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Customer Satisfaction Based Evaluation Method of Voltage Sag in the Modern Power System

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Abstract

This paper is based on interval data of power customer satisfaction degree. The evaluation method of voltage sag or dip is an analytical one which is used to consider the satisfaction of not only the utility but also the user side. Determining function is from the length of fault line and the voltage magnitude in the modern transmission and distribution network. The critical failure positions method is getting through analytical algorithm combined with iterative features. The range characteristics of satisfaction degree of customer side and the distribution regularities of the uncertainty region are considered in the paper. Then, the quantitative frequency of voltage sag is determined using the interval sag frequency. A small size network and IEEE 30-bus RTS are chosen to comparing with existing and traditional methods. And this novel method is proved to have much more academic value and practical foreground.

Keywords: *power customer satisfaction degree, evaluation method, critical failure positions, interval data*

1. Introduction

The fundamental objective for both customer side and utilities is meeting their satisfaction at the same time[1], especially under the background of the development of smart grid [2]. With the promotion and application of microelectronics technologies, the characteristic of electrical equipment has undergone a

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fundamental change. The complaint from power quality problems caused by voltage sag is increasingly prominent. Expressly with the widely application of sensitive equipments [3-4], including PC, PLC, ASD and ACC, the complaints caused by voltage sag present a rising trend year by year. According to international association of Electrical and Electronics Engineers (IEEE), the voltage sag is defined as a sudden dip or decrease of its RMS value during 0.5 cycles of the whole period to 1 min called duration. And the dip magnitude is in the extent from 0.1 to 0.9p.u. From the above, the promotion of the satisfaction degree relies heavily on the assessment of voltage dip frequency.

The internal factors including different sensitivity equipment types, working conditions, network topologies, loading types and have great influence on satisfaction degree. And the external factors are no exception, which means the type, location and impedance of fault [6].

Traditional voltage sag evaluation methods are based on the voltage magnitude of its RMS. The measurement statistic [7] and analytical modeling [8-9] are the principal methods. The former requires long surveying time and high installation and maintain cost even though it is simple and reliable. The later one has promotion and predictability due to its complex stochastic model but lacking of consideration for customer. The critical distance method, classical fault locations and analytical approach are the conventional methods.

After the scientific understanding of interval data of customer satisfaction degree in network, a novel analytic evaluation method is presented. With the help of Newton iteration method, this proposed method is validated as an accurate and applicable one under the small size network and IEEE 30-bus RTS.

2. The concept of power customer satisfaction degree and interval data

Customer satisfaction in a power system can be defined as the satisfaction indicators synthesized the power supply capacity, power, electricity, and power efficiency, utility and so on. Because of that prices are influenced by the impact on various aspects of capacity, electricity consumption and power sales contracts related, the customer satisfaction is decide by the operating conditions of weather it is normal. Therefore, the comprehensive concept of customer satisfaction is shown by the probability of the normal operation time divide by total operation time. The S % called power customer satisfaction is shown by the following expression:

$$S\% = \frac{T_s}{T_s + T_c} \times 100\% = \frac{T_s}{T_t} \times 100\% \tag{1}$$

Where, T_s means the normal operation time; T_t means the practical operation time of sensitivity equipment; and T_c is the non-normal operation time, which depends on the power quality of supply side and VTC of user side. Starting the point of power customer, their satisfaction is an essential serve.

Except the sag severity, the voltage tolerance is the principal element of electricity customer satisfaction degree. The VTC of equipment is constituted by the upper and lower thresholds shown in Fig. 1. The maximum and minimum thresholds of VTC about voltage amplitude and dip duration are expressed by $U_{\max}$ and $U_{\min}$, $T_{\max}$ and $T_{\min}$. Showed in the picture, when voltage sag happen in the external of curve one which is called satisfaction area, the sensitivity device operates normally as usually. Furthermore, the sensitivity device will take place the opposite situation if the real sag happens inside the curve 2. Even more critical is that the operation state of sensitivity device is uncertain when dip occurs in L- area mixed with the two curves, which are shown in Table 1 [3-4].

