impacts on industrial customers, which has gone through three stages including experience accumulation, observation and statistics, quantitative assessment [5]. The first stage is to recognize voltage sag as the major cause of equipment trip and processes halt. In the second stage, a large number research about surveying, testing and statistics of typical equipment and industrial processes are presented. After a period of accumulation, the Computer Business Equipment Manufacturers’ Association (CBEMA) and the Semi-conductor Equipment and Materials International (SEMI) have respectively developed CBEMA curve and SEMI F47. The third stage has proposed probabilistic, fuzzy, interval and multi-uncertain evaluation methods to study equipment sensitivity assessment. The importance and urgency of voltage sag severity has been recognized while the cognition for the concept of voltage sag severity and its existing conditions, intension and extension, index system and assessment measure is insufficient. Further research on evaluation methods based on scientific concept is in urgent need.

Based on voltage tolerance curve, Qader and Bollen first proposed voltage sag severity index in 1999 for the purpose of contrasting the measurement and reference of magnitude, duration and their combined. Taking into account its limitation, the vulnerability area and sag region were presented from the view of utility. Severity can also be reflected in low-voltage ride-through problem existed in
wind or solar generation plant. Consequently, a thorough research on sag severity in the power source-network-load sides needs appropriate evaluation measure and methods combined with characteristics and requirements [6]-[8]. Further research on evaluation methods based on scientific concept is in urgent need [9].

2. Research status of voltage sag severity

2.1. Research situation

Interest in voltage sag severity has significantly increased due to its huge damage. Current study mainly concentrates on many contents related to voltage sag including impact level, testing, simulation, evaluation and standard setting.

2.1.1 Impact and economic losses. A large number of investigations have been made on industrial equipments in hi-tech zone in North America, Europe, South Africa, Taiwan, and other areas. Investigation content comprises failure rates, operation reliability and economic losses. The losses of per voltage sags in different industry were given in Figure 1.

![Figure 1. Economic losses caused by voltage sag.](image)

2.1.2 Testing and experiment. On the basis of normative disturbance source, mass testing and experiment were found in typical equipments and industrial processes. The thresholds of voltage tolerance for typical equipment are summarized in Table 1.

| Equipment Type | $U_{\text{min}}$(%) | $U_{\text{max}}$(%) | $T_{\text{min}}$(ms) | $T_{\text{max}}$(ms) |
|---------------|---------------------|---------------------|---------------------|---------------------|
| PLC           | 30                  | 90                  | 20                  | 400                 |
| ASD           | 59                  | 71                  | 15                  | 175                 |
| PC            | 46                  | 63                  | 40                  | 205                 |

2.1.3 Simulation tool. Many scholars have studied the response characteristics of typical equipment by transient behavior simulation systems for the purpose of equipment sensitivity prediction. The main simulation tools include EMTP, PSCAD/EMTDC, MATLAB, and so on. As for non-electricity expression of sag characteristics and consequence state, such as temperature and speed, further study should focus on multi-physical attributes and multi-uncertain factors.

2.1.4 Evaluation method. It is well known that probability evaluation method and fuzzy assessment method are more common among the existing evaluation methods. The former describes distribution rule in uncertain region of voltage tolerance curve, including uniform, normal and exponential distribution as well as determined by maximum entropy model. The latter establishes the membership function based on specialist experiences. Based on combining the two uncertain properties which
reflect the intension and extension of influencing factors, fuzzy-random, and multi-uncertain assessment model are presented. In addition, measure theory is introduced into the methodology for severity assessment, but only for cursory analysis.

2.2. Representative teams and organizations

The study of voltage sag severity originated in North America and other industrialized countries, expanding to the Southeast Asia, South Africa, Eastern Europe, Asia, and even the whole world. A mass statistics and test on typical load, production lines and hi-tech zone are made in North America, Europe, South Africa, India, Iran, Korea, and China. Some representative team, including Bollen in Sweden, Milanovic in British, Lu Chan Nan in Taiwan, and Chinese colleges etc., are focused on evaluation measure and evaluation methods.

Serious concerns over severity have been raised by International academic organizations and standardization institutions. CBEMA curve represents the typical performance of computers in certain voltage magnitude and duration conditions, as important for sensitivity evaluation. While the SEMI F47 standard specifies a new sensitivity curve for semiconductor-based devices. In addition, from 2006 to 2010, a joint working group constituted by CIGRE, CIRED and UIE has gathered technical knowledge on immunity of equipment, installations and processes against voltage sag. And the final results produced by the former joint C4.110 are reported detailed in [10].

