An Adjustment Scheme of Rewarding and Penalizing Electricity Charges considering unbalanced Responsibility

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Abstract

In this paper, the three-phase unbalanced system is taken as the research object, aiming to establish a reasonable adjustment scheme of rewarding and penalizing electricity charges. First of all, the traditional unbalance responsibility indexes and responsibility division methods are analysed, which proves theoretically that the evaluation essence of each responsibility index is different. Secondly, Secondly, according to the decomposition of apparent power by IEEE Std.1459-2010 power theory, a new division method of the unbalance responsibility considering index weight under the multi-index system is proposed, which can comprehensively consider the influence of negative-sequence voltage and negative-sequence current. Thirdly, in view of the shortcomings of the current adjustment scheme of electric charges, this paper puts forward an adjustment scheme of rewarding and penalizing electric charges considering the unbalance responsibility. Finally, the rationality of the new scheme is verified by a specific simulation example.

Keywords: unbalance responsibility, index weight, IEEE Std.1459-2010, apparent power, adjustment scheme of electricity charges.

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1. Introduction

Under the background of the rapid development of the economy and modern industry, the more and more asymmetric loads are connected to the power grid, such as electric arc furnace, electric locomotive and electric welding machine, which makes the power quality problem of three-phase voltage unbalance in the public power grid increasingly serious [1]-[3].

When the three-phase voltage of the power system is unbalanced, it will produce a series of adverse effects, such as the electrical equipment can't operate safely and stably, increasing the power loss of transmission lines, and the capacity of the transformer can't be fully utilized, etc.[4]. Besides, the negative-sequence component of voltage and current will affect the accuracy and rationality of electric energy metering. Therefore, to restrain the power consumption behavior of power customers and effectively solve the power quality problem of three-phase voltage unbalance in the power grid, it is necessary to develop a reward and penalty power supply scheme, and the premise for the successful implementation of the reward and penalty scheme is to reasonably divide the unbalance responsibilities of power suppliers and consumers.

At present, the adjustment scheme of electric charge in China is the Power Factor Adjustment Electric Charge Method, which mainly assesses the reactive power of customers. However, with the increasing number of non-linear and unbalanced loads in the power grid, the existing adjustment scheme of electricity charges exposes many shortcomings, such as low assessment standard, low charging intensity and long charging period, etc., and does not assess the customer's unbalance responsibility, which can no longer meet the demand of the current power market [5], [6].

In reference [7], the shortcomings of the existing power factor metering methods are analysed and proposes a new method of power factor calculation based on metering error under harmonic condition, but the influence of three-phase unbalance is not considered in this method.

The reference [8] analysed the influence of negative-sequence on the metering accuracy of energy meters and considers that negative sequence electrical energy should be measured but does not give a specific scheme.

In reference [9], the influence of negative-sequence on the active energy measurement method and puts forward a new metering scheme which takes the positive-sequence active energy as the measurement subject because of the irrationality of the traditional energy metering method under the negative-sequence condition. However, this scheme does not consider the customer's unbalanced responsibility, which is not conducive to the treatment of electrical energy pollution. At present, there are relatively more researches on harmonic source location and responsibility division methods at home and abroad [10]-[12], but there are relatively few studies on the identification of unbalanced source and responsibility division methods.

The references [13], [14] mainly researches the compensation and control strategy of three-phase unbalance, which does not involve the evaluation of the three-phase unbalance level, so it is unable to further divide the unbalanced responsibility of utility side and customer side.

In references [15]-[17], the harm of three-phase unbalances in the power system is realized, and gradually began to study the identification methods of three-phase unbalanced sources. However, these methods identify the main unbalanced sources in the system from a qualitative point of view and do not quantify the unbalance responsibility of each source.

In references [18]-[20], it is realized that the accurate division of the responsibility of each unbalanced source is the scientific basis for the power sector to carry out economic rewards and penalties, and the method of quantitative division of the unbalance responsibility of the unbalanced sources has been studied. But the results of the division of responsibility obtained by using different responsibility indexes and methods are quite different. Besides, when the unbalance responsibility of each unbalanced source is clear, how to carry out the corresponding reward and penalty has not given a specific scheme.

In references [22], [23], the current situation of China's power market is analysed in detail, pointing out that there are still shortcomings, which need to be improved continuously.

In view of the problems existing in the above literature, this paper is organized as follows:

Part 2 analyses the traditional unbalance responsibility indexes and responsibility division methods and proves that the evaluation essence of each responsibility index is different.

In part 3, according to the decomposition of apparent power by IEEE Std.1459-2010 power theory, a new division method of the unbalanced responsibility considering the index weight under the multi-index system is proposed.

Part 4 puts forward an adjustment scheme of rewarding and penalizing electric charges considering the unbalance responsibility.

In part 5, the rationality of the new adjustment scheme of rewarding and penalizing electricity charges is verified by a specific simulation example.

2. Analysis of the traditional method of unbalance responsibility division

2.1 Establishment of negative-sequence equivalent circuit model

Figure 1 is a schematic diagram of the three-phase three-wire unbalanced power system.

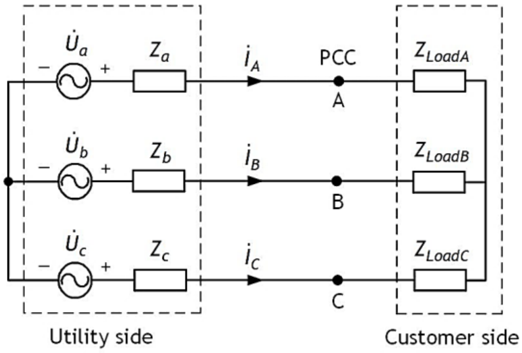

Figure 1. Schematic diagram of the three-phase three-wire power system

In Figure 1, $\dot{U}_a$, $\dot{U}_b$ and $\dot{U}_c$ are the three-phase unbalance power supply on the utility side, Z_a , Z_b and Z_c are the equivalent impedance of the internal impedance of the power supply and the equivalent impedance of the line, and Z_{LoadA} , Z_{LoadB} and Z_{LoadC} are the asymmetrical load impedances on the customer side. Because the three-phase voltage unbalance at the point of common coupling (PCC) is caused by the interaction of the utility and customer sides, both sides are equivalent to an unbalanced source.