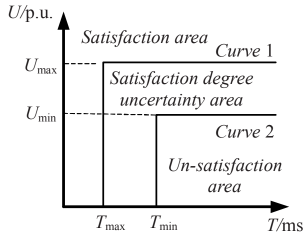

Fig.1. Uncertain range of customer satisfaction degree

Table1. The uncertainty extent of some typical equipment

Typical Equipment	U_{min}(%)	U_{max}(%)	T_{min}(ms)	T_{max}(ms)
PC	46	63	40	205
ASD	59	71	15	175
PLC	30	90	20	400

The existing methods are based on sensitivity characteristics of equipment VTC. Because of the classic stochastic principle or fuzzy judgement rules, they are not easy to understand. While the randomness merely reflect a single uncertain property for the part of deficiency of cause and effect rule, similarly, the fuzziness can only presents the indeterminacy for the deficiency excluding rule. Actually, the randomness and fuzziness always appear concurrently. Hence, the interval number can describe the uncertain ranges characteristic of magnitude and dip duration of faulted voltage.

$$U_{Interval} = [U_{\min}, U_{\max}] \text{ and } T_{Interval} = [T_{\min}, T_{\max}] \tag{2}$$

Combining with Fig. 1, the value of S% is an uncertain variable between zero and hundred. The satisfaction degree S% equals to one hundred when voltages sag in the power customer satisfaction area and is zero when dropping-into the un-satisfaction area. In this paper, voltage magnitude is the single factor used to evaluate for its convenience by an interval data.

$$S = [0,100] \tag{3}$$

We can see that, if $U \geq U_{\max}$, S%=100; if $U \leq U_{\min}$, S%=0.

3. Interval Data of Voltage Sag Frequency Considering the Power Customer Satisfaction Degree

In the power supply system shown in Fig. 2, we choose one bus named I as the connecting site of sensitivity device. When one fault called f happens on the line from m to n, the features between position f b and bus I can presented by the sequence transfer impedances seen in the following expressions.

$$Z_{if}^{k} = (1-x)Z_{im}^{k} + xZ_{in}^{k} \tag{4}$$

$$Z_{ff}^{k} = (1-x)^2 Z_{mm}^{k} + xZ_{nn}^{k} + 2x(1-x)Z_{mn}^{k} + x(1-x)z_{mn}^{k} \tag{5}$$

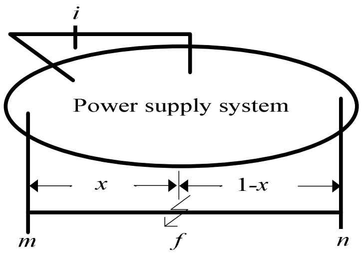

Fig.2. Typical power supply system structure

It is can be seen, k=0, 1, 2 are represent for zero-sequence, positive-sequence, and negative-sequence separately; Z_{mm}^{k}, Z_{nn}^{k} and Z_{ii}^{k} are the sequence driving-point normalization impedances of bus m, n and i; Z_{im}^{k}, Z_{in}^{k} and Z_{mn}^{k} are transfer normalization impedances; z_{mn}^{k} is the unit-kilometer impedance for the line m-n.

If one fault with the type of single line-to-ground occur in f, the magnitude of the voltage sag at bus i can be get form formula (6). In the expression, V_i^{pf} means the pre-fault voltages of bus i. Similarly, other types of fault can be getting at the same way.

$$V_i = V_i^{pf} - \frac{Z_{if}^0 + Z_{if}^1 + Z_{if}^2}{Z_{ff}^0 + Z_{ff}^1 + Z_{ff}^2} V_f^{pf} \tag{6}$$

Combine the variation of voltage sag and interval range of power customer satisfaction degree, the interval number of voltage dip frequency can be expressed.

$$N_i = [N_c, N_c + N_u] \tag{7}$$

Where, N_i is the dip frequency interval number in a power network, N_c and N_u are voltage sag frequency interval numbers fallen in the un-satisfaction and uncertain area considering satisfaction degree separately.

4. Analytical Evaluation Method

4.1. Critical failure point

When pre-fault voltage V_i drops to the threshold V_{th} of the equipment after the failure, the critical fault point means the fault position of threshold x_{crit}, which can be solved by

$$f(x_{crit}) = V_{th} - V_i = 0 \tag{8}$$

Due to the high-order equation including (2)-(5), the solution is very difficult in practice. Newton iteration method is a good countermeasure to the problem.

$$x_{n+1} = x_n - \frac{f(x_n)}{f^*(x_n)} \text{ and } (n = 0,1,2...) \tag{9}$$

In expression (9), n, n+1 are iteration times of vector x, and the function $f^*(x_n)$ is the derivative of function $f(x_n)$. But $f(x_n)$ does not exist in many cases, for this reason, the secant iteration is proposed. This iterative algorithm is used to solve the issue.

$$x_{n+1} = x_n - \frac{x_n - x_{n-1}}{3f(x_n) - 4f(\frac{x_n + x_{n-1}}{2}) + f(x_{n-1})} f(x_n) \tag{10}$$

4.2. Power Customer Dissatisfied area

The un-satisfaction also called dissatisfied area in the power system means the stoppage point of sensitivity equipment caused by voltage sag, which is the reason of complaint. The correct and reasonable power customer un-satisfaction area should include all the critical fault positions in each line. The decision processes can be presented as:

Step I: When the magnitude of voltage RMS below the values of fault at x=0 and x=1 in Fig. 2, so the satisfaction area must include this calculated line.

