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A New Method for Determination of Harmonic Responsibility Based on Quality Engineering Theory

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ABSTRACT At present, the essence of traditional methods for determination of harmonic responsibility among different parts in power system is mainly based on the contribution of relevant physical quantity on the point of common coupling (PCC) of both utility side and customer side. However, theoretical basis of various methods is of much difference, leading to a large difference in the final calculation result of harmonic responsibility. Therefore, there is no reliable approach applied in actual cases. This project aims to fill the current gap in literature, proposing a new method to determine harmonic responsibility from the perspective of economic loss. Firstly, according to power theory of IEEE Std.1459-2010 and quality engineering theory, the index set of harmonic pollution evaluation on PCC is established, and the expressions of calculation of economic loss are obtained. Secondly, collecting relevant data on PCC, the parameters of Norton equivalent models of utility side and customer side are obtained by the reference impedance method, then contributions of corresponding physical quantity on PCC can be analyzed. Based on relevant expressions of economic loss, calculation results of economic loss are all obtained. At the same time, values of harmonic responsibility of utility side and customer side are calculated. Finally, new adjustment scheme of rewarding-penalizing electricity charge (RPEC) is discussed and compared with other traditional schemes. After comparison, Results of comparative analysis show that the new adjustment scheme can not only increase the penalty for harmonics but also reflect commodity characteristic of electricity energy. In this manner, calculation result of electricity charge is more reasonable. Hence, electricity environment on PCC can be improved.

INDEX TERMS Harmonic responsibility, IEEE Std.1459-2010, quality engineering theory, economic loss, adjustment scheme of electricity charge.

I. INTRODUCTION

In recent years, a large number of power electronic devices are put into power system, thus harmonics have become more and more serious. At the same time, harmonic affects quality of electricity energy seriously. In fact, the essence of electricity energy is commodity. So, harmonic can bring certain economic loss to power supply company and related customers. Aim at this situation, more and more experts and scholars have begun to pay attention to the various problems caused by harmonics, carrying out in-depth research from

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various perspectives such as governance, compensation and charging.

The literature [1]–[3] briefly describe harmonic hazard and carry out relevant research from the perspective of compensation. However, these literatures only analyze compensation effect after putting into relevant devices, but they do not involve harmonic responsibility analysis. The literature [4]–[8] gradually realize the importance of distinguishing harmonic contribution on PCC of utility side and customer side, thus deriving the topic of location of main harmonic source on PCC. Through the location of main harmonic source, harmonic emission level of utility side and customer side can be evaluated. But, this kind of method is not

quantitative, thus the specific results of harmonic responsibility percentage of utility side and customer side cannot be obtained quantitatively. In the literature [9], Professor Wilson firstly proposes the method for quantitative determination of harmonic voltage responsibility and harmonic current responsibility based on superposition projection principle. Subsequently, this method has been widely used. Based on it, the literature [10]–[13] carry out in-depth research on calculation of harmonic impedance of utility side, but it in fact uses traditional method based on superposition projection principle to calculate harmonic responsibility quantitatively, which does not effectively innovate quantitative calculation method of harmonic responsibility. The literature [14] carries out research on quantitative calculation method of harmonic responsibility based on the principle of superimposed projection, which realizes harmonic source can be divided into two kinds, one kind is augmentation harmonic source, the other kind is subtraction harmonic source. The essences of augmentation harmonic source and subtraction harmonic source are both harmonic source, and subtraction harmonic source has a certain improvement effect on the harmonic pollution on PCC, while augmentation harmonic source has an aggravating effect. In literature [15]–[17], it points out that the judgment basis of harmonic voltage responsibility and harmonic current responsibility based on superposition projection principle is of much difference, thus leading the final results of harmonic responsibility of utility side and customer side based on different indexes are also quite different.

At present, there is no any standard which illustrates the situation on how to make a choice of harmonic voltage index or harmonic current index, thus leading some researchers prone to misuse the indexes [18], [19]. In literature [20], the shortcomings of the traditional methods for determination of harmonic responsibility are further analyzed, it points out that the traditional methods based on superposition projection principle can only determine harmonic responsibility under a certain frequency, and how to combine different frequencies of harmonic responsibility is also worth studying. On the basis of weighting methods, the literature [21] proposes a new method to calculate harmonic responsibility comprehensively from the perspective of harmonic current and harmonic voltage. In literature [22], the index set of harmonic responsibility calculation is established according to new power theory of IEEE Std.1459-2010, which covers all harmonic physical quantities. Compared with the index set in literature [21], the index set according to IEEE Std.1459-2010 is more reasonable, so the final result is also more reliable. And the most key point is that literature [22] firstly points out the adjustment scheme of electricity charge should consider harmonic responsibility, and it emphasizes the closeness relationship between harmonic responsibility and electricity charge. But, both methods proposed in literature [21], [22] apply subjective weight and objective weight which may have many interference factors, leading the two methods are not easily applied in the actual case. Based on analyzing single harmonic source, the literature [23], [24] propose methods

on how to determine harmonic responsibility among multiple harmonic sources, which are closer to actual power system. In literature [25], [26], the quality engineering theory is used as a tool to assess economic loss of voltage sag in power system, which reflects that quality engineering theory has a certain application prospect in assessment of economic loss of power quality. In literature [27], the economic losses corresponding to different ranges of amplitude of voltage sag are converted into different multiples of certain interruption loss, which provides a method for calculation of parameters required in economic loss function of voltage sag based on quality engineering theory. Literature [28] proposes the reference impedance method to calculate parameters of Norton equivalent model of utility side and customer side, thus calculating the actual impedance of customer and utility sides is unnecessary. Literature [29] introduces the current standard of power quality, but this standard only limits the value of voltage distortion rate and rms value of harmonic current on PCC. When the limit is exceeded, the standard lacks of measure to punish related customers. Literature [30] is the current adjustment scheme of electricity charge of China.