With referring to the modelling idea of harmonic source equivalent circuit [24], the negative-sequence network in Figure 1 can be equivalent to the negative-sequence equivalent circuit shown in Figure 2, that is, the utility and customer sides are modelled by Norton equivalent model respectively.

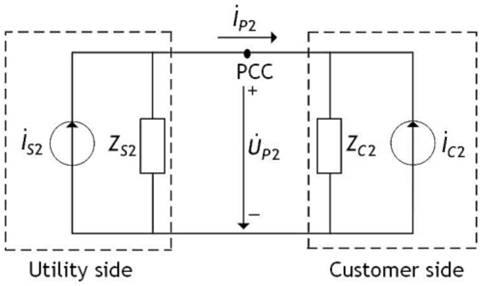

Figure 2. Negative-sequence equivalent circuit

Where $\dot{I}_{S2}$ and Z_{S2} are the equivalent negative-sequence current source and negative-sequence reference impedance on the utility side; $\dot{I}_{C2}$ and Z_{C2} are the equivalent negative-sequence current source and negative-sequence reference impedance on the customer side; $\dot{U}_{P2}$ and $\dot{I}_{P2}$ are the negative-sequence voltage and negative-sequence current at the PCC respectively (the subscript number 2 of the variable in this paper represents the negative-sequence).

In this paper, the reference impedance method is used to solve the equivalent negative-sequence reference impedance of the utility side and customer side [20]. The equivalent negative-sequence reference impedance Z_{C2} of the customer side can be directly replaced by the positive-sequence impedance Z_{C1} of the customer [17], and the difference between the actual value and the reference value of the customer side equivalent negative-sequence impedance is converted into the change of the customer side equivalent negative-sequence current source value, while Z_{C1} can be calculated by the positive-sequence voltage $\dot{U}_{P1}$ and current $\dot{I}_{P1}$ at the PCC, as shown in equation (1) (the subscript number 1 of the variable in this paper represents the positive-sequence).

$$Z_{C2} = Z_{C1} = \frac{\dot{U}_{P1}}{\dot{I}_{P1}} \tag{1}$$

The value of the equivalent negative-sequence reference impedance Z_{S2} on the utility side is the sum of the impedance of the last transformer before the PCC and the short-circuit impedance of the power grid, which can also be replaced by the actual impedance on the utility side [20].

According to figure 2, we can get

$$\dot{I}_{S2} = \frac{\dot{U}_{P2}}{Z_{S2}} + \dot{I}_{P2} \tag{2}$$

$$\dot{I}_{C2} = \frac{\dot{U}_{P2}}{Z_{C2}} - \dot{I}_{P2} \tag{3}$$

According to the superposition theorem, when the utility side acts alone, we can get the following formulas.

$$\dot{I}_{SP2} = \frac{Z_{S2}}{Z_{S2} + Z_{C2}} \dot{I}_{S2} \tag{4}$$

$$\dot{U}_{SP2} = \frac{Z_{S2} Z_{C2}}{Z_{S2} + Z_{C2}} \dot{I}_{S2} \tag{5}$$

When the customer side acts alone, we can get

$$\dot{I}_{CP2} = -\frac{Z_{C2}}{Z_{S2} + Z_{C2}} \dot{I}_{C2} \tag{6}$$

$$\dot{U}_{CP2} = \frac{Z_{S2} Z_{C2}}{Z_{S2} + Z_{C2}} \dot{I}_{C2} \tag{7}$$

Where $\dot{I}_{SP2}$ and $\dot{U}_{SP2}$ are the negative-sequence current and voltage generated at PCC point when the utility side acts alone, and $\dot{I}_{CP2}$ and $\dot{U}_{CP2}$ are the negative-sequence voltage and current generated at PCC when the customer side acts alone.

According to the superposition theorem, the negative-sequence voltage $\dot{U}_{P2}$ and current $\dot{I}_{P2}$ at PCC are

$$\dot{U}_{P2} = \dot{U}_{SP2} + \dot{U}_{CP2} \tag{8}$$

$$\dot{I}_{P2} = \dot{I}_{SP2} + \dot{I}_{CP2} \tag{9}$$

2.2 The traditional method of unbalance responsibility division

The traditional method of dividing unbalance responsibility is to use negative-sequence voltage and current index to share the responsibility of the utility and customer sides.