Step II: When the magnitude of voltage RMS is greater than the biggest value of the fault at $0 \le x \le 1$ p.u.in Fig. 2, un-satisfaction area must include this calculated line.

Step III: When the magnitude of voltage RMS is between the minimum and the maximum of $0 \le x \le 1$ p.u., just one critical fault point exists in this line, which is the part of the un-satisfaction area.

Step IV: When the the magnitude of voltage RMS below the maximum value of $0 \le x \le 1$ p.u. and exceed both the biggest and the least of *x*=0, 1 p.u., two critical fault points exist there. And the un-satisfaction area has two parts of this line.

4.3. Estimation chart for the voltage sag interval frequency

According to the content of above, the evaluation process is shown in Fig.3.

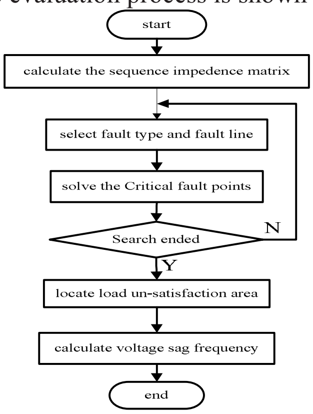

Fig.3. Technological process of the novel assessment method

5. Case Analysis in a five-Bus Network

A small size network is chosen for the test system, which has only five buses [10] .And the per-unit values of each line and generator are indicated in the Fig.4

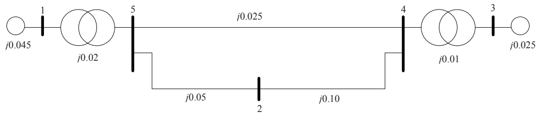

Fig.4. Small size network topology

It is assumed that threshold voltage of the power customer satisfaction is 0.3 p.u of voltage RMS. When a fault of three-phase type occurs in the system, the assessment results of frequency with the proposed method and the traditional method are compared in Table 2.

Table 2.The result of annual voltage sag frequency at various buses

Bus number	Proposed method	Fault position method		
		P=10	P=100	P=1000
5	6.676	8.4	6.92	6.7
4	4.115	5.6	4.28	4.116
2	22.23	24.4	22.52	22.252

Table3. The Numbers of Iteration at Various Busses

Buss number	Proposed method	Secant iteration method
5	8	11
4	8	12
2	9	18

Obviously, as shown in Table 2, the assessment results from the novel method are closely related to the number of fault position to the traditional fault position method. There will be a bigger error if position number is not reasonable. And the proposed method is proved to be more validate with all most the same results by the method in [9]. The results of comparison of the novel method and the secant iteration method are presented in Table 3. Under the condition of the same system architecture, the proposed method can identify power customer un-satisfaction range much more efficiently and precisely.

6. Case Analysis in IEEE 30-Bus RTS

As a testing network, IEEE 30-bus test system is used in this paper. Form the Fig.5, it consists of 6 generator units, 37 lines and 4 transformers to interconnect 30 buses, the connection type of different transformers is Y_0/Δ-11. And there are four types of fault are taken into account.

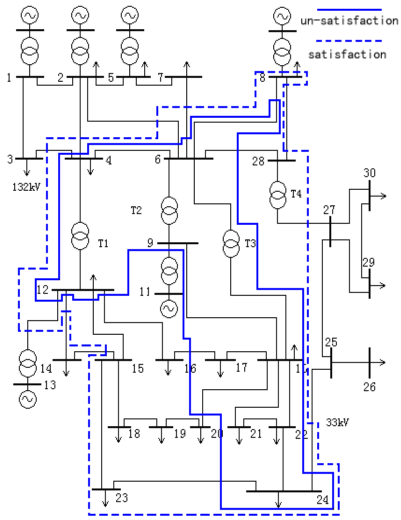

Fig.5. Uncertain area of power customer satisfaction in bus 21 by three-phase fault.