3. Voltage sag severity and indices

3.1. Severity

High-quality power supply is an essential feature of smart grid, having the important significance for improving energy efficiency and energy-saving and enhancing satisfaction of utility, customer and society. In fact, voltage sag severity not only means the problem of equipment response and tolerance, but also is described by fault rate or malfunction, even the efficiency. As a result, the concept of severity should be investigated on both a broad and narrow sense. In narrow terms, severity refers to the abnormal operation of equipment suffering sag, judging by loss rate, involving only direct damages. In a broad way, the study of severity should be combined with the different characteristics and requirements in the power source-network-load sides, according to the direct and indirect loss, and assessing the damage of functionality, security, economic, structural, and effectiveness ways. Voltage sag severity can be regarded as a complex system due to the diversity and uncertainty of sag characteristics and equipment response. In the process from complex to simple, the seriation, hierarchical and certainty methods should be taken to research the measure and indices of severity.

As early as 1999, the IEEE P1564 draft documents introduce severity index which is defined based on the retained voltage in per unit and the duration by comparing these values with the SEMI F47 curve. The algorithm for calculating voltage sag severity index \( S_e \) is as in:

\[
S_e = \frac{1-U}{1-U_{\text{curve}}(d)}
\]

Where \( U \) is the retained voltage, \( d \) is the duration of event and \( U_{\text{curve}}(d) \) is the retained voltage of the reference curve for the same duration.

Subsequently, other scholars developed this index taking magnitude and duration into account. Similar indices, MSI and DSI, use a scale of 0 to 100, with 0 as minimum severity and 100 as maximum severity to translate physical sag characteristics into the level of severity posed by the linear disturbance. Unfortunately, the difference among power source-network-load sides, measure existence condition, and multi valued mapping property are all ignored here.
Unfortunately, these indices could reflect neither energy efficiency nor loss in safety, structure or function. In practice, severity evaluation is a measure problem. According to measure theory, it is hard to meet countable additive constraints in existence condition of classic measure. Furthermore, only considering the structure, function, efficiency of equipment, can embodies the uncertain of severity. So the uncertain measure is a suited tool to express the complex of equipment response.

The severity in the power source-network-load sides is affected by response characteristics, disturbance cause and intensity, etc. The uncertain property of intension, extension and boundary of severity is different in each case. Therefore, voltage sag severity is in the power system all the time. Owing to variety of influencing factors consist of network structure, disturbance causes, propagation mechanism, etc., and the characteristic of nonrepeatability and small sample, it is very important to select a reasonable measure. Many factors like operating mode, unit commitment, fault type, geographic environment, protected pattern, and electricity characteristics, will affect the uncertain measure of severity. Thus, the disturbance characteristics of system-lines-equipment, damage and loss, as well as new characteristics and new requirements should be taken into the research on evaluation measure, which is an irresistible trend.

3.2. Indices

In view of the complexity and diversity of voltage sag severity, the assessment system of severity is established on the indices of different levels. And the classificatory principle of different levels is the physical and mathematical properties. In order to clearly describe the complicated hierarchy structure in severity assessment system, Figure 2 shows the severity indices considering basic parameters, state performance, and response mechanism in the power source-network-load sides.

![Figure 2. The framework of voltage sag severity index.](image)
3.2.1. Indices in the power source side.

(1) Torque and speed. The behavior of induction motor is critical for the disturbance characteristic. It has been proved that the reducing speed would cause unwanted torque ripple or oscillation, even the risk of braking or outage in severe cases.

$$
M = \frac{p}{\omega_1} \left[ I_2^2 \frac{r_2}{s} - I_2^2 \frac{r_1}{s} \right] 
$$

Where, $p$ is the number of pole pairs; $\omega_1$ is synchronous frequency; $I_2$ and $r_2$ are the current and resistance of rotor; $s$ is positive sequence slip of rotor.

(2) Low-voltage ride-through capability. Modern grid codes determine that wind generation plants must not be disconnected from the grid during some levels of voltage sags and contribute to network stabilization, which are not completely achieved at present. Low-voltage ride-through capability defined as the ability of the power plant to remain connected to the grid during voltage sags, as one of the severity index.

(3) Efficiency. Not only power but also electromagnetic coil impedance loss and permeability material loss are provided by generator. Furthermore, the effect of voltage sag is the decrease of the developed torque and increase of the copper loss due to the negative-sequence currents. Additional losses will surely result in the poor efficiency.

3.2.2. Indices in the network side.

(1) Load variation. Since a transmission line is an important component of the power system, the variation of line performance taken by the types of load cause power losses. Therefore, the load variation connected to the line should be deserves more attention. The measurement of load variation during voltage sags is based on the variation of the load curve with respect to the forecasted load curve.

(2) Non delivered energy. Non delivered energy (NDE) due to voltage sags refers to the energy the utility is not able to supply due to end-user disruption, quantifying voltage sag severity. Except the security constraints of transmission capacity, this index reflects the power quality reliability from both utility and customer.

$$
\Delta E = \int \Delta P dt 
$$

Where, $\Delta E$ is the non-delivered energy, $\Delta P$ is the difference between the forecasted load and the actual one, $T$ is the duration of voltage sag.