The (a) and (b) diagrams in Figure 3 are the phasor diagrams of negative-sequence voltage and current, U_{SP} and U_{CP} are the projections of phasor $\dot{U}_{SP2}$ and $\dot{U}_{CP2}$ in the direction of phasor $\dot{U}_{P2}$, I_{SP} and I_{CP} are the projections of phasor $\dot{I}_{SP2}$ and $\dot{I}_{CP2}$ in the direction of phasor, U_{P2} and I_{P2} are the module (effective values)of phasor $\dot{U}_{P2}$ and $\dot{I}_{P2}$, so

$$U_{P2} = U_{SP} + U_{CP} \tag{10}$$

$$I_{P2} = I_{SP} + I_{CP} \tag{11}$$

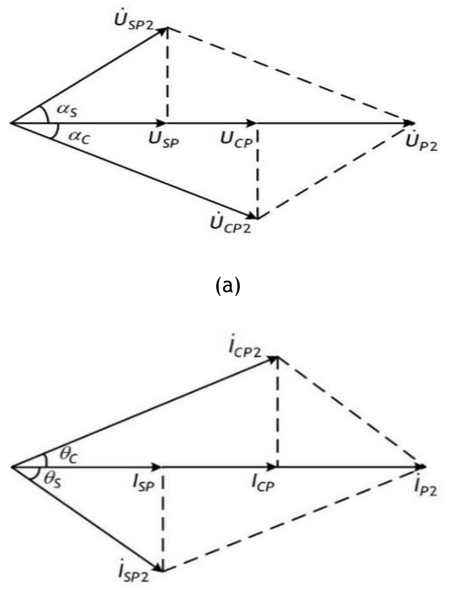

Figure 3. Negative-sequence voltage and current phasor diagram

To divide the unbalance responsibility by the negative-sequence voltage index, the quantitative calculation expressions of the responsibility that the utility and customer sides should bear are shown in formula (12) and formula (13) respectively.

$$R_{S-U} = \frac{U_{SP}}{U_{P2}} \times 100\% = \frac{U_{SP2}\cos a_S}{U_{P2}} \times 100\% \tag{12}$$

$$R_{C-U} = \frac{U_{CP}}{U_{P2}} \times 100\% = \frac{U_{CP2}\cos a_C}{U_{P2}} \times 100\% \tag{13}$$

where a_S is the included angle between the phasor $\dot{U}_{SP2}$ and $\dot{U}_{P2}$, a_C is the included angle between the phasor $\dot{U}_{CP2}$ and $\dot{U}_{P2}$.

Similarly, when the negative-sequence current index is used to divide the unbalance responsibility, we can get

$$R_{S-I} = \frac{I_{SP}}{I_{P2}} \times 100\% = \frac{I_{SP2}\cos\theta_S}{I_{P2}} \times 100\% \qquad (14)$$

$$R_{C-I} = \frac{I_{CP}}{I_{P2}} \times 100\% = \frac{I_{CP2}\cos\theta_C}{I_{P2}} \times 100\% \qquad (15)$$

where θ_S is the included angle between the phasor $\dot{I}_{SP2}$ and $\dot{I}_{P2}$; θ_C is the included angle between the phasor $\dot{I}_{CP2}$ and $\dot{I}_{P2}$.

2.3 *Rationality analysis of negative-sequence voltage and current responsibility index*

Negative-sequence voltage and current are two key responsibility indexes which are commonly used in the research on the division of unbalanced responsibility at present. In the same circuit, when the negative-sequence voltage and negative sequence current responsibility indexes are used to judge the unbalance responsibility, the following situations will appear:

- 1) When $U_{SP} > U_{CP}$ and $I_{SP} > I_{CP}$, both methods determine the utility side as the main unbalance responsible party;
- 2) When $U_{SP} < U_{CP}$ and $I_{SP} < I_{CP}$, both methods determine the customer side as the main unbalance responsible party;
- 3) When $U_{SP} > U_{CP}$, $I_{SP} < I_{CP}$ or $U_{SP} < U_{CP}$, $I_{SP} > I_{CP}$, the results of the two methods are inconsistent.

It can be seen from this that when different indexes are selected for unbalance responsibility judgment, the judgment results will be inconsistent. The reason is that the evaluation essence of the selected responsibility indexes is different.

The theoretical proof is given as follows. According to the voltage relationship and triangular formula shown in (a) of Figure 3, we can get:

$$U_{SP2}^2 = U_{P2}^2 + U_{CP2}^2 - 2U_{P2}U_{CP2}\cos a_C \qquad (16)$$

$$U_{CP2}^2 = U_{P2}^2 + U_{SP2}^2 - 2U_{P2}U_{SP2}\cos a_S \qquad (17)$$

From equations (16) and (17), it can be obtained that

$$U_{SP} = U_{SP2}\cos a_S = \frac{U_{P2}^2 + U_{SP2}^2 - U_{CP2}^2}{2U_{P2}} \qquad (18)$$

$$U_{CP} = U_{CP2}\cos a_C = \frac{U_{P2}^2 + U_{CP2}^2 - U_{SP2}^2}{2U_{P2}} \qquad (19)$$

By subtracting formula (18) and formula (19), we can get:

$$U_{SP} - U_{CP} = \frac{U_{SP2}^2 - U_{CP2}^2}{U_{P2}} \qquad (20)$$

where U_{SP2} and U_{CP2} are the module of the phasor $\dot{U}_{SP2}$ and $\dot{U}_{CP2}$ respectively.

From equations (4), (6) and (20), it can be obtained that:

$$U_{SP} - U_{CP} = \frac{|Z_{S2}Z_{C2}|^2}{|Z_{S2}+Z_{C2}|^2 U_{P2}}(I_{S2}^2 - I_{C2}^2) \qquad (21)$$

It can be seen from equation (21) that if $U_{SP} > U_{CP}$, and only if $I_{S2} > I_{C2}$.

Similarly, according to the current relationship shown in (b) of Figure 4 and the corresponding formula, it can be concluded that:

$$I_{SP} - I_{CP} = \frac{|Z_{S2}|^2 I_{S2}^2 - |Z_{C2}|^2 I_{C2}^2}{|Z_{S2}+Z_{S2}|^2 I_{P2}} \qquad (22)$$

where I_{S2} and I_{C2} are the module of phasor $\dot{I}_{S2}$ and $\dot{I}_{C2}$ respectively. It can be seen from equation (22) that if $I_{SP} > I_{CP}$, and only if $|Z_{S2}|I_{S2} > |Z_{C2}|I_{C2}$.