Through above description, it can be believed that the calculation result of harmonic responsibility should be closely related to economy. If quantitative calculation method of harmonic responsibility lacks of relationship with economy, the finally calculation result of harmonic responsibility may not be easy to convince. On the basis of realizing the close relationship between economy and harmonic responsibility, this paper firstly proposes a new method to calculate harmonic responsibility from perspective of economic loss, which prominently reflects the essence of electricity energy is commodity. Secondly, a new adjustment scheme of electricity charge is compared with traditional schemes, comparative result shows that new scheme is more reasonable. Meanwhile, it enriches research achievement in the fields of energy metering and determination of harmonic responsibility of power quality.

II. THE ANALYSIS OF TRADITIONAL CALCULATION METHOD OF HARMONIC RESPONSIBILITY

In literature [9], Professor Wilson firstly proposed calculation method based on superposition projection principle of harmonic responsibility of harmonic current and harmonic voltage on PCC, which has an important impact on future research. At first, Norton equivalent model is used to model utility side and customer side, which is shown in Figure 1.

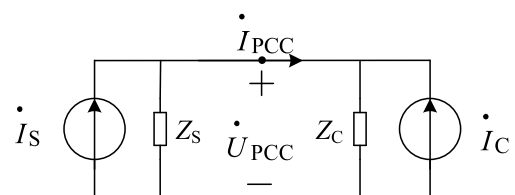


FIGURE 1. Calculation modeling of harmonic responsibility.

In Figure 1, I_S and I_C are rms value of harmonic current source of Norton equivalent model of utility side and customer side; Z_S and Z_C are harmonic impedance of Norton equivalent model of utility side and customer side; I_{PCC} and U_{PCC} are rms value of harmonic current and harmonic voltage on PCC.

Because Norton equivalent model is established under a certain frequency, the Figure 1 can be decomposed based on superposition projection principle, which is shown in Figure 2.

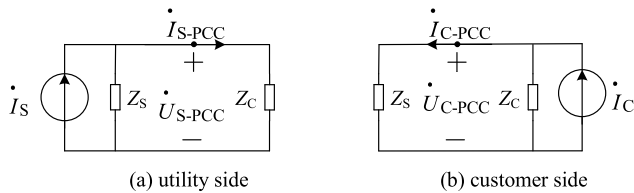


FIGURE 2. Decomposed Norton equivalent circuit.

Based on Figure 2, the contributions of harmonic current and harmonic voltage on PCC of utility side and customer side can be obtained as follows:

$$U_{S-PCC} = I_S \cdot \frac{Z_S Z_C}{Z_S + Z_C}, \quad (1)$$

$$U_{C-PCC} = I_C \cdot \frac{Z_S Z_C}{Z_S + Z_C}, \quad (2)$$

$$I_{S-PCC} = I_S \cdot \frac{Z_S}{Z_S + Z_C}, \quad (3)$$

$$I_{C-PCC} = I_C \cdot \frac{Z_C}{Z_S + Z_C}. \quad (4)$$

where U_{S-PCC} and I_{S-PCC} are contributions of harmonic voltage and harmonic current on PCC of utility side, U_{C-PCC} and I_{C-PCC} are contributions of harmonic voltage and harmonic current on PCC of customer side.

According to the ration of projection contribution of utility side and customer side onto total harmonic current and total harmonic voltage on PCC, harmonic responsibility of utility side and customer side can be determined. Take projection contribution of harmonic current of utility side and customer side add up onto PCC as an example to introduce, which is shown in Figure 3.

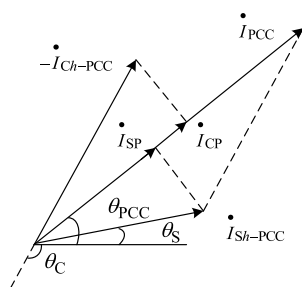


FIGURE 3. Quantitative calculation of harmonic responsibility.

In Figure 3, I_{SP} and I_{CP} are rms value of projection contribution of harmonic current of utility side and customer side

onto total harmonic current on PCC, θ_{PCC} , θ_S and θ_C are angle of total harmonic current on PCC, contribution of harmonic current of utility side and contribution of harmonic current of customer side.

According to Figure 3, harmonic responsibility of utility side and customer side can be obtained as follows:

$$R_C = \frac{I_{CP}}{I_{PCC}} \times 100\%, \quad (5)$$

$$R_S = \frac{I_{SP}}{I_{PCC}} \times 100\%, \quad (6)$$

where R_S and R_C are harmonic responsibility percentage of customer side and customer side respectively.

