Voltage Sag Frequency Assessment Considering Customer Satisfaction Degree

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ABSTRACT

To meet the customer's satisfaction degree (CSD) is the essential responsibility of the utilities. Considering CSD, an analytical interval assessment method is proposed. By the determination function derived from the relationship function of the voltage magnitude and the fault line length, the critical fault positions are determined using iterative algorithm. After the interval sag frequency on hand, the quantitative value is determined. This method was applied to a five-buss system and IEEE 30-buss RTS system. The simulation results comparing with existing methods prove that this method is credible and correct. It is suitable for practical application.

I INTRODUCTION

Customer satisfaction degree (CSD) is the main concern for the utilities and customers [1-2]. In fact, the customer needs not only enough power but also CSD [3-4]. With the increasing of sensitive equipments in customer side, the customer complaints due to voltage sag are increasing [5-9]. In order to meet the CSD, voltage sag frequency must be assessed rightly taking the CSD into account.

CSD is a risk measure for the customers. For different customer, the CSD is different while the voltage sag depends on system topology, fault types, fault location and impedance [6-7, 10-11]. Therefore, the customer's complaints are uncertain [12] and it can be presented by an interval data.

The existing voltage sag assessment methods include measurement-statistic [13] and modeling methods. The former is direct and reliable but requires long monitoring periods and costly installation. The later includes analytical method, probability method [11, 13-14], fuzzy method [11, 13] and other uncertainty method [15]. The main goal is to present the uncertainty of system fault. But these models based on assumptions or expert experiences may be unreasonable. Some improved methods are proposed [16-17] also but the CSD is not considered. Considering the interval characteristics of CSD and combining with the secant iteration and Newton iteration method, an interval method was presented in this study.

II CUSTOMER SATISFACTION DEGREE AND ITS INTERVAL CHARACTERISTIC

The CSD is an essential measure for the customer. It is defined as the percentage between equipment normal operation time and total operation time, the details are as follows.

Sets the total operation time is T_t; the normal operation time as T_s; the abnormal operation time as T_c; T_t=T_s+T_c, then, the CSD presented by S % is:

$$S\% = \frac{T_s}{T_s + T_c} \times 100\% = \frac{T_s}{T_t} \times 100\% \qquad (1)$$

The CSD varies in a range. It is presented by an interval data based on the upper and lower thresholds of equipment voltage tolerance. This interval is shown in Fig. 1, where U_{max} and U_{min}, T_{max} and T_{min} are the thresholds to voltage magnitude and sag duration. If sag occurs in the area outside the curve 1, the equipment operates normally. This area is customer satisfaction area. Contrarily, the area inside the curve 2 is un-satisfaction area. The area between the curve 1 and 2 is the uncertainty area. The typical uncertain ranges of equipments are in Tab. 1 [5-8].

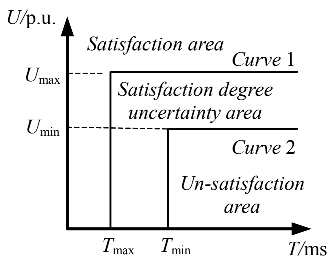

Fig.1 Uncertainty region of load satisfaction

Tab. 1 the uncertain ranges of sensitive equipments

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

Usually, the voltage acceptable characteristics of equipment are described by voltage tolerance curve (VTC) and the distribution rules of VTC. In fact, the uncertain ranges of VTC can be described by an interval number as Eq. (2).

$U_{Interval}$=[U_{min}, U_{max}] and $T_{Interval}$=[T_{min}, T_{max}] (2)

If voltage sag occurs in the satisfaction area, S%=100. In un-satisfaction area, S%=0. In the uncertainty area, S% varies in an interval range. Because the voltage magnitude and sag duration are independent variables in power system, if only consider voltage magnitude, the S% is:

$$S\%=[0, 100] \quad (3)$$

where, if $U \le U_{\min}$, S%=0; if $U \ge U_{\max}$, S%=100.

III VOLTAGE SAGS ASSESSMENT UNDER INTERVAL MEASURE

For the test system in Fig. 2, bus *i* is equipment connecting bus randomly selected. If one fault occurs at *f* on line *m*-*n*, *x* is the distance between *m* and *f*, $0 \le x \le 1$ in p.u, the transfer sequence impedance is expressed as follows[26].

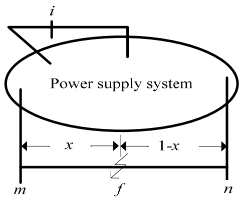

Fig.2 Distances from a fault position *f* to the endpoints on line *m-n*

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

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

where, *k*=0, 1, 2 are zero-, positive-, and negative-sequence; Z_{mm}^k, Z_{nn}^k and Z_{ii}^k sequence driving-point impedances; Z_{im}^k, Z_{in}^k and Z_{mn}^k transfer impedances; z_{mn}^k the unit impedance.