According to the above theoretical analysis, the evaluation essence of the index of negative-sequence voltage and current is different. Therefore, in the same circuit, when the different responsibility indexes are used to divide the unbalance responsibility, the results may be contradictory. Let's take the experimental data in Table 1 as an example to verify the results.

Table1. Experimental data

Impedance property	U_{P2}/V	I_{P2}/A	Z_{S2}/Ω	Z_{C2}/Ω
Both sides are perceptual	18	2	2+j9	6+j25

We take the angle β between negative-sequence voltage and current at PCC as the independent variable, the change curve of unbalance responsibility of utility and customer sides with negative-sequence voltage and current as responsibility index is made, as shown in Figure 4.

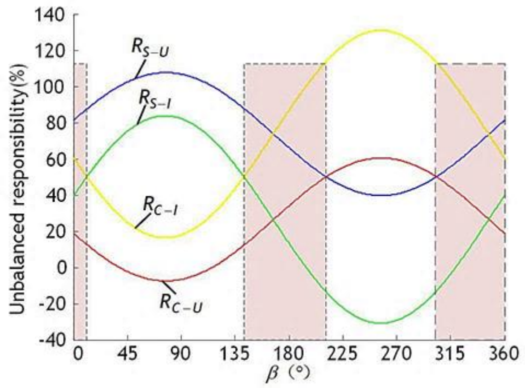

Figure 4. Unbalanced responsibility curve of utility side and customer side with β

It can be seen from figure 4 that there is a contradiction between the result of the unbalanced responsibility division obtained by the negative-sequence voltage and current responsibility index, as shown in the coloured region, the correctness of the above theoretical analysis results is verified.

3. A new method to divide the unbalance responsibility

3.1 Decomposition of equivalent apparent power

IEEE std.1459-2010 power theory advocates the separation of fundamental positive-sequence components and fundamental unbalanced components [21]. Next, taking the three-phase three-wire unbalanced power supply system as the research object, the apparent power is decomposed.

The calculation expression of the equivalent apparent power is:

$$S_e = 3U_e I_e \tag{23}$$

Where U_e is the equivalent voltage, I_e is the equivalent current.

For the three-phase three-wire system, equivalent voltage and current can be expressed as follows.

$$U_e^2 = \frac{U_{AB}^2 + U_{BC}^2 + U_{CA}^2}{9} \tag{24}$$

$$I_e^2 = \frac{I_A^2 + I_B^2 + I_C^2}{3} \tag{25}$$

As we all know, we can generally measure the line voltage in three-phase three-wire system, to get the relationship between the equivalent voltage and sequence component, it is necessary to get the relationship between the line voltage and sequence component.

According to the symmetrical component method, we can get

$$\begin{bmatrix} \dot{U}_A \\ \dot{U}_B \\ \dot{U}_C \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{bmatrix} \begin{bmatrix} \dot{U}_1 \\ \dot{U}_2 \\ \dot{U}_0 \end{bmatrix} \tag{26}$$

$$\begin{bmatrix} \dot{I}_A \\ \dot{I}_B \\ \dot{I}_C \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{bmatrix} \begin{bmatrix} \dot{I}_1 \\ \dot{I}_2 \\ \dot{I}_0 \end{bmatrix} \tag{27}$$

where $a = 1\angle 120^\circ$; $\dot{U}_1$, $\dot{U}_2$ and $\dot{U}_0$ are the positive, negative and zero-sequence components of three-phase voltage, respectively; $\dot{I}_1$, $\dot{I}_2$ and $\dot{I}_0$ are the positive, negative and zero-sequence components of three-phase current, respectively.

According to equation (26), it can be concluded that

$$\dot{U}_{AB} = \dot{U}_A - \dot{U}_B = (\dot{U}_1 + \dot{U}_2 + \dot{U}_0) - (a^2\dot{U}_1 + a\dot{U}_2 + \dot{U}_0)$$

$$= \sqrt{3}b\dot{U}_1 + \sqrt{3}b\dot{U}_2 \tag{28}$$

Similarly, equations (29) and (30) can be obtained, as following:

$$\dot{U}_{BC} = \dot{U}_B - \dot{U}_C = \sqrt{3}(b^*)^3\dot{U}_1 + \sqrt{3}b^3\dot{U}_2 \tag{29}$$

$$\dot{U}_{CA} = \dot{U}_C - \dot{U}_A = \sqrt{3}b^5\dot{U}_1 + \sqrt{3}(b^*)^5\dot{U}_2 \tag{30}$$

where $b = 1\angle 30^\circ$. The superscript * represents conjugate.

Obviously, the relationship between line voltage and sequence component is as follows:

$$\begin{bmatrix} \dot{U}_{AB} \\ \dot{U}_{BC} \\ \dot{U}_{CA} \end{bmatrix} = \sqrt{3} \begin{bmatrix} b & b^* & 0 \\ (b^*)^3 & b^3 & 0 \\ b^5 & (b^*)^5 & 0 \end{bmatrix} \begin{bmatrix} \dot{U}_1 \\ \dot{U}_2 \\ \dot{U}_0 \end{bmatrix} \tag{31}$$

It can be seen from equation (31) that when the sequence component is known, the line voltage can be obtained, but the sequence component cannot be obtained from the line voltage. However, there is a conversion relationship between line voltage and phase voltage [25], as shown in equation (32).

$$\begin{bmatrix} \dot{U}_A \\ \dot{U}_B \\ \dot{U}_C \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} \begin{bmatrix} \dot{U}_{AB} \\ \dot{U}_{BC} \\ \dot{U}_{CA} \end{bmatrix} \tag{32}$$