Through above introduction, it can be found that the greatest advantage of traditional method is that it has clear physical meaning, the essence of tradition method is actually to calculate contribution ration of harmonic current and harmonic voltage which utility side and customer side generate onto total harmonic current and total harmonic voltage respectively on PCC. However, traditional method does not reflect actual economic loss caused by harmonics in power system, thus the harmonic responsibility calculated by traditional method lacks of relationship with economy.

In fact, harmonic responsibility is an intermediate result, the ultimate goal of power supply company is to take economic measures to punish related customers through calculation of harmonic responsibility, which both ensures commodity characteristic of electricity energy and reduce hazard of harmonics in power system.

In addition, traditional calculation method of harmonic responsibility has following main defects:

- 1) Traditional calculation method only calculates harmonic responsibility under a certain frequency, which lacks of analysis of relationship among different frequencies.
- 2) Under one certain frequency, calculation results of harmonic responsibility have a large difference based on choosing different indexes.
- 3) The focus of traditional methods is mainly on harmonic current and harmonic voltage, but, whether harmonic current and harmonic voltage can totally reflect harmonic environment on PCC is worthy further research.

Based on these defects, more and more experts have proposed various methods to overcome defects of traditional method. However, judging from current research situation, there are few research on relationship between calculation result of harmonic responsibility and economy. Therefore, this paper proposes a new method to calculate harmonic responsibility on PCC from the perspective of economy.

III. PRINCIPLE OF QUALITY ENGINEERING THEORY

A. INTRODUCTION OF QUALITY ENGINEERING THEORY

The quality engineering theory is the unprecedented fierce competition production for quality competition in the international market in the 1970s, and the classification of quality characteristics was studied by Japanese quality management

specialist Taguchi. And then, quality engineering is used to evaluate product quality.

At present, more and more experts have put much focus on the quality engineering theory to evaluate product quality more accurately. In literature [25], it introduces the principle of quality engineering theory, which is that when the evaluation index of corresponding quality characteristic deviates from target value, it will result in certain economic loss, and with greater deviation, the greater economic loss. It can also be judged from this principle that as long as the quality characteristic of commodity deviates from target value, it will cause economic loss. Therefore, although the international standard limits rate of voltage distortion on PCC is within 5%, there is still certain economic loss.

In literature [25], it roughly classifies quality characteristic, which can be divided into three parts of visual characteristic, large characteristic and small characteristic. Among them, target value of visual characteristic is limited, target value of large characteristic is infinite, and target value of small characteristic is zero.

Based on it, the concept of economic loss function of quality characteristic gradually appears, which is mainly used to quantitatively calculate the economic loss caused by the deviation of quality characteristic offset target value. In literature [26], the general expression of the economic loss function of quality characteristic is defined as follows:

$$E_L(x) = K \cdot F(x - T). \tag{7}$$

where $E_L(x)$ is the actual economic loss cause by deviation of the quality characteristic offset target value, K is maximum economic loss by deviation of the quality characteristic offset target value, x is value of quality characteristic, T is target value of quality characteristic.

B. THE STEPS OF ECONOMIC LOSS CALCULATION BASED ON QUALITY ENGINEERING THEORY

In general, it needs three steps to calculate economic loss based on quality engineering theory.

Step one: According to each index in the evaluation index set of economic loss, the function form of economic loss applicable to each index should firstly be determined, and then, actual economic loss corresponding to each index can be obtained.

Refer to the theoretical analysis of traditional forms of economic loss function of quality characteristic, and based on it, considering that the inverse normal function has strong advantages in both stability and practicability, this paper adopts it to evaluate economic loss of quality characteristic of corresponding index, its expression is shown as follows:

$$E_{L-i}(x) = K_i \left\{ 1 - \exp \left(- \frac{(x_i - T_i)^2}{2\sigma_i^2} \right) \right\}. \tag{8}$$

where $E_{L-i}(x)$ is the actual economic loss cause by deviation of quality characteristic offset target value of corresponding

index i , K_i is maximum economic loss by deviation of the quality characteristic offset target value of corresponding index i , x_i is value of quality characteristic of corresponding index i , T_i is target value of quality characteristic of corresponding index i , σ_i is sensitivity parameter of corresponding index i .

According to Equation (8), the calculation formula of σ_i is expressed as follows:

$$\sigma_i = \frac{(x_i - T_i)^2}{2 \ln \left(\frac{K_i}{K_i - E_{Li}} \right)}. \tag{9}$$

Step two: the corresponding signal-to-noise ratio of each index in the evaluation index set is calculated, and then, corresponding weight of each index is also obtained.

Signal-to-noise ration (SNR) has certain relationship with commodity performance, which can be used to evaluate economic loss. In the general situation, the larger SNR, the better commodity performance and the smaller economic loss. The formula for calculation of SNR is expressed as follows:

$$\eta_i = \left| 10 \lg \frac{(S - V)/m}{V} \right|. \tag{10}$$

where m is number of detection, expressions of S and V are shown as follows:

$$S = \frac{1}{m} \left(\sum_{j=1}^m x_j \right)^2, \tag{11}$$

$$V = \frac{1}{m - 1} \sum_{j=1}^m (x_j - \bar{x}_i)^2. \tag{12}$$

where x_j is corresponding detection value of index i , \bar{x}_i is corresponds average value of the quality characteristic x of index i .

