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A Business Model Incorporating Harmonic Control as a Value-added Service for Utility-owned Electricity Retailers

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***Abstract*—With the deepening of electricity market reform in China, the competition in the electricity retail market becomes increasingly intense. Electricity retailers (ERs) need to explore new business models to enhance their competitiveness in the retail market. Meanwhile, with the improvement of industrial production and people's living standards, more and more nonlinear electrical equipment have been put into use, leading to severe harmonic pollution problems. Harmonic pollution causes loss of electricity, resulting in the economic loss of customers, especially for large industrial customers. In the above contexts, this paper proposes a novel business model that incorporates harmonic control as a value-added service into electricity retail contracts for utility-owned ERs. Both utility-owned ERs and customers can benefit from the designed business model. For customers, it helps them to improve the power quality while saving the electricity cost. For ERs, it helps them to cultivate the customer loyalty and improve the customer satisfaction. A case study is performed to demonstrate the effectiveness of the proposed business model.**

***Index Terms*—Electricity market reform; Retailer; Business model; Harmonic control; Value-added service.**

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I. INTRODUCTION

The increasing penetration of intermittent renewable energy poses huge challenges to power system operations. Although some measures, such as accurate power forecasting technologies [1-4] and demand response [5-8], can be utilized to mitigate the negative impacts, they still can't address the issues fundamentally. The rigidity of China's electricity sector regime runs counter to the flexibility requirement for accommodating intermittent renewables, and that it is essential to perform the reform of the electricity market to enhance the renewable energy integration [9]. The State Council and the Central Committee of the Communist Party promulgated *Several Opinions on Further Deepening the Reform of Electric Power System (Zhongfa [2015] Document #9)* in March 2015 [10], signifying the launch of new electricity market reforms (new reforms) in China. Six critical accompanying documents were then released subsequent to the issuance of *Document #9*, detailing the implementation paths and measures for the reforms to the electricity market, transaction system, power generation and utilization, electricity transmission & distribution (T&D) tariffs and electricity demand side management [11]. The overall objective of the new reforms is to establish a market-orientated power system. The new reforms are characterized by 'regulating the middle and deregulating the two ends', which means regulating the T&D segments and introducing competitions into the generation and retail segments of the electricity sector [12]. Utility companies are to be stripped of their monopolies in the retail segment, allowing other participants to engage in electricity retail.

This research is performed under an existing market structure. Fig. 1 shows the existing electricity market structure. Electricity is bought, sold and traded in wholesale and retail markets. The wholesale market refers to the buying and selling of power between the generators and resellers (entities that purchase goods or services with the intention to resell them to someone else) [13]. Resellers include electricity utility companies, electricity retailers (ERs) and electricity marketers. In this paper, we mainly focus on ERs. After electricity is bought by ERs in the wholesale market, it can be sold to end-user customers in the retail market.

According to the difference of ownership, the ERs in China can be broadly classified into two categories: 1) utility-owned ERs; 2) privately-owned ERs. Utility-owned ERs are established by utility companies (such as The State

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Grid Corporation of China, i.e. the largest utility company in the world), which are designed to operate the electricity retail business. Privately-owned ERs are established by third-party companies (such as Internet companies). In this paper, we will focus on the utility-owned ERs.

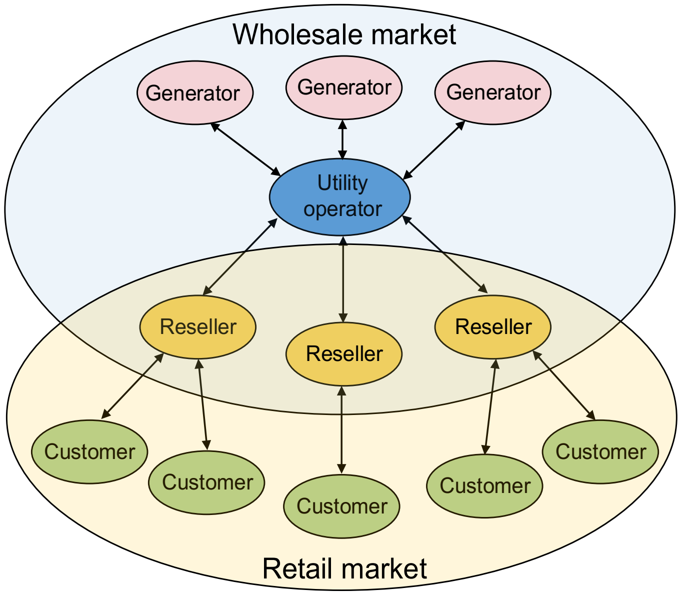

Fig. 1. Illustration of the electricity market structure.