According to equation (26) and equation (32), the relationship between line voltage and sequence component is obtained, and the equation can be expressed as follows:

$$\begin{bmatrix} \dot{U}_1 \\ \dot{U}_2 \\ \dot{U}_0 \end{bmatrix} = \frac{\sqrt{3}}{9} \begin{bmatrix} b^* & b^3 & (b^*)^5 \\ b & (b^*)^3 & b^5 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{U}_{AB} \\ \dot{U}_{BC} \\ \dot{U}_{CA} \end{bmatrix} \tag{33}$$

Therefore, the equivalent voltage and current can be expressed in the form of positive and negative sequence components, as follows

$$U_e^2 = U_1^2 + U_2^2 \tag{34}$$

$$I_e^2 = I_1^2 + I_2^2 \tag{35}$$

The equation of the equivalent apparent power is

$$S_e^2 = 9(U_1^2 + U_2^2)(I_1^2 + I_2^2)$$

$$= (3U_1I_1)^2 + (3U_1I_2)^2 + (3U_2I_1)^2 + (3U_2I_2)^2$$

$$= S_1^2 + S_{IU}^2 + S_{UU}^2 + S_2^2 = S_1^2 + S_U^2 \tag{36}$$

where $S_1 = 3U_1I_1$ is the fundamental positive-sequence apparent power, $S_{IU} = 3U_1I_2$ is the current unbalance apparent power, $S_{UU} = 3U_2I_1$ is the voltage unbalance apparent power, $S_2 = 3U_2I_2$ is the fundamental negative sequence apparent power, and $S_U^2 = S_{IU}^2 + S_{UU}^2 + S_2^2$ is the fundamental unbalanced apparent power. The decomposition form of equivalent apparent power in the three-phase three-wire unbalanced system is shown in Figure 5.

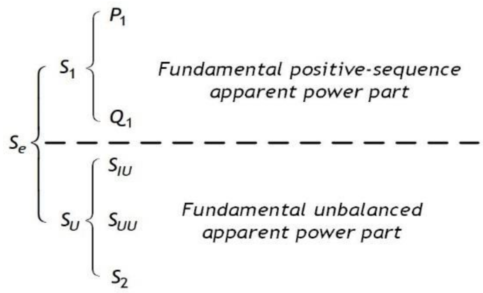

Figure 5. The decomposition of the equivalent apparent power

3.2 A new method to divide the unbalance responsibility

This paper proposes a new method of unbalance responsibility division under the multi-index system, so as to avoid the conflict between the results of the unbalance responsibility division under the single index. The implementation process of the new method is as follows:

Step 1. Establish the multi-index system of unbalanced responsibility division.

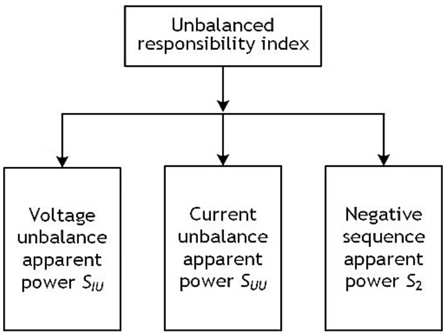

Figure 6. Multi-index system of unbalanced responsibility division

Step 2. Adopt G1 method to calculate the subjective weight of each index.

G1 method is a subjective weighting method with strong operability [26]. This method first needs to establish the ranking relationship between each index according to expert experience and relevant professional knowledge, such as A_1>A_2> >A_n, and then gives the rational assignment between adjacent indexes Ak-1 and A_k according to the relative importance of each index. The assignment method is as follows:

$$a_k = \frac{H_{g(k-1)}}{H_{gk}} \quad (k=n,\ldots,2) \tag{37}$$

where n is the number of selected responsibility indexes.

The assignment of a_k is shown in Table 2, and the rational assignment needs to satisfy equation (38).

$$a_{k-1} > \frac{1}{a_k} \tag{38}$$

Table 2. The assignment table of a_k

Values of a_k	Interpretation of meaning
1	A_{k-1} *is* equally important as A_k
1.2	A_{k-1} is slightly more important than A_k
1.4	A_{k-1} is more important than A_k
1.6	A_{k-1} is obviously more important than A_k
1.8	A_{k-1} is strongly more important than A_k
1.1, 1.3, 1.5, 1.7	The importance of adjacent indexes is in the above situation

If the rational assignment given satisfies equation (38), there are

$$H_{gn} = (1 + \sum_{k=2}^{n} \prod_{i=k}^{n} a_i)^{-1} \tag{39}$$

So, the subjective weight of each responsibility index is:

$$H_{g(k-1)} = a_k H_{gk} \quad ((k=n,n-1,\ldots2)) \tag{40}$$

Step 3. Adopt Variation Coefficient Method (VCM) to calculate the objective weight of each index.

VCM is an objective weighting method, which is similar to the entropy weighting method [27]. The key to get the weight of each index by this method is to establish a fuzzy evaluation matrix. In this paper, according to the value of physical quantity corresponding to each index D in the multi index system, it is divided into h evaluation grades, so that the fuzzy mapping d from each index A_k to the evaluation grade can be obtained, as follows

$$A_k \to d(A_k) = (d_{k1}, d_{k2} \ldots d_{kh}) \in D$$

According to the definition of fuzzy transformation, the fuzzy evaluation matrix D is determined as

$$D = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1h} \\ d_{21} & d_{22} & \cdots & d_{2h} \\ \vdots & \vdots & & \vdots \\ d_{n1} & d_{n2} & \cdots & d_{nh} \end{bmatrix} \tag{41}$$

On the basis of fuzzy evaluation matrix D, it is necessary to calculate the average value of index *i* :

$$\bar{d}_i = \frac{1}{h} \sum_{j=1}^{h} d_{ij} \tag{42}$$

where h is the number of evaluation grades for the division of physical quantities corresponding to each responsibility index, and d_{ij} is the element in row *i* and column *j* of evaluation matrix D.

