Allocation of Load-Loss Cost Caused by Voltage Sag

X Gao
State Grid Energy Research Institute, Beijing 102209, P.R.China
Email: gaoxiao@sgeri.sgcc.com.cn

Abstract. This paper focuses on the allocation of load-loss cost caused by voltage sag in the environment of electricity market. To compensate the loss of loads due to voltage sags, the load-loss cost is allocated to both sources and power consumers. On the basis of Load Drop Cost (LDC), a quantitative evaluation index of load-loss cost caused by voltage sag is identified. The load-loss cost to be allocated to power consumers themselves is calculated according to load classification. Based on the theory of power component the quantitative relation between sources and loads is established, thereby a quantitative calculation method for load-loss cost allocated to each source is deduced and the quantitative compensation from individual source to load is proposed. A simple five-bus system illustrates the main features of the proposed method.

1. Introduction

According to IEEE Standard 1159-1995 [1], a voltage sag is defined as an rms variation with a magnitude between 10% and 90% of nominal and a duration between 0.5 cycles and one minute. In distribution networks, voltage sag is an increasingly important issue to electricity consumers at all levels of voltage. It causes malfunction of equipments and economic losses of consumers. A serious voltage sag at the terminals of customer may lead to machine/process downtime, scrap cost, clean up costs, product quality and repair costs. For example, voltage sags can cause the most sensitive equipments like ASD’s, PLC’s to trip, thus affecting industrial production process leading to revenue loss. The possible action for customers to decrease the effects of voltage sag is to purchase auxiliary equipments like UPS, adapt the producing process, and so on. The total cost of all these actions is called load-loss cost, which contribute to make voltage sags costly to the customers. It is obviously unreasonable that customers undertake the total load-loss cost themselves under electricity markets. So who are the objects responsible for the load-loss cost and how to quantitatively allocate this cost to the objects are urgent problems in electricity markets.

Although no indices are part of any standard document, a set of voltage sag indices are widely used, especially by utilities. The most commonly referred index is the System Average RMS variation Frequency Index (SARFI) [2], which provides a count or rate of voltage sags, swells, and interruptions for a system. The sag energy method of characterization gives total “lost energy” on a bus, such as Sag Energy Index (SEI), which is the sum of the voltage sag energies for all qualified events at a given bus during a given period [3]. For three-phase systems the sag energy is added for the three phases. Some other methods for the evaluation of voltage sag are proposed in reference [4]-[9]. However, no direct index is available for the customers’ loss due to voltage sag yet.

In this paper, the quantitative evaluation of voltage sag is illustrated at first. Then the objects...
responsible for load-loss cost and the allocation principle are analyzed and proposed. What is more, the load-loss cost allocated to each load is determined by the quantitative evaluation index of voltage sag. At last, each source compensate for load-loss cost to load based on the complex-power relation between sources and loads.

2. Economic Evaluation of Voltage Sag

Voltage sags may have significant economic effects on some facilities. Based on the voltage sag indices the average LDC [10], an evaluation index load-loss cost is identified to quantify the economic effects from voltage sag. In power systems, load customers are usually divided into four types: resident, commercialist, small industries and large industries. LDC indicates the average cost of one type of customer at the same bus when the expected demand affected by sags is 1kW. LDC is associated with actions that customer take on their own behalf to reduce the effects of voltage sags. Thus the load-loss cost of one type of customer can be expressed as:

\[
\sigma = LDC \cdot P
\]  

(1)

Where, \(\sigma\) is the load-loss cost, \(P\) is the expected demand affected by sags of the customers of the same type. Because the LDC is the average cost of one type of customer, the load-loss cost calculated in this way is imprecise. The total customers’ load-loss cost of one bus is the sum of the cost of four types of customers. Of course, the total cost of a power system is the sum of the cost over all buses in this system.

3. Load-loss Cost Allocation Rules

In our opinion, a load-loss cost should satisfy the following two rules. First, the payers responsible for the load-loss cost are defined; second, how much each entity has to pay is identified.