After calculating SNR of each corresponding index in evaluation index set, the corresponding weight ω_i of index i can be obtained as follows:

$$\omega_i = \frac{1/\eta_i}{\sum_{i=1}^n 1/\eta_i}. \tag{13}$$

where n is the number of index in evaluation index set.

Step three: based on step one and step two, the total economic loss of multi indexes can be obtained as follows:

$$E_L(x) = \sum_{i=1}^n \omega_i E_{L-i}(x). \tag{14}$$

where $E_{L-i}(x)$ is corresponding economic loss of index i , $E_L(x)$ is the total economic loss of multiple indexes, ω_i is the weight of index i , n is the number of index in evaluation index set.

IV. THE NEW METHOD TO CALCULATE HARMONIC RESPONSIBILITY

A. EVALUATION OF TOTAL ECONOMIC LOSS OF HARMONIC ON PCC

At first, index set of assessment of economic loss on PCC should be determined. According to detailed definition of various power physical quantities under harmonic condition of IEEE Std.1459-2010, index set of economic loss can be established. The decomposition of apparent power under harmonic condition under IEEE Std.1459-2010 is shown in Figure 4.

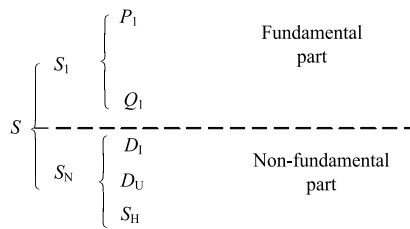


FIGURE 4. Decomposition of apparent power under harmonic condition.

In Figure 4, S_I and S_N are fundamental apparent power and non-fundamental apparent power, D_I , D_U and S_H are current distortion power, voltage distortion power and harmonic apparent power. P_I and Q_I are fundamental active power and fundamental reactive power.

It can be seen from Figure 4, non-fundamental apparent power S_N covers all harmonic physical quantities, which consists of D_I , D_U and S_H . Therefore, in order to consider harmonics more comprehensively, D_I , D_U and S_H are used as indexes to evaluate economic loss of harmonic pollution on PCC respectively, and then, the evaluation index set is established.

The calculation expressions of D_I , D_U and S_H are shown as follows:

$$D_I = U_I I_H = U_I I_1 \frac{I_H}{I_1} = S_I \text{THD}_I, \quad (15)$$

$$D_U = U_H I_1 = S_I \text{THD}_U, \quad (16)$$

$$S_H = U_H I_H = S_I \text{THD}_I \text{THD}_U. \quad (17)$$

It can be seen from Equations (15)–(17), current distortion power D_I essentially reflects current distortion rate THD_I on PCC, voltage distortion power essentially reflects the voltage distortion rate THD_U on PCC, and harmonic apparent power S_N comprehensively reflects THD_I and THD_U in the form of multiplying. Therefore, when choosing D_I , D_U and S_H as indexes to establish index set of evaluation of harmonic economic loss, it essentially reflects THD_I , THD_U and multiplying of THD_I and THD_U on PCC.

Based on establishment of index set of harmonic economic loss on PCC, economic loss on PCC corresponding to each index can be obtained according to Equations (8) – (13). Therefore, according to Equation (14), total harmonic economic loss on PCC can be determined.

B. CALCULATION OF HARMONIC RESPONSIBILITY OF UTILITY SIDE AND CUSTOMER SIDE

According to Figure 2, the contributions on PCC of harmonic current and harmonic voltage of utility side and customer side can be obtained under any harmonic frequency, and then, according to superposition projection principle, the projections on PCC of harmonic voltage contribution and harmonic current contribution of utility side and customer side onto total harmonic voltage and total harmonic current can be obtained. The contributions of total harmonic current distortion rate of utility side and customer side on PCC are shown as follows:

$$\text{THD}_{I-S} = \frac{\sum_{h \neq 1} I_{h-SP}^2}{I_1}, \quad (18)$$

$$\text{THD}_{I-C} = \frac{\sum_{h \neq 1} I_{h-CP}^2}{I_1}. \quad (19)$$

where THD_{I-C} and THD_{I-S} are contributions of total harmonic current distortion rate on PCC of customer side and utility side, I_{h-CP} and I_{h-SP} are projections of harmonic current contributions of utility side and customer side onto total harmonic current I_{h-PCC} under harmonic order of h on PCC, I_1 is fundamental current on PCC.

Similarly, the total harmonic voltage distortion rate contributions of utility side and customer side on PCC are shown as follows:

$$\text{THD}_{U-C} = \frac{\sum_{h \neq 1} U_{h-CP}^2}{U_1} \quad (20)$$

$$\text{THD}_{U-S} = \frac{\sum_{h \neq 1} U_{h-SP}^2}{U_1} \quad (21)$$

where THD_{U-C} and THD_{U-S} are contributions of total harmonic voltage distortion rate on PCC of customer side and utility side, U_{h-CP} and U_{h-SP} are projections of harmonic voltage contributions of utility side and customer side onto total harmonic voltage U_{h-PCC} under harmonic order of h on PCC, U_1 is fundamental voltage on PCC.