(3) Cost. This index is related to the total cost caused by voltage sags. It is cannot be ignored the financial cost of decreasing transmission capacity. Moreover, asset utilization to minimize the disturbance damage should be calculated to the cost index.

3.2.3. Indices in the loadside.

(1) Vulnerability area. The area of vulnerability is the region in the power system where the occurrence of faults will lead to voltage sags at a sensitive load point. Bigger of the vulnerability area, the affected load is more. This index has the properties of overlapping, interval, and diversity because of different load characteristic.

(2) Sag frequency. This index means the annual number of voltage sags exceeds the voltage threshold. Customer satisfaction, equipment immunity, efficiency and other factors should be considered carefully besides the failure rate, fault location, fault type and protective characteristics.

(3) Losses. Direct and indirect losses are two important parts of losses by voltage sag. There is great difference between their methodologies to assess related to the industry, equipment type, even the market. Thus the technique economy method may be the key approach.
4. Standard of equipment and process immunity

The voltage sag immunity, also called acceptable level, sensitivity, equipment tolerance, and vulnerability, are all used to describe the influence by disturbance from the different disciplines or requirements. Nevertheless, the definition is not united in the concept of the immunity. The Computer Business Equipment Manufacturers’ Association (CBEMA) developed the first sensitivity curve (1977) and it represents the typical performance of computers in certain voltage magnitude and duration conditions, which is shown in Figure 3. The equipment malfunction will happen outside the curve and normal inside. Furthermore, mandatory specification for Semiconductor Processing Equipment Voltage Sag Immunity (SEMI) standard F47 specifies a new sensitivity curve for semiconductor-based devices shown in Figure 4. The equipment must be able to continuously operate without interruption during conditions identified in the area above the defined solid line.

![Figure 3. Voltage tolerance curve in CBEMA.](image)

From 2006 to 2010, CIGRE/CIRED/UEI Joint Working Group C4.110 presents a report aiming at improving the understanding of the compatibility between installations and the electricity supply. The process immunity time (PIT), defined as the maximum time the process can continue without electricity, is the basis of immunity assessment in industrial process, which is illustrated in Figure 5. Starting with the nominal process parameter value \( p_{\text{nom}} \), supply voltage sag is assumed to occur at \( t_1 \). As a result, the process parameter starts to deviate from its nominal value. A delay might be associated with the tripping of the equipment \( \Delta t \) seconds after the actual supply voltage interruption, or with a “dead time” in the process response. At time \( t_2 \), the process parameter value crosses the lower boundary \( p_{\text{limit}} \), below which normal operation of the process cannot be maintained. Starting from \( t_2 \) onwards, the process no longer operates as intended and must be either shut down, or restarted, or otherwise corrected. Therefore, PIT can be seen as proposed standard of immunity.

![Figure 4. SEMI F47 curve.](image)
5. Measure and Uncertainty Evaluation

5.1. Single uncertainty methodology

There are two types of evaluation methods of sensitive equipment failure events: measurement and statistics model based on stochastic theory, fuzzy theory and etc. they are thought to be direct and reliable but not predictive. Probability evaluation method base on the disturbance intension and equipment tolerance is aimed at getting the distribution of uncertainty region in VTC as shown in Figure 6. Considering the magnitude and duration, the probability evaluation model of sensitive equipment failure caused by voltage sags is:

$$P = \int_{U_{min}}^{U_{max}} f(x_1)dx_1 \int_{T_{min}}^{T_{max}} f(x_2)dx_2$$

(6)

Where, $U_{min}$ and $U_{max}$, $T_{min}$ and $T_{max}$ are the minimum and maximum of voltage sag magnitude and duration; $U_0$ and $T_0$ are the characteristic value of evaluated sag; $f(x_1)$ and $f(x_2)$ are the probability density function of variable $U$ and $T$.

Besides, fuzzy assessment method is aimed at fuzzy sets membership functions confirmed by ESKOM windows or CBEMA curve. Retained voltage magnitude and sag duration are the inputs variable of the proposed system. Meanwhile, in view of the interval characteristics of information, interval probability evaluation method is proposed based on the confidence interval. The analogous evaluation method is used in reliability parameters such as connection number, etc. In nature, voltage sag severity is influenced by many factors, such as voltage sag characteristics, equipment voltage tolerance, response status, operation condition and so on. The single uncertainty methodology is hard to describe all the uncertain properties with different characters, variations, and mathematical expressions. Hence, it is necessary to search a more general and compatible methodology.
5.2. Double-uncertain and multi-uncertain methodology

The impact of voltage sags on equipment can be attributed to electromagnetic compatibility between the power supply disturbances and the voltage tolerance level of equipment. The former depend on network topology, operating mode, fault location, fault impedance, and protection features. And the latter is influenced by equipment type, operation location, equipment life, and operation environment, etc. Consequently, voltage sag severity is considered as a double value issue.