In liberalized power markets, an unbundled power supply utility is the owner of transmission and distribution grids and is responsible for the power quality service. The power is provided by the generators, then transmitted by the transmission network and distributed by the distributed system, at last delivered to the loads. In this process, voltage sag can be caused by fault conditions within the plant or power system and lasts until the fault is cleared by protective device. So each entity can cause voltage sags. The utility owning the grids is also one source of voltage sags. Obviously, all the probable sources causing voltage sag should be responsible for load-loss cost. Therefore, the payers responsible for the load-loss cost are the independent generators, the utility owning distribution and transmission grids and the loads. The first two entities serve loads together. How much each entity should pay for the load-loss cost is a complicated problem concerning circuit and economics theory. Three relevant rates are defined. One, denoted by \(\lambda_u\) denotes the rate at which utility owing grids is charged for the load-loss cost. The second, denoted by \(\lambda_s\) denotes the rate at which loads are charged for the load-loss cost. The third, denoted by \(\lambda_g\) denotes the rate at which generators are charged for the load-loss cost. It is difficult to assign financial responsibility for voltage sag to utility, generators and loads exactly since all of them maybe the source of voltage sag. Thus the load-loss cost could be allocated to entities by their contribution to voltage sags. The rates can be calculated as follows.

\[
\lambda_u = \frac{t_u}{t_u + t_s + t_j}
\]
\[
\lambda_u = \frac{t_u}{t_u + t_s + t_l}
\]

\[
\lambda_s = \frac{t_s}{t_u + t_s + t_l}
\]

Where, \(t_u\) is the total number of sags caused by utility, \(t_s\) by all generators, and \(t_l\) by all loads. The entity that causes more voltage sags would be charged more for load-loss cost by this method. It is reasonable and predictable. But these equations only give a simple way to determine the three rates. In the actual network operation, more factors might effect the determination of them. The factors include the amount of equipments sensitive to voltage sags, the sensitivity of loads, the reliability of grids, and so on.

Another effective method to obtain the rates is authority survey. The questionnaires are designed to seek the respondent’s opinion and judgement on issues about these rates. According to statistic and analysis on the response, a set of reasonable rate can be determined. This method avoids the errors in the calculation of rates. In our regard, the unbundled power supply utility shoud be charged for most of the load-loss cost, then loads for less, and sources for the least. \(\lambda_u\) value is set to 0.5, \(\lambda_s\) is 0.15, and \(\lambda_l\) is 0.35. The reasons are as follows. One, the utility is responsible for the voltage support service in liberalised power markets round the world. Two, those facilities improving voltage quality are attached to the responsibility of the transmission and distribution utilities. Three, usually voltage sags are mostly caused by faults in electric transmission and distribution grids, such as short-circuits, switchings, lightings. Four, loads are another major source causing voltage sags, such as large motor starting and load switching. Five, power sources can cause voltage sags in case of internal short-circuit.

Consequently, the allocating rules about load-loss cost are proposed. The load-loss cost of individual load is divided into three parts. The load is charged for \(\lambda_l\) of the load-loss cost by itself, the utility owing grids is charged for \(\lambda_u\), and all generators are charged for \(\lambda_s\) together. The load-loss cost allocated to generators or load is less than that to utility. And this case coincides with the physical fact that the overall contribution of transmission and distribution grids to voltage sags is much more than generators or loads. The cost each entity responsible for is also reasonable in economical benefit.

4. Allocation of Load-loss Cost to Customers

In the power grid, the loads at individual buses are different in composition. So the load vulnerability and LDC at buses are not the same, and this lead to the difference of load-loss cost among each bus. The bigger the LDC at a bus, the bigger the load-loss cost of customer at this bus. The above analysis focuses on a particular type of customer. Likewise, the four types of customers can obtain their own load-loss cost. If residential, commercial, small industrial and large industrial customers at a bus obtain the load-loss cost \(\sigma_R\), \(\sigma_C\), \(\sigma_{SI}\) and \(\sigma_{LI}\), the load-loss costs that these customers should be charged for by themselves are \(\lambda_l\sigma_R\), \(\lambda_l\sigma_C\), \(\lambda_l\sigma_{SI}\) and \(\lambda_l\sigma_{LI}\) respectively. Among the same type of customers, each should be charged for \(\lambda_l\) of its load-loss cost by itself.