According to relevant equations, harmonic economic loss caused by utility side and customer side on PCC can be obtained, which is shown as follows:

$$E_{L-S}(x) = \sum_i \omega_{i-S} E_{LS-i}(x) \quad (22)$$

$$E_{L-C}(x) = \sum_{i=1}^3 \omega_{i-C} E_{LC-i}(x). \quad (23)$$

where $E_{L-S}(x)$ and $E_{L-C}(x)$ are total harmonic economic loss on PCC caused by utility side and customer side respectively, $E_{LS-i}(x)$ and $E_{LC-i}(x)$ are harmonic economic loss on PCC corresponding to index i of utility side and customer side respectively, ω_{i-S} is the weight corresponding to index i of

utility side, ω_{i-C} is the weight corresponding to index i of customer side.

Based on calculation of total harmonic economic loss on PCC, harmonic economic loss on PCC caused by utility side and customer side, the percentage of harmonic responsibility of utility side and customer side can be obtained, which are shown as follows:

$$R_S = \frac{E_{L-S}(x)}{E_L(x)} \times 100\%, \quad (24)$$

$$R_C = \frac{E_{L-C}(x)}{E_L(x)} \times 100\%. \quad (25)$$

where R_S and R_C are harmonic responsibility percentage of utility side and customer side respectively.

C. FLOW CHART OF CALCULATION OF HARMONIC RESPONSIBILITY

Based on above two subsections, the flow chart of new method to determine harmonic responsibility is established in this subsection, which mainly includes the following sub-routines: data acquisition subroutine, modeling subroutine, calculation of harmonic economic loss subroutine and quantitative calculation of harmonic responsibility subroutine.

V. SIMULATION ANALYSIS

A. EXAMPLE OF QUANTITATIVE CALCULATION OF HARMONIC RESPONSIBILITY

The content of harmonics generated by a single harmonic source is very low, however, the power system of different countries is developing rapidly, more and more power electronic products such as rectifier equipment begin to be put into the power system, thus the content of harmonics generated by multi-harmonic sources is very high because of superposition principle. According to this phenomenon, it is very meaningful for power supply company to calculate the harmonic responsibility of single harmonic source.

So, the simulation model shown in Figure 6 is established in Matlab/Simulink. It can intuitively introduce and analyze the method of this article. Aim at multi-harmonic sources, computing essence of harmonic responsibility is same as single harmonic source.

The utility side contains certain background harmonics, whereas the customer side is an uncontrollable rectifier circuit.

In Figure 6, u_s is background harmonic voltage source of utility side, R_S and L_S are resistance and inductance of utility side respectively, u_{PCC} and i_{PCC} are harmonic voltage and harmonic current on PCC, K_1 , K_2 and K_3 are switch 1, switch 2 and switch 3, R_{C1} and L_{C1} are resistance and inductance corresponding to branch of switch 1, R_{C2} and L_{C2} are resistance and inductance corresponding to branch of switch 2, R_{C3} and L_{C3} are resistance and inductance corresponding to branch of switch 3.

The purpose of setting the switch is to simulate the fluctuation of customer side. It is assumed that harmonics on PCC is detected three times one day, and different detection order

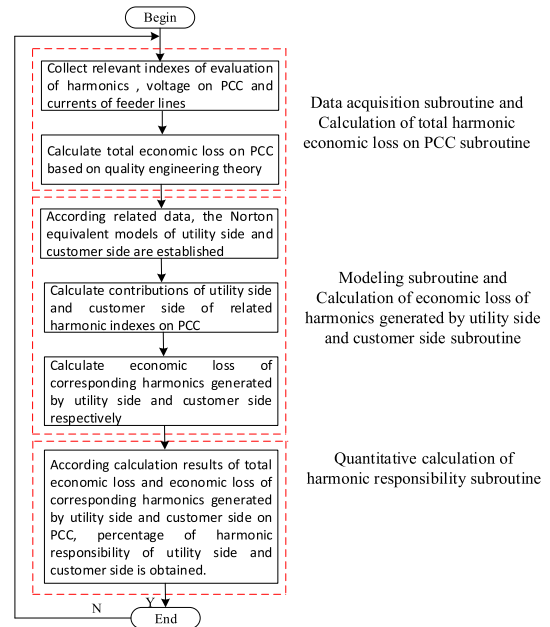


FIGURE 5. Flow chart of harmonic responsibility calculation.

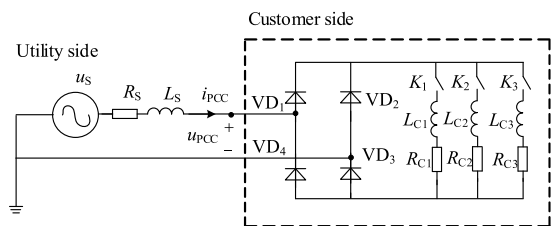


FIGURE 6. Simulation model.

corresponds to different closed state of switch. The parameter settings are shown in Table 1.

TABLE 1. The parameters of the simulation.

Parameter	\dot{U}_{S1}	\dot{U}_{S3}	\dot{U}_{S5}	R_S	L_S	/
Value	$220\angle -90^\circ \text{V}$	$8\angle -60^\circ \text{V}$	$6\angle -30^\circ \text{V}$	0.02Ω	0.064mH	/
Parameter	R_{C1}	L_{C1}	R_{C2}	L_{C2}	R_{C3}	L_{C3}
Value	3Ω	9mH	1Ω	10mH	7Ω	2mH

In Table 1, values of resistance and inductance of utility side source from literature [10], which use power recording equipment to conduct on-site measurement of four households in a power district in Shanghai, and then, the harmonic impedance of utility side is calculated according to symbol discrimination method. Therefore, calculation result of harmonic impedance of utility side is more accurate and reliable.