Then the standard deviation of index *i* needs to be calculated:

$$\sigma_i = \sqrt{\frac{1}{h} \sum_{j=1}^{h} (d_{ij} - \bar{d})^2} \tag{43}$$

Next, it is necessary to calculate the coefficient of variation of index *i*:

$$b_i = \frac{\sigma_i}{\bar{d}_i} \tag{44}$$

Finally, the objective weight of the index *i* is obtained by normalization:

$$V_i = \frac{b_i}{\sum_{i=1}^{n} b_i} \tag{45}$$

Step 4. Calculate the comprehensive weight of each responsibility index.

According to the principle of minimum discriminant information, the comprehensive weight function as shown in the formula (46) is established on the basis of steps 2 and 3:

$$W_i = \frac{\sqrt{H_{gi} V_i}}{\sum_{1}^{n} \sqrt{H_{gi} V_i}} \tag{46}$$

Step 5. Comprehensive calculation of unbalanced responsibility.

According to the contents in Section 2.1 and the calculation expressions of physical quantities corresponding to each responsibility index in formula (36), we can obtain the apparent power S_{IU-S} and S_{IU-C} of current unbalance, the apparent power S_{UU-S} and S_{UU-C} of voltage unbalance, the apparent power S_{2-S} and S_{2-C} of fundamental negative-sequence, which generated by the utility and customer sides act alone, and the calculation expressions are as follows.

$$S_{IU-S} = 3U_{P1} I_{SP2} \tag{47}$$

$$S_{IU-C} = 3U_{P1} I_{CP2} \tag{48}$$

$$S_{UU-S} = 3U_{SP2} I_{P1} \tag{49}$$

$$S_{UU-C} = 3U_{CP2} I_{P1} \tag{50}$$

$$S_{2-S} = 3U_{SP2} I_{SP2} \tag{51}$$

$$S_{2-C} = 3U_{CP2} I_{CP2} \tag{52}$$

Taking the negative-sequence apparent power responsibility index as an example, the unbalance responsibilities of the utility and customer sides are defined as $R_{2\text{-}S}$ and $R_{2\text{-}C}$ respectively, and their calculation expressions are shown in formula (53) and formula (54):

$$R_{2-S} = \frac{S_{2-S}}{S_{2-S} + S_{2-C}} \times 100\% \tag{53}$$

$$R_{2-C} = \frac{S_{2-C}}{S_{2-S} + S_{2-C}} \times 100\% \tag{54}$$

Similarly, the unbalanced responsibility of utility and customer sides can be obtained under the other responsibility indexes.

On the basis of the above work, we can get the unbalanced liability of the utility and customer sides, respectively, and its calculation expression is as follows:

$$R_S = \sum_{i=1}^{n} W_i R_{i-s} \tag{55}$$

$$R_C = \sum_{i=1}^{n} W_i R_{i-C} \tag{56}$$

4. An adjustment scheme of rewarding and penalizing electricity charge

At present, the problem of three-phase unbalanced power quality in the power system is becoming more and more serious. However, the current adjustment scheme of electricity charges does not assess the customer's unbalance responsibility, which is not conducive to the treatment of three-phase unbalance by the electric power department. Based on the above problems, this paper discusses a new adjustment scheme of rewarding and penalizing electricity charges considering the unbalance responsibility. The expression of the electricity charge adjustment function is shown in formula (57):

$$Y = f(Y_1, Y_{F1}, R_C, Y_2) \tag{57}$$

where *Y* represents the total electricity charge that the customer should pay, Y_1 represents the electricity charge of fundamental positive-sequence active electric energy, Y_{F1} represents the electricity charge adjusted by the power factor of fundamental positive-sequence, R_C represents the value of unbalance responsibility on the customer side, Y_2 represents the electricity charge of three-phase unbalance economic evaluation in the power grid.

In the new adjustment scheme of electricity charges proposed in this paper, the total electricity charges of customers consist of three parts, namely, the electricity charges of fundamental positive-sequence active power, the electricity charges adjusted by the power factor, and the three-phase unbalanced economic evaluation charge. The specific value of the three-phase unbalance economic evaluation electric charge should be given by the relevant pricing department after the comprehensive evaluation of the direct economic loss, indirect economic loss caused by the three-phase unbalance and the cost required for the treatment of the three-phase unbalance.

According to Figure 6 (*supra*), the fundamental unbalanced apparent power includes all unbalanced power quantities, which can fully evaluate the degree of system unbalance. Based on this, this paper discusses a simple and easy way to charge the electricity charge of three-phase unbalance economic evaluation, that is, to meter the fundamental unbalanced apparent power, to make the corresponding unit price of electricity charge, and then to charge a certain amount of electricity charge of three-phase unbalance economic evaluation according to the customer unbalanced responsibility.

This method can not only effectively reduce the complexity of three-phase unbalanced economic loss evaluation, save the investment of manpower and material resources, but also avoid the repeated evaluation of loss cost by the relevant pricing departments.

Through the above analysis, this paper attempts to give the specific function expression of the new adjustment scheme of rewarding and penalizing electricity charges, as shown in formula (58):

$$Y = Y_1 + Y_{F1} + Y_2$$

$$= P_1 t X_1 + P_1 t X_1 X_{PF1} + S_U t R_C X_2 \quad (58)$$

Where P_1 is the fundamental positive-sequence active power, S_U is the fundamental unbalanced apparent power at PCC, X_{PF1} is the percentage of power factor adjusted charge for electricity, X_1 is the electricity price of the fundamental positive-sequence active power, X_2 is the electricity price of the fundamental unbalanced apparent power, and t is the customer's power consumption time.