5. Allocation of Load-loss Cost to Sources

5.1 Allocation Method. The sources for a distribution grid commonly include independent generators and upgrade systems in the system. If a generator is the only source for the loads in the
distribution grid with one power injecting bus, this generator should be charged for $\lambda_s$ of the total load-loss cost of the distribution grid alone. When two or more sources connected to the distribution system, $\lambda_s$ of the load-loss cost should be allocated to each source. In this case, how to accurately allocate the total load-loss cost of all customers at one bus to each individual source is the key problem in this cost allocation. Therefore, this paper begins the analysis with a simple power system. For the simplicity of analysis, the steady-state model is used in the discussion. The load is represented by constant MVA. And annual average loads are used for cost allocation. All the customers connected to one load bus are considered as one equivalent load. The demand of an equivalent load is equal to the sum of total demand of all loads connected to this bus. According to the theory of complex power components incurred by individual generators [11, 12], the allocation procedure is as follows. Firstly, the power that one source provides for one equivalent load is calculated. Secondly, the relation between source and load connected to a bus is quantified. At last, $\lambda_s$ of the load-loss cost of all customers at each bus is allocated to individual sources according to the above quantitative relation.

5.2 Power Contribution of A Source to A Load. A 3-bus distribution system in Figure 1 consisting of two sources and one load is used in this section. An independent generator is connected to the end of the distribution network, which connects to another source S via two lines. The impedance of each line and the power from each source to the network are also shown in Figure 1. The equivalent load at bus 2 is $P_L + jQ_L$ (MVA). Bus 3 is selected as slack bus, its voltage is $U_3 \angle 0 \, kV$.

![3-bus distribution system](image)

We denote the power flowing from source S to the distribution network by $P_S + jQ_S$ (MVA), the voltages at buses 1 and 2 by $U_1 = U_1 \angle \theta_1$ and $U_2 = U_2 \angle \theta_2$, respectively. The total current injecting into the load at bus 2 is

$$I_L = (\frac{(P_L + jQ_L)}{U_2}) = a_L + jb_L$$

This current is supplied by the source S and the independent generator together. Therefore the equivalent impedance of the load is

$$Z_L = \frac{U_2}{I_L} = r_L + jx_L$$

In the calculation of the power relation of one source to a load, we suppose that only the considered source work. So the power contribution of this single source to load is determined. Assuming that bus 3 disconnects to the source S, only the independent generator G will supply power to the load in this distribution network. In this case, the response current of $Z_L$ is

$$I_G = (\frac{(P_G + jQ_G)}{U_1}) = a_G + jb_G$$
Based on the complex power components incurred by individual sources, the active power delivered to the load and withdrawn from the generator is

\[ P_{Gl} = r_L (I_G \cdot I_L) = r_L (a_G a_L + b_G b_L) \]  

(2)

The linear admittance model of network is simple and unambiguous. Although this relation is based on linear network, it illustrates the power contribution of the source to the load directly.

Likewise, the active power delivered to the load and withdrawn from source S is

\[ P_{Sl} = r_L (I_S \cdot I_L) = r_L (a_S a_L + b_S b_L) \]  

(3)

Where \( I_S \) is the response current of \( Z_L \) when the distribution network connects to the source S and disconnects to generator G. And it is expressed as follows:

\[ I_S = \left( \left( P_S + jQ_S \right)/U_j \right)^* = a_S + j b_S \]