The pre-fault voltage at position *f* is:

$$V_f^{pf} = V_m^{pf} + (V_n^{pf} - V_m^{pf})x \quad (6)$$

where, V_m^{pf} and V_n^{pf} are pre-fault voltage at bus *m* and *n*.

If a single line-to-ground fault occurs at *f*, the distance from *f* to *m* is *x*, to bus *n* is 1-*x*, the voltage magnitude is:

$$V_i = V_i^{pf} - \frac{Z_{if}^0 + Z_{if}^1 + Z_{if}^2}{Z_{ff}^0 + Z_{ff}^1 + Z_{ff}^2} V_f^{pf} \quad (7)$$

A similar study can be conducted for other faults. Based on short circuit analysis, the voltage variation can be obtained. At this time, the voltage sag frequency is an interval range depending on CSD. The interval number of voltage sag is:

$$N_i = [N_c, N_c + N_u] \quad (8)$$

where, N_i is the total uncertain interval number, N_c and N_u are the interval numbers of voltage sag in un-satisfaction area and uncertain area.

IV PROPOSED ANALYTICAL METHOD

A. Critical fault location

If one fault occurs, the pre-fault voltage V_i will drop to V_{th} . V_{th} is the limit voltage. The fault position x_{crit} is the critical fault point.

$$f(x_{crit}) = V_{th} - V_i = 0 \quad (9)$$

Eq. (9) is a high-order equation, direct solution is difficult. Using Newton iteration method, the iteration equation is:

$$x_{n+1} = x_n - \frac{f(x_n)}{f^*(x_n)} \quad (n = 0, 1, 2\cdots) \quad (10)$$

where the x_n , x_{n+1} are iteration values,. $f^*(x_n)$ is the derivative of $f(x_n)$. If the derivative does not exist, it is difficult to solve. The secant iteration method [28] can solve the problem.

$$x_{n+1} = x_n - \frac{x_n - x_{n-1}}{3f(x_n) - 4f(\frac{x_n + x_{n-1}}{2}) + f(x_{n-1})} f(x_n) \quad (11)$$

The iteration method combines the two iteration methods in the previous [28].

B. Un-satisfaction area

The un-satisfaction area is the fault area resulting customer un-satisfaction. For a given CSD, the critical fault point x_{crit} can be generated using the voltage magnitude analytic expressions, the area containing all the critical fault points is the un-satisfaction area, and the details are:

Step I: if the voltage limit is less than the voltage sag magnitude both in the fault line beginning and the end, $x = 0$ and $x = 1$ p.u., the bus is in the satisfaction area.

Step II: if the voltage limit is more than the voltage sag magnitude in all the point, namely more than $0 \le x \le 1$ p.u, the bus is in the un-satisfaction area.

Step III: the voltage limit is between the voltage sag magnitude in the bus beginning and the end, there is a critical fault point and the line is partly in the un-satisfaction area.

Step IV: if the voltage limit is less than the maximum in all the point, and more than the voltage sag magnitude both in the beginning and the end, there are two critical fault points and the line have two parts in the un-satisfaction area.

C. Assessment of Voltage Sag Frequency Based on Un-satisfaction area

Based on the customer un-satisfaction area, the voltage sag frequency resulting in custom un-satisfaction can be assessed. Length of fault line in this area multiplies with the fault rate and the accumulating summation is the voltage sag frequency. Uniform distribution of fault position along the transmission line was assumed, the sag frequency is:

$$N_i = \sum_{j=1}^{n} \delta_j l_j \quad (12)$$

where δ_j and l_j are the fault rate and fault line length in customer un-satisfaction area; *n* is the bus number.

V CASE STUDIES IN A SMALL SYSTEM

A five-bus power system shown in Fig. 3 [19] is simulated. The impedances are indicated in p.u.

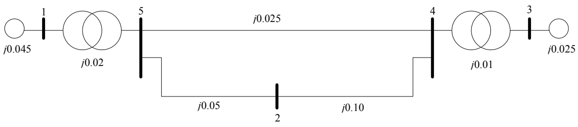

Fig.3 Five-bus system

The limited value of customer satisfied voltage is 0.3 p.u., use the proposed method to assess the voltage sag frequency, three-phase fault along the transmission line was assumed. Tab.2 lists the results comparing with fault position method.