In order to better reflect the reward and penalize intensity of the new scheme, the calculation formula of the Electricity price of the fundamental unbalanced apparent power is designed in this paper as shown in formula (59):

$$X_2 = \frac{S_U}{P_1} X_1 \quad (59)$$

The flowchart of realizing the new adjustment scheme of rewarding and penalizing electricity charges proposed in this paper is shown in Figure 7.

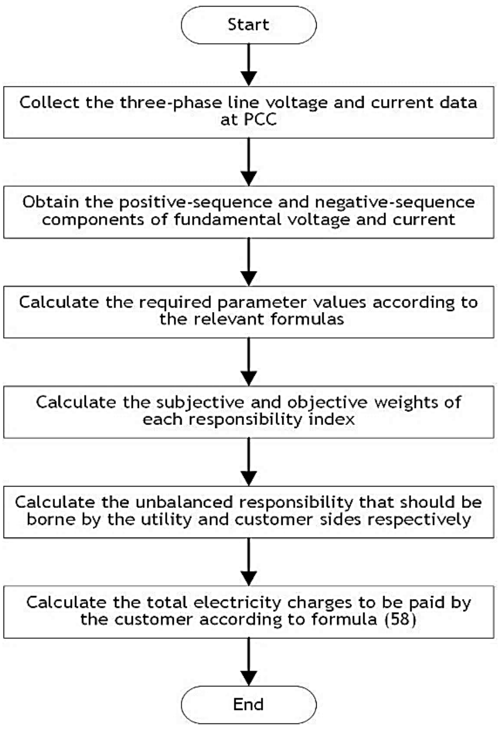

Figure 7. The flowchart of realizing the new adjustment scheme of electricity charges

5. Simulation analysis

The traction power supply system for the electrified railway is a typical unbalanced power supply system, and it is also a large power consumer with high voltage and large capacity. Therefore, this paper takes it as an example and builds a simulation model in MATLAB/Simulink software, as shown in Figure 8.

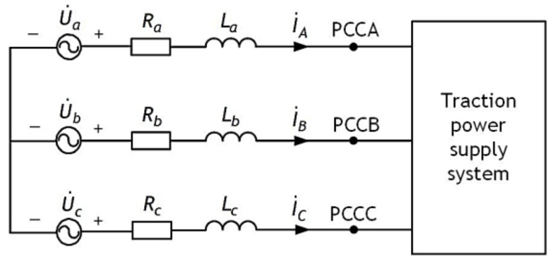

Figure 8. Simulation model

The three-phase voltage of the utility side is unbalanced, and the customer side is asymmetric traction load. The simulation model of locomotive adopts CRH2 EMU in reference [28], the traction transformer adopts V/X wiring form, and the power supply mode is AT power supply.The simulation parameter settings of the utility side in the simulation model are shown in Table 3 (where $R_a = R_b = R_c$, $L_a = L_b = L_c$).

Table3. Simulation parameters of the utility side

Parameter	Value	Parameter	Value
$\dot{U}_a$ / kV	$105\angle 3°/\sqrt{3}$	R_a / Ω	10
$\dot{U}_b$ / kV	$106\angle 235°/\sqrt{3}$	L_a / mL	140
$\dot{U}_c$ / kV	$114\angle 112°/\sqrt{3}$		

The simulation data of voltage and current at PCC are obtained, as shown in Table 4.

Table4. The simulation data of voltage and current at PCC

At PCC	Measured value	Calculated value
	$\dot{U}_{AB} = 107.41\angle 26°$	$\dot{U}_{P1} = 61.37\angle -5.67°$
Voltage/kV	$\dot{U}_{BC} = 108.47\angle 263°$	$\dot{U}_{P2} = 1.90\angle 125.03°$
	$\dot{U}_{CA} = 103.10\angle 144°$	
	$\dot{I}_A = 66.56\angle 7.3°$	$\dot{I}_{P1} = 56.73\angle -14.08°$
Current/A	$\dot{I}_B = 76.93\angle 213.4°$	$\dot{I}_{P2} = 24.82\angle 63.71°$
	$\dot{I}_C = 33.96\angle 93°$	

According to the simulation data in Table 4, the value of the corresponding physical quantity of each responsibility index at PCC can be calculated, respectively, as shown in Table 5.

Table 5. The value of the corresponding physical quantity of each responsibility index at PCC

Name	S_{IU}/kVA	S_{UU}/kVA	S_2/kVA
Value	4569.61	323.36	141.47

Combined with expert experience and professional knowledge, it is concluded that the ranking relationship among the indexes is as follows:

$S_{IU} > S_{UU} > S_2$

According to Table 2, the rational assignment can be given as:

a_2=1.8, a_3=1.1

According to formula (37) and formula (38), the subjective weight of each responsibility index can be obtained as follows:

H_1=0.4853, H_2 =0.2696, H_3 =0.2451

According to the value range of the corresponding physical quantity of each responsibility index in a certain period ,which is assumed to be 2 S in this paper, it is divided into four intervals on average, which represent the high-quality, good, medium and qualified levels, respectively. Then probability statistics method is used to calculate the probability that the value of each physical quantity falls on each interval, which can form the fuzzy evaluation matrix D. Its specific form is as follows.

$$D=\begin{bmatrix}0.2076 & 0.4229 & 0.2684 & 0.1011\\ 0.0148 & 0.4062 & 0.3909 & 0.1881\\ 0.1312 & 0.4891 & 0.3526 & 0.0271\end{bmatrix}$$

According to step 3, the objective weight of each responsibility index can be obtained as follows.

V_1=0.2539, V_2=0.3507, V_3=0.3954

According to step 4, we can get the comprehensive weight of each responsibility index as follows.