According to flow chart of the new method to calculate harmonic responsibility shown in Figure 5, the relevant steps are implemented in turn, thus obtaining final harmonic responsibility of utility side and customer side.

Step one: Collect relevant data.

Take comprehensive consideration of harmonics under order of 3 and 5 as an example in this paper.

TABLE 2. Data collection.

Detection	Index	Physical quantity	Value/VA
Switch K1 is closed (first detection)	THD _I	Current distortion power on PCC	3014.57
	THD _U	Voltage distortion power on PCC	553.57
	THD _I •THD _U	Harmonic apparent power on PCC	130.53
Switch K2 is closed (second detection)	THD _I	Current distortion power on PCC	7636.15
	THD _U	Voltage distortion power on PCC	927.56
	THD _I •THD _U	Harmonic apparent power on PCC	295.52
Switch K3 is closed (third detection)	THD _I	Current distortion power on PCC	327.57
	THD _U	Voltage distortion power on PCC	307.86
	THD _I •THD _U	Harmonic apparent power on PCC	14.84

TABLE 3. The maximum economic loss of each index.

Index	Corresponding maximum capacity/kVA	Maximum economic loss/RMB
THD _I	7.64	15280
THD _U	0.93	1860
THD _I •THD _U	0.30	600

Because harmonic on PCC is detected three times a day, thus collecting relevant data corresponds to different detection sequences, results of data collection are shown in Table 2.

Step Two: Calculate total economic loss of harmonics on PCC.

Because physical quantity corresponds to each index occupies the capacity of PCC in the form of capacity, and capacity has a close relationship with the price of active power filter (APF). Therefore, with reference to unit price of active power filter in the electricity market in China (2000 RMB/kVA), the maximum economic loss *K* (governance cost) corresponds to each index is obtained.

Refer to current power quality standard [29], which considers that when total voltage distortion rate on PCC is within 5% and both rms values of harmonic current under harmonic order of 3 and 5 on PCC are 62A (total rms value of harmonic current is 87.68A), harmonics on PCC conform to power quality standard, which also means that there is no need to invest any compensation device. So, the most important hazard of harmonics of PCC within limited range is to increase line loss. Therefore, the method in literature [29] is adopted to calculate relevant parameters of economic loss function based on power quality engineering, which converts economic loss of harmonics on PCC conforming to critical requirement of power quality standard [29] to be 0.1 times of maximum economic loss of corresponding index. The calculation results are shown in Table 4.

It should be noted in Table 4 that harmonic current rate THD_I on PCC in power quality standard essentially reflects rms value of harmonic current to judge whether harmonic current is qualified.

According to Table 3 and Table 4, and substitute relevant data into Equation 9, and then, corresponding parameters σ of

TABLE 4. The economic loss under critical harmonic requirement.

Index	Critical characteristic of quality	Critical maximum economic loss / RMB
THD _I	87.68A	1528
THD _U	5%	186
THD _I •THD _U	87.68×5%	60

TABLE 5. The value of σ of different indexes.

Index	Corresponding σ
THD _I	191.01
THD _U	0.11
THD _I •THD _U	9.55

economic loss functions of different indexes can be obtained, calculation results are shown in Table 5.

According to Equation 8, harmonic economic loss on PCC corresponds to each index can also be obtained. Based on it, corresponding weight of each index can be calculated according to Equations (10) – (13), and then, total harmonic economic loss on PCC can also finally obtained. Calculation results are shown in Table 6.

Step three: Based on reference impedance method, parameters of Norton equivalent model of utility side and customer side under different detections are calculated.

Firstly, relevant data on PCC is measured, and then, according to related equations of reference impedance method in literature [28], the parameters of Norton equivalent model under different cases can be obtained.

Step four: calculate contributions of corresponding index of economic loss on PCC of utility side and customer side.

According to the principle of superposition projection, the contributions of corresponding index on PCC of utility side and customer side under different detections can be obtained, which are shown in Table 7.

According to Table 7, average contribution of each index of utility side and customer side can also be obtained, which is shown in Table 8.

TABLE 6. The calculation result of total harmonic economic loss on PCC.

Index	Average value of characteristic of quality	SNR	Weight	Economic loss / RMB	Total economic loss / RMB
THD _I	16.82A	1.93	0.3799	59.13	
THD _U	4.24%	21.95	0.0334	133.17	27.79
THD _I •THD _U	0.6764	1.25	0.5866	1.50	

TABLE 7. The contribution of each index of utility side and customer side.

Detection	Responsible party	THD _I	THD _U	THD _I • THD _U
Switch K1 is closed (first detection)	Utility side	2.15A	4.64%	0.09976
	Customer side	11.66A	0.34%	0.039644
Switch K2 is closed (second detection)	Utility side	3.48A	4.83%	0.168084
	Customer side	31.76A	1.00%	0.3176
Switch K3 is closed (third detection)	Utility side	1.39A	4.54%	0.063106
	Customer side	0.13A	0.01%	1.3×10 ⁻⁵

TABLE 8. The average contribution of each index of utility side and customer side.