5.3 Compensation to Loads by Each Source. Supposing that there are \( n \) sources in an \( m \)-bus system and source \( G_i \), \( (i=1,2,...,n) \) (including generator, transmission grid and adjacent distribution grid) supplies active power \( P_{Gij} \) to the equivalent load \( L_j \), \( (j=1,2,...,m) \). Given that only the source \( G_i \) supplies power to loads and other sources open, the circuit then contains only source \( G_i \) and all equivalent impedances of loads, the current through an equivalent impedance from source \( G_i \) is determined by KCL and KVL. The active power to the same load from \( G_i \) is also obtained according to equations (2) and (3). At a load bus, \( \lambda \) of the sum of load-loss cost of all customers at load bus \( L_j \) is allocated to individual sources in proportion to \( P_{Gij} \). We denote by \( \eta_j \) the ratio of load-loss cost charged by the source \( G_i \), then we have

\[ \eta_j = \frac{P_{Gij}}{\left( \sum_{k=1}^{n} P_{Gjk} \right)} \]

(4)

Provided that the sum of load-loss cost of all customers at bus \( j \) is \( A_j \), source \( G_i \) takes the share of \( \lambda_j \eta_j A_j \). In another word, \( G_i \) should pay \( \lambda_j \eta_j A_j \) to the equivalent load \( L_j \) for the load-loss cost.

As for the whole system, the load-loss cost paid by one source is equal to the sum of the cost paid by this source at each bus in this system. So after obtaining the cost that one source pays at each bus, the total cost that this source pays can be determined. We denote by \( B_i \) the part of cost \( G_i \) is responsible for.

\[ B_i = \sum_{h=1}^{m} \lambda_h \eta_h A_h \]

(5)

The total amount of load-loss cost charged by \( G_i \) is \( B_i \). Then all this money should compensate to each load according to the LDC.

6. A 5-bus Example

A simple 5-bus power system shown in Figure 2 is employed in this section. An independent
generator $G_1$ is at the end of this network, connecting with another source $G_2$. Between $G_1$ and $G_2$ four lines connected in series. All parameters of the system are shown in Figure 2.

![Figure 2. 5-bus distribution grid](image)

Bus 5 in the distribution network is selected as reference. The voltage at this bus is $U_5 = 35.3 \angle 0$ (kV). Based on the data in Figure 2, the power flow results are given in Table I. The power delivered to bus 5 and withdrawn from transmission system $G_2$ is $4.8806+j2.4624$ MVA, the total power loss is $0.08105141+j0.1631660$ MVA, and the voltage at each bus is also shown in Table I.

| Voltage $V_i$(kV) | 1      | 2      | 3      | 4      | 5      |
|-------------------|--------|--------|--------|--------|--------|
| Phase $\delta_i$(rad) | -0.02161 | -0.02309 | -0.01857 | -0.009325 | 0      |

The equivalent current through each equivalent impedance of loads and the current withdrawn from each single source are determined based on the initial power flow solution of the system, as shown in Table II.

| Current $I(kA)$ | $G_1$ | $G_2$ | $L_1$ | $L_2$ |
|-----------------|-------|-------|-------|-------|
| Phase (rad)     | -0.8977 | -0.4636 | -0.5571 | -0.5671 |

The load $L_1$ consists of only one residential customer, $L_2$ consists of one residential, one commercial, one small and one large industrial customer. Investigation and statistic analysis show that each type of customer’s expected demand affected by voltage sags. This demand and the LDC are illustrated in Table III. Thus the load-loss cost is determined, which is also shown in Table III.
In this distribution grid, $\lambda_r$, $\lambda_c$ and $\lambda_l$ equals 0.5, 0.15 and 0.35 respectively. Consequently, the load-loss cost of load $L_1$ is 187.57 $ and the cost of $L_2$ 27422 $. At bus 2, the utility owing grids pays 93.79 $ for load-loss cost to customer, all sources pay 28.137 $, and the customer is charged 65.653 $. Furthermore, as for the part of cost which all sources are responsible for, source $G_1$ and $G_2$ are charged 5.907 $ and 22.227 $ respectively. Similarly at bus 3, all sources compensate load $L_3$ 4113.3 $ for load-loss cost together, the utility pays 13711 $ and all customers are charged 9597.7 $. Source $G_1$ pays 904.8 $ and $G_2$ pays 3208.5 $. As a result, in the total distribution system, $G_1$ pays 910.707 $ and $G_2$ pays 3230.727 $. Further at bus 3, the cost allocated to each type customers is $\lambda_r$ of the total load-loss cost of the same type customers. Thus the residential customers are charged 89.964 $, commercial ones are charged 3427.2 $, little industrial customers are charged 2735.236 $ and large industrial customers are charged 3345.3 $ respectively.