W_1=0.3619, W_2=0.3171, W_3=0.3210

Based on the above work, we can get the unbalanced responsibility values of the utility and customer sides under each index, as shown in Table 6.

Table6. Unbalanced responsibility values of the utility and customer sides under each index

Responsibility index	Responsibility on the system side	Responsibility on the customer side
S_{IU}	10.41%	89.59%
S_{UU}	73.59%	26.41%
S_2	24.46%	75.54%

According to formula (49) and (50), the unbalance responsibility values of utility and customer sides can be calculated as follows:

R_S=34.95%, R_C=65.05%

According to the simulation data in Table 4 and the contents in Section 2.1, the unbalanced responsibility values of the utility and customer sides are calculated respectively when the traditional negative sequence voltage and negative sequence current indexes are adopted. The results are as follows:

$$R_{S-U}=\frac{2.95\times\cos 3.68^{\circ}}{1.90}\times 100\%=154.94\%$$

$$R_{C-U}=\frac{1.06\times\cos(-169.98^{\circ})}{1.90}\times 100\%=-54.94\%$$

$$R_{S-I}=\frac{2.72\times\cos 56.58^{\circ}}{24.82}\times 100\%=6.04\%$$

$$R_{C-I}=\frac{23.43\times\cos(-5.53)^{\circ}}{24.82}\times 100\%=93.96\%$$

It can be seen from the above calculation results that when the traditional unbalance responsibility index is adopted to divide the unbalance responsibility of the utility and customer sides, the results are quite different. However, the new division method of the unbalance responsibility proposed in this paper comprehensively considers the influence of negative sequence voltage and negative sequence current, which is more reasonable and fair than the traditional method.

The standard value of power factor assessment for the high-voltage power supply industrial customers above 160 kVA in China is 0.9, and the specific calculation method of the percentage of power factor adjusted electricity charge is shown in Table 7.

Table 7. Percentage of electricity charges adjusted by power factor

Value range	Percentage (%)
$\cos\varphi \geq 0.95$	-0.75
$0.9 < \cos\varphi \leq 0.95$	$(0.9-\cos\varphi)\times 15$
$0.7 < \cos\varphi \leq 0.9$	$(0.9-\cos\varphi)\times 50$
$0.65 < \cos\varphi \leq 0.7$	$10+(0.7-\cos\varphi)\times 100$
$\cos\varphi \leq 0.65$	$15+(0.65-\cos\varphi)\times 200$

According to the simulation data in Table 4 (*infra*), it is achievable to calculate the fundamental positive-sequence active power and positive-sequence power factor of the customer.

Then according to the percentage of electricity charge adjusted by the power factor in Table 7, the result of the electric charge that should be paid by the customer after working for 24 hours can be calculated as shown in Table 8.

Table 8. Electricity charges under the current adjustment scheme of electricity charges

Name	Value
Fundamental positive-sequence active power (kW)	10332.25
Total electric energy consumed (kW · h)	247974
Fundamental positive-sequence power factor	0.99
Active electricity charges payable (Yuan)	161753.44
Electricity charges adjusted by power factor (Yuan)	–1213.15
Total electricity charges (Yuan)	160540.29

Legend: The "–" in the table indicates that the customer is rewarded

Refer to the electricity price standard of the large industry in a province of China; the electricity price of positive-sequence active power is 0.6523 Yuan/kWh.

According to the charging standard of the new adjustment scheme of rewarding and penalizing electricity charges, the charging result of electricity charges that should be paid by the customer after working for 24 hours can be calculated, as shown in Table 9.

Table 9. Electricity charges under new adjustment scheme of rewarding and penalizing electricity charges

Name	Value
The fundamental unbalanced apparent power at PCC (kVA)	5034.44
The consumption of fundamental unbalanced apparent power(kVA · h)	120826.56
Responsibility on the customer side (%)	65.05
Electricity price of fundamental unbalanced apparent power (Yuan)	0.3179
Customer's three-phase unbalanced evaluation electricity charges (Yuan)	24986.20
Total electricity charges (Yuan)	185526.49

By comparing the data in Table 8 and Table 9, it can be seen that the new adjustment scheme of rewarding and penalizing electricity charges proposed in this paper assesses the customer's unbalance responsibility. According to the unbalance responsibility that the customer should bear, a certain three-phase unbalance evaluation electricity charge will be charged to the customer. This new scheme can force the power customers who cause negative-sequence pollution to the power grid to take measures to treat the power pollution by economic means, to effectively improve the power quality and maintain the economic benefits of both sides. Therefore, compared with the current adjustment scheme, the new scheme proposed is more reasonable.

6. Conclusions

This paper first analyses the rationality of the traditional unbalance responsibility index and the method of responsibility division, then puts forward a new method of the unbalance responsibility division, and discusses a new adjustment scheme of rewarding and penalizing electricity charges. The main conclusions are as follows:

1) The evaluation nature of the traditional unbalance responsibility index is not consistent, so in the same circuit, when adopting different index to divide the unbalance responsibility, the results may be contradictory.

2) A new method of the unbalance responsibility division considering the index weight under the multi-index system is proposed. The method takes the influence of negative-sequence voltage and current into account, which is more reasonable than the traditional method.

3) This paper discusses a new adjustment scheme of rewarding and penalizing electricity charges considering unbalanced responsibility, which considers the customer's unbalanced responsibility and is conducive to improving the power quality and maintaining the economic interests of both sides.

4) The adjustment scheme of rewarding and penalizing electricity charges proposed mainly considers the unbalanced responsibility of the customers, but does not consider the harmonic responsibility. If comprehensively considered the unbalanced responsibility and harmonic responsibility of customers, the adjustment scheme of electricity charges will be more reasonable, which needs further research.

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