In order to accurately evaluate the complicated equipment failure probability caused by voltage sags, the fuzzy-random assessment method takes into account both the randomness of power quality disturbances and the fuzziness of equipment sensitivity. With respect to the voltage magnitude and sag duration, voltage sag intensity and the equipment voltage tolerance level are denoted by \( s(V, T) \) and \( r(V, T) \). Therefore, the event of the equipment failure which is denoted by variable \( \xi \) can be described as \( s > r \).

\[
P(\xi) = P(s > r) = \int_0^\infty u_D(s) f(s) ds
\]

Where, the membership function of \( \xi \) is denoted as \( u_D(s) \), and \( f(s) \) is the probability density function of voltage sag intensity.

The complexity and diversity of severity cannot be expressed accurately by the double-uncertain methodology, necessitating multi-uncertain methodology to distinguish the intension and extension uncertainties of influencing factors. According to the expression of different uncertain factor based on probability theory, fuzzy theory, the multi-uncertain evaluation model can be expressed as:

\[
P(\xi) = \frac{\int_{x_{min}}^{x_{max}} \mu(x) f(s) dx ds}{\int_{x_{min}}^{x_{max}} \mu(x) dx} + \int_{x_{min}}^{x_{max}} f(s) ds
\]

Where, \([x_{min}, x_{max}]\) is the interval range of equipment tolerance; \( \mu(x) \) is the membership function of tolerance.

And the operation state is an in-between state under voltage sag, which can be expressed as follows:

\[
\mu_{D}(s) = \frac{\int_{x_{min}}^{x_{max}} \mu(x) dx}{\int_{x_{min}}^{x_{max}} \mu(x) dx}
\]

It has been proved that voltage sag severity is a spatio-temporal definition with complicated uncertain properties. There are a lot of limitations of understanding on uncertain factors, sample characteristics, parameters characteristics, and response characteristics, etc. Therefore, it is necessary to study form the physical and mathematical essence of severity.

5.3. Uncertain system methodology

Uncertain properties is the key role to evaluate the sag severity accurately, which is relate to not only physical phenomena containing system malfunction, lightning, capacitor switching, but also voltage sag characteristic and propagation pattern, even the security, reliability, and economic indicators in the power source-network-load sides. Meanwhile, the voltage sag severity measure and evaluation method should be combined to a variety of factors such as electromagnetic compatibility and uncertain risk.

Measure is taken as a concept of axiomatization condition, the establishment of which lies in whether it is consistent with the actual situation. Let \((\Omega, F)\) be a measurable space, and \(\mu\) a function of \(F\) on the value range of \(\mathbb{R}_+ = [0, \infty]\). If \(\mu(\emptyset) = 0\), and function \(\mu\) meets the countable additivity as follows:
\[ A_n \in \mathcal{F}, \ n \geq 1, A_n \cap A_m = \emptyset, \ n \neq m \Rightarrow \mu(\bigcup_{n=1}^{\infty} A_n) = \sum_{n=1}^{\infty} \mu(A_n) \] (10)

Then, function is defined as the measure in measurable space \( \Omega \).

As mentioned above, it is very hard to meet assumed condition including additivity, single-valued mapping, and determine value. In practice, there are so many cases don’t meet these conditions in the power system, such as the generator rides though the low-voltage occasionally; the equipment operates in either the normal or the broken-down manner; response issue to voltage sag presents a multiple value state, and etc.

6. Conclusions and future scope

This paper presents a comprehensive survey on the current situation and development in voltage sag severity which is the major area of research in the field of power system. And there are urgent needs to work on the following points:

1) The voltage sag severity index system and the standard under the new characteristics and requirements in the power source-network-load sides. According to the granularity theory, the complexity can be decomposed into be a number of simple blocks according to their respective characteristics and performance. The classification principle of granular layer is the different properties of consequence on the safety, reliability and economy. The further work should focus on the hierarchical evaluation system reflecting the mapping rule and comprehensive standard.

2) The complicated uncertainty analysis theory and evaluation method on severity. From the point of simplifying the complexity and quantifying the uncertainty, the unified uncertainty models and analysis methods of severity should be established on the properties of intension and extension consist of types such as stochastic, fuzzy, rough, etc.

3) Researchers have attempted to study the technical standard and management measures against the proposed immunity, aiming at promoting the establishment of regulation on voltage sag severity.

4) Combined with the fundamental theory and key technology of the common development on power source-network-load, the achievement on severity can be extend to energy efficiency management, and smart transmission and distribution system, and other fields related to power system.

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