7. Conclusions

For a distribution grid, the transmission grid, the adjacent distribution grid, the independent generator and the load are responsible for voltage sags. As a result, they are responsible for the load-loss cost together from an economical benefit point of view. Obviously, the probable sources of voltage sag are responsible for load-loss cost. Taking example for a simple power system with only residential user connected to the bus, the quantitative evaluation index of load-loss cost is determined. When many sources are in the power system, the share of load-loss cost of all customers at one bus paid by each source is in proportion to the power contribution supplied by corresponding source to equivalent load at the same bus. Further, the compensation from sources is allocated to each type of loads in the direct ratio of load-loss cost. Thus each customer gets its compensation on the basis of its power flow. The load-loss caused by voltage sag is usually analyzed by considering the characterization of voltage change merely. Nevertheless the method proposed in this paper achieves to analyze voltage sag with its physical and financial characteristics. The utility owing grids, generators and loads will do more things to solve the voltage sag problems under financial incentives. So that all sources of voltage sag are responsible for the load-loss cost can improve power system safety.

References
IEEE 1995 Recommended Practice for Monitoring Electric Power Quality. IEEE Standard 1159-1995.

[2] Bollen M H J, Sabin D D and Thallam R S 2003 Voltage-sag indices – recent developments in IEEE P1564 Task Force. CIGRE/IEEE-PES on Quality and Security of Electric Power Delivery Systems 10 34-41.

[3] Martinez J A and Martin-Arnedo J 2002 Voltage sag analysis using an electromagnetic transients program. IEEE Power Engineering Society Winter Meeting 2 1135-40

[4] Lamoree J, Mueller D, Vinett P, Jones W, and Samotiy M 1994 Voltage Sag Analysis Case Studies. IEEE Transaction on Industry Applications 30 1083-89

[5] Su C L 2010 Stochastic evaluation of voltages in distribution networks with distributed generation using detailed distribution operation models. IEEE Transactions on Power Systems 25 786-795.

[6] Heine P, Pohjanheimo P, Lehtonen M, and Lakervi E 2002 A method for estimating the frequency and cost of voltage sags. IEEE Transactions on Power Systems 17 290-296.

[7] Tan R H G and Ramachandaramurthy V K 2012 Voltage sag acceptability assessment using multiple magnitude duration function. IEEE Transactions on Power Delivery 27 1984-90

[8] Bollen M H J, Tayjasanant T and Yalcinkaya G 1997 Assessment of the number of voltage sags experienced by a large industrial customer. IEEE Transactions on Industry Applications 33 1465-71.

[9] Park C H, Hong J H and Jang G 2010 Assessment of system voltage sag performance based on the concept of area of severity. IET Generation, Transmission & Distribution 4 683-693.

[10] Lee Geun-Joon, Albu M M and Heydt G T 2004 A power quality index based on equipment sensitivity, cost, and network vulnerability. IEEE Transactions on Power Delivery 19 1504-10.

[11] Peng J C and Jiang H 2002 Contributions of individual generators to complex power losses and flows-part 1: fundamental theory. IEE Proceedings on Generation, Transmission and Distribution 149 182-185.

[12] Peng J C and Jiang H 2002 Contributions of individual generators to complex power losses and flows-part 2: algorithm and simulations. IEE Proceedings on Generation, Transmission and Distribution 149 186-190.