Responsible party	THD _I	THD _U	THD _I • THD _U
Utility side	2.34A	4.67%	0.11
Customer side	14.52A	0.45%	0.12

TABLE 9. The SNR and weight of index on PCC of harmonics generated by customer side.

Name	THD _I	THD _U	THD _I • THD _U
SNR	3.106	3.339	8.533
Weight	0.436	0.405	0.159

TABLE 10. The SNR and weight of index on PCC of harmonics generated by utility side.

Name	THD _I	THD _U	THD _I • THD _U
SNR	6.589	30.02	5.970
Weight	0.430	0.095	0.475

Step five: calculate the corresponding Signal-to-noise ration (SNR) and weight of each corresponding index on PCC of utility side and customer side.

According to Equations (10) – (13), the corresponding Signal-to-noise ration and weight of each index which utility side and customer side generate respectively are obtained, calculation results are shown in Table (9) - (10).

Step six: calculate economic loss on PCC caused by harmonics generated by utility side and customer side respectively.

According to step 2, the maximum economic loss K_i and sensitivity parameter σ_i of corresponding index i are calculated, thus obtaining economic loss of corresponding index

TABLE 11. The calculation results of harmonic economic loss of utility side and customer side on PCC.

Responsible party	Index	Economic loss/RMB	Total economic loss/RMB
Utility side	THD _I	1.15	
	THD _U	160.29	15.74
	THD _I • THD _U	0.04	
Customer side	THD _I	44.08	
	THD _U	1.56	19.68
	THD _I • THD _U	0.05	

on PCC caused by harmonics generated by utility side and customer side respectively, and then, the total economic loss on PCC caused by harmonics generated by utility side and customer side respectively can also be obtained. Calculation results are shown in Table 11.

Step seven: calculate harmonic responsibility of utility side and customer side.

According to total economic loss E_L on PCC, economic loss on PCC E_{L-C} caused by customer side and economic loss on PCC caused by utility side E_{L-S} , harmonic responsibility of utility side and customer side can be obtained according to Equations (24) – (25).

$$R_S = \frac{E_{L-S}(x)}{E_L(x)} \times 100\% = 56.64\%,$$

$$R_C = \frac{E_{L-C}(x)}{E_L(x)} \times 100\% = 71.46\%.$$

It can be seen from the calculation results of harmonic responsibility of utility side and customer side that the sum of harmonic responsibility of utility side and customer side is greater than 100%. The main reasons are as follows: 1) According to simulation model shown in Figure 6, the harmonic voltage generated by customer side reduces the total

harmonic voltage distortion rate on PCC, the customer side is subtraction harmonic source, while the harmonic voltage generated by utility side aggravates the total harmonic voltage distortion rate on PCC, the utility side is augmentation harmonic source. And because customer side is subtraction harmonic source, the rms value of projection of harmonic voltage contribution on PCC of utility side is greater than rms value of total harmonic voltage on PCC. According to traditional methods of calculation of harmonic responsibility, the harmonic responsibility of utility side is greater than 100 percentage, while harmonic responsibility of customer side is negative. Some scholars refer to ‘‘Tort liability law’’ in China for judgment of environment pollution responsibility, it is found that harmonic responsibility is similar to environment pollution, and as long as the customer side is harmonic source, it should bear certain harmonic responsibility and accept corresponding punishment, instead it is not punished. Therefore, although the customer side reduces total harmonic voltage distortion rate on PCC, its subjective purpose is not to improve harmonic environment on PCC. In other words, the behavior of customer side for improving harmonic environment has certain contingency, whereas the customer side still needs to bear certain harmonic responsibility; 2) According to Equation 8, it can be found that the function of economic loss of quality characteristic is nonlinear, it cannot satisfy superposition principle like traditional calculation method of harmonic responsibility. Even if the direction of projections of harmonic contributions of utility side and customer side is same, the sum of harmonic economic loss caused by utility side and customer side is not equal to actual total harmonic economic loss on PCC.

B. DISCUSSION ON NEW SCHEME OF ELECTRICITY CHARGE

In most literatures, how to combine calculation result of harmonic responsibility and adjustment scheme of electricity charge is often not discussed. Therefore, power supply company cannot punish related customers based on calculation result of harmonic responsibility. Aim at this situation, the literature [24] firstly proposes a new adjustment scheme of electricity charge considering harmonic responsibility, the formula of new scheme is as follows:

$$M = M_1 + M_{PF1} + M_H = P_1tX + P_1tXX_{PF1} + HR = P_1tX + P_1tXX_{PF1} + S_NtX_3R. \tag{26}$$

where M_1 is electricity charge of fundamental active power, M_{PF1} is adjustment electricity charge based on power factor (it mainly charge for reactive power), M_H is harmonic electricity charge, P_1 is fundamental active power, X is the price of fundament active power, X_{PF1} is adjustment percentage of fundamental electricity charge based on power factor, and the value of it can be found in related document, S_N is non-fundamental apparent power, X_3 is the price of non-fundamental apparent power, R is harmonic responsibility of customer side, t is measurement time.

TABLE 12. The electricity charge of customer side under new scheme.