Tab.2 Voltage sags per year at various busses

Buss Number	Proposed Method	Fault Positions Method P=10	P=100	P=1000
2	22.23	24.4	22.52	22.252
4	4.115	5.6	4.28	4.116
5	6.676	8.4	6.92	6.7

It is shown that the number of the fault position is vital importance to the fault position method. If the number of the fault position is less, the result error is bigger. For more positions, the results are closer to the results obtained by the proposed method. It proves the correctness of this method.

Tab.3 gives the numbers of iteration comparison between the proposed method and the secant iteration method solving the critical fault points. It indicates that the proposed method locates the un-satisfaction area more quickly and accurately.

Tab.3 The numbers of iteration at various busses

Buss Number	Proposed Method	Secant Iteration Method
2	9	18
4	8	12
5	8	11

VI CASE STUDIES IN IEEE30-BUS SYSTEM

The simulated system shown in Fig.5 consists of 6 generator units, 30 buses interconnected by 37 lines and 4 transformers. If transformers are $Y_0/\tilde{\Delta}11$ connecting. Four types of faults including three-phase fault, single-line-to-ground fault, line-to-line fault and double-line-to-ground fault are taken into account.

If the sensitive equipment is ASD, the interval data of CSD [0.59,0.71] can be identified. If bus 21 is the customer connecting bus, the uncertainty region can be calculated when a three-phrase short circuit fault occurs, the results shown in figure 4. The area inside real line is the un-satisfaction region; the area between the dotted and real line is the uncertainty region, other fault types are familiar.

In the uncertainty region, the voltage sag frequency interval leading to customer satisfaction can be evaluated, the potential hazard of the system can be forecasted, and evidence can be provided to improve the customer satisfaction degree.

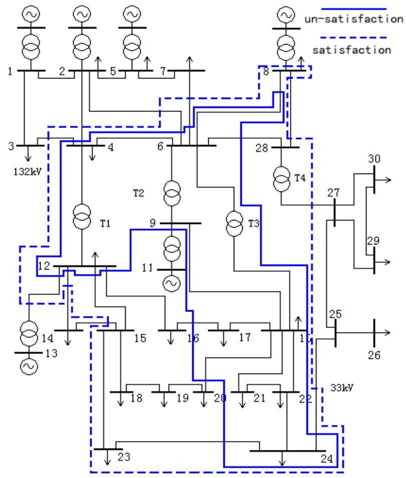

Fig.4 Uncertainty region of load satisfaction in buss 21 for three-phase faults

The result accuracy can be verified by Monte Carlo Simulation. In order to verify this method, bus 7, 15, 21, 26, 30 are randomly chosen as the equipment connecting bus, and the equipments are PC, PLC and ASD. By the proposed method and Monte Carlo Simulation respectively, the results are shown in Tab.4. It is clear that the proposed method is in keeping with the Monte Carlo Simulation.

Tab.4 Voltage sags per year for different assessment methods

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

As shown in Tab.4, the evaluation results which taking the CSD into account are no longer a single value, but an interval data. So the voltage sag frequency will not exceed the gained interval as long as the changing of CSD does not exceed the predetermined range, therefore, in order to reduce the amount of calculation, repeatedly single value evaluation is not necessary. If a quantitative evaluation is needed, variances can be sampled from the obtained interval results according to risk tolerance of the customers and the distribution rule of acceptable interval of customer equipment, and this variance can be regarded as the final result. Based on the research of [15], when PC, PLC, ASD are evaluated, they are assumed to comply with the normal distribution, exponential distribution, negative exponential distribution respectively, corresponding evaluation results are shown in Tab 5.

As it is shown in Tab 5, different distribution rules have a huge influence on the evaluation results of voltage sag frequency. The interval characteristics of the uncertainty region of customer satisfaction, and the influence of distribution rules of customer equipment sensitivity on voltage sag frequency should be taken into full account when choosing the customer access point. In the simulation experiment of this paper, when the sensitivity degree of ASD complies with the normal and exponential distribution, bus 15 should be regarded as the best access point; when the sensitivity degree complies with the negative exponential distribution, the bus 7 should be regarded as the best access point. It can clearly be seen that the evaluation result which has taken the characteristics of customer satisfaction interval into account has more information, and has a certain application prospect.

Tab.5 Voltage sags per year for different sensitivity distributions

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

VII CONCLUSIONS

(1)This paper based on interval data of CSD identifies the customer un-satisfaction area by an analytic method. It is adaptive for radical network and meshed networks.

(2)The evaluation results taking the CSD into account can reflect how much the customers are influenced by the voltage sag. It has certain directive significance both for choosing the customer connecting site and system operation.

(3)Simulation results have proved that the proposed method is correct and suitable for practical applications.

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