According to customer acceptability, the interval data of ASD is [0.59, 0.71]. The customer connecting site with ASD equipment is at Bus 21. When a three-phrase short circuit fault happens in the test power system, the customer satisfaction area is shown in Fig. 5. The surrounded region in the real line is the un-satisfaction region and the area outside the dotted line is customer satisfaction region. Furthermore, the region between the two lines is the user satisfaction uncertainty area. Then the voltage sag frequency interval data is calculated as previously described. After that, the potential cost of customer in this system can be estimated.

The result of Monte Carlo method for the assessment of voltage dip interval frequency is taken for the true value. Its essence is to get the random number within the interval range. Then voltage sag frequency in different circumstances is calculated. Then, the maximum and minimum voltage sag frequency is picked from all the others considered these various conditions. For the reasons of the diversity of the network topology, the Monte Carlo method is reasonable and persuasive for the large system with many interactional factors.

ASD, PLC and PC are assumed to connect to the customer connecting sites which including bus 7, 15, 21, 26, and 30 in the test power system. The assessment results of the novel method and Monte Carlo method are both presented in Table 4. We can clearly see that the proposed method is correct with less amount of calculation.

From the Table 4, the evaluation results of the voltage sag frequency considered the satisfaction degree are the interval range instead of a point. And these interval data can reflect the allowable extent of voltage dip frequency.

In practical applications, the customers risk tolerance is combined with the distribution rule of equipments' VTC to estimate the quantitative value. Based on the research of [11], it is assumed that the distribution of sensitive equipments respectively obey normal, exponential, and negative exponential distribution rule. The final consequences are presented in Table.5. It is clear that distributions have significant influence on the results. The interval characteristics of power customer satisfaction degree and the distribution rule of equipments' VTC are the primary consideration in selecting customer connecting site.

In the simulation experiments of this paper, bus 7 is the best choice for ASD if its distributions submit to negative exponential distribution and bus 15 is chosen while normal and exponential distributions rule. It is thus clear that the evaluation results considering the interval characteristics of customer satisfaction degree can cover more information and demonstrate great potentiality for the practical application.

Table 4. Annual Voltage Sags frequency for Different Assessment Methods

Bus number	ASD		PLC		PC	
	Monte Carlo	Novel method	Monte Carlo	Novel method	Monte Carlo	Novel method
7	[8.4264, 11.880]	[8.4242, 11.882]	[2.6157, 27.568]	[2.5829, 27.591]	[5.2848, 9.4808]	[5.2767, 9.4815]
15	[5.5859, 14.150]	[5.5851, 14.155]	[0.9309, 32.217]	[0.9107, 32.225]	[1.6674, 8.2391]	[1.6521, 8.2443]
21	[8.2879, 16.052]	[8.2822, 16.054]	[1.5520, 34.203]	[1.5481, 34.207]	[3.4316, 10.545]	[3.4297, 10.548]
26	[12.367, 19.909]	[12.358, 19.933]	[1.6654, 36.070]	[1.6478, 36.081]	[6.5614, 14.086]	[6.5612, 14.075]
30	[12.408, 18.510]	[12.400, 18.511]	[4.9952, 36.111]	[4.9606, 36.118]	[8.5904, 14.284]	[8.5902, 14.288]

Table5. Annual Dip frequency for Different Distributions Rule

bus	ASD			PLC			PC		
	Uniform	Exponential	Negative exponential	Uniform	Exponential	Negative exponential	Uniform	Exponential	Negative exponential
30	15.417	13.438	11.902	20.497	6.9952	34.11	16.017	11.406	9.6455
26	16.094	13.863	11.98	18.817	3.6654	34.07	17.67	10.296	8.1877
21	12.137	9.9159	8.5039	17.829	3.552	32.203	13.923	6.9693	5.0736
15	9.8411	7.3628	6.2515	16.529	2.9309	30.217	12.1	4.9399	3.2844
7	10.126	7.958	7.0777	15.051	4.6156	25.567	8.7375	7.3629	5.8761

7. Conclusions

This paper presents a novel assessment method of voltage sag frequency considered the power customer satisfaction degree.

It consists of the following advantages: First of all, the analysis method can avoid the insufficient of the traditional method to evaluate the voltage sag frequency in user un-satisfaction area. Secondly, the assessment results considered interval data which can reflect the true influence extent of voltage sag. It has certain guiding significance for rational selection of customer and transformation of system. Finally, the simulation results have shown that this proposed method can meet the reality much better.

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