Name	Electricity charge of active power/RMB	Electricity charge of reactive power/RMB	Harmonic electricity charge/RMB	Total electricity charge/RMB
Electricity charge	168.73	-1.86	4.12	170.99

However, according to adjustment scheme shown in Equation 26, there are following two problems: 1) the adjustment scheme only assesses harmonic responsibility of customer side, lacking assessment of harmonic responsibility of utility side, 2) how to determine unit price of non-fundamental apparent power S_N for calculation of harmonic electricity charge needs to be carefully considered. Based on above two problems, the scheme proposed in literature [24] is not easily applied in actual case. Therefore, this paper attempts to propose a new adjustment scheme of electricity charge, the formula of it is as follows:

$$M = M_1 + M_{PF1} + M_H = P_1tX + P_1tXX_{PF1} + (E_{L-C}(x) - E_{L-S}(x)) = P_1tX + P_1tXX_{PF1} + E_L(x) \cdot (R_C - R_S). \tag{27}$$

where $E_L(x)$ is total economic loss caused by harmonics on PCC, $E_{L-C}(x)$ is economic loss caused by harmonics generated by customer side on PCC, $E_{L-S}(x)$ is economic loss caused by harmonics generated by utility side on PCC, R_C and R_S are harmonic responsibility of customer side and utility side respectively.

It is worth noting that harmonic electricity charge M_H is not related to time t . Because when the customer is connected to power system which contains certain background harmonics, it directly affects harmonic electrical environment on PCC. According to quality engineering theory, it considers that when quality characteristic deviates from quality target, there is certain economic loss on PCC. Therefore, harmonic electricity charge M_H reflects influence of utility side and customer side on commodity characteristic of electricity energy, which also means that the new adjustment scheme shown in Equation 27 can better reflect commodity characteristic of electricity energy. For electricity charge of fundamental active power and fundamental reactive power, traditional methods are still adopted.

Based on the new adjustment scheme of electricity charge, the electricity charge of customer side shown in Figure 6 which works 24 hours (each switch is closed for 8 hours) is obtained, calculation results are shown in Table 12.

Compare with traditional scheme 1 (using the fundamental power factor), traditional scheme 2 (using the total power factor) and the new scheme proposed in this paper, the comparison results are shown in Figure 7.

It can be seen form comparison results in Figure 7, traditional scheme based on fundamental power factor does

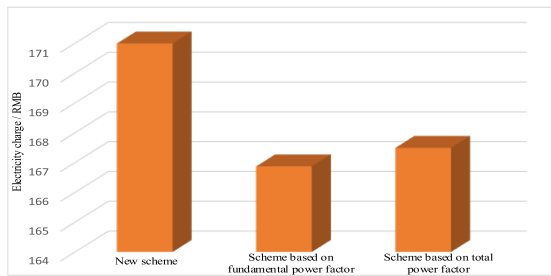


FIGURE 7. Comparison results of electricity charge.

not consider harmonics, which is not suitable for the power system with increasing harmonics. Compared with scheme 1, scheme 2 based on total power factor has a low penalty for harmonic electricity charge, but superimposed harmonics may cause great hazard to power system, it indicates that scheme 2 based on the total power factor becomes no longer applicable in this case. The new adjustment scheme of electricity charge discussed in this paper incorporates harmonics into the commodity characteristic of electricity energy, and carries out assessment of economic loss of harmonics, which reflects commodity property of electricity energy and also effectively prevent serious hazard of harmonics to power system. And in the calculation process of electricity charge, the harmonics generated by utility side and customer side are both considered, which is fairer for customers.

VI. CONCLUSION

The core objective of this paper is to explore reliable approach to measure harmonic responsibility from the new perspective of economic loss. Compared with other methods, it has following advantages:

1) The new method can evaluate harmonic responsibility comprehensively under different harmonic frequencies, and compared with comprehensive calculation of harmonic responsibility based on combination weighting method, it is easier to get applied in reality problems.

2) From the perspective of economy, it associates harmonics with economic loss, which effectively reflects the influence of the harmonics generated by different responsible parties on the economic loss of power system.

3) After discussing and comparing the new adjustment scheme of electricity charge with traditional schemes, harmonic electricity charge in new scheme not only better reflects the influence of the harmonics generated by customer side and utility side on quality characteristics of electricity energy in power system, but also more effective reflects the essential characteristic of electricity energy.

4) With reference to the Tort Liability Law, it is believed that when the responsibility part is not to reduce pollution subjectively, no matter whether it actually pollutes the relevant environment or not, it should take certain harmonic responsibilities. Compared with traditional methods, the new approach has stricter management of responsible parties for harmonics, thereby avoiding greater harmonic hazards.

In the calculation process of harmonic economic loss, the corresponding target value T of economic loss function of quality characteristic of corresponding index is assigned 0. Whether certain amounts of harmonics are allowed on PCC and corresponding economic loss of allowed harmonics is 0 by default, it should be further negotiated among the power supply company and customers.

The focus of this paper is mainly on calculation method of harmonic responsibility from the perspective of economic loss, and based on it, a new scheme of electricity charge is discussed. During the course of the work done in this paper, some areas could be improved and further researched. In the future, how to entirely take harmonic responsibility and unbalance responsibility into consideration and establish a much fairer and more comprehensive responsibility division system is a question worth discussing.

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