In recent three years, the number of ERs is growing at an unprecedented speed in China. It is estimated by the National Energy Administration (NEA) that there are more than 2500 registered ERs in China by the end of April 2018 [14]. The existing of a large number of ERs enables customers have options for purchasing electricity. They can choose from a number of competitive ERs to find the service that best fits their needs. In such a competitive retail market, an ER needs to explore new business models in order to enhance its own competitiveness in the retail market and attract more customers. In addition to lower electricity prices, diversified value-added services have become an important means for ERs to attract customers.

With the continuous improvement of industrial production and people's living standards, more and more nonlinear electrical equipments are put into use, leading to severe harmonic pollution problems [15-18]. The harmonics of current or voltage waveform refer to the summation of various higher frequency sinusoidal components that are an integer multiple of the fundamental frequency. The magnitude of harmonics injected from transformer cores, arc furnaces, induction heating systems, rectifiers, switching power converters, welding equipment, electric motor drives, etc., can be considerable especially for those large industrial customers. The harmonics have negative impacts on customers in many aspects. 1) From the perspectives of economic, harmonics cause severe loss of electricity, leading the economic loss of customers 2) From the perspectives of electrical equipment, harmonics accelerate the insulation and aging of electrical equipment, thus resulting in the decrease of service life [19]. Therefore, it is essential to conduct harmonic control, especially for those large industrial customers suffering from significant negative impacts [20].

This paper aims to explore a new business model for utility-owned ERs to provide customized value-added service for large industrial customers.

The main contributions of this paper can be summarized as follows.

(1) A novel business model incorporating harmonic control as a value-added service into electricity retail contracts is proposed for utility-owned ERs in this paper. Both customers and utility-owned ERs can benefit from the designed business model. For customers, the business model helps them to improve the power quality while saving the electricity cost. For ERs, the business model helps them to cultivate the customer loyalty and improve the customer satisfaction so as to enhance their competitiveness in the retail market.

(2) Simulations are performed to verify the effectiveness of the proposed business model. The unique advantage of utility-owned ERs compared to privately-owned ERs on performing the harmonic control is also demonstrated in a case study.

The rest of the paper is organized as follows: Section II analyses the economic loss caused by harmonics to customers. In section III, two kinds of harmonic control methods are introduced and their costs are analyzed. The business model incorporating harmonic control services is designed in Section IV. Simulation study is performed to verify the effectiveness of the proposed business model in Section V. Section VI highlights the concluding remarks and future works.

II. Analysis of Economic Losses Caused by Harmonics

The presence of harmonics poses many problems to industrial customers. This section will focus on the economic losses caused by the harmonics and conduct a quantitative assessment. The economic loss caused by harmonics is mainly reflected in the power loss of transformers and transmission lines.

A. Additional power losses on transmission lines and transformers caused by harmonics

1) Transmission lines

The power loss on transmission lines denoted by P_{loss} can be expressed as Eq. (1) [21, 22].

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$$\begin{aligned} P_{loss} &= \sum_{n=1}^{h} I^2{}_n R_n \\ &= I_1^2 R_1 + \sum_{n=2}^{h} I^2{}_n R_n \\ &= I_1^2 R_1 (1 + \sum_{n=2}^{h} \sqrt{n} HRI_n^2) \end{aligned} \tag{1}$$

where n is the order of harmonic currents. h is the maximum order of harmonics. R_1 is the resistance of transmission line without harmonics. HRI_n is the content of each harmonic, which is the ratio of each harmonic current to the fundamental current.

The power losses on transmission lines can be divided into two parts: fundamental losses and harmonic losses [23]. The fundamental loss is generated by the fundamental current.

The harmonic loss is generated by the harmonic current, which is k_l times of the fundamental loss. The k_l can be calculated by Eq. (2).

$$k_l = \sum_{n=2}^{h} \sqrt{n} HRI_n^2 \tag{2}$$

Formula (2) indicates that the effect of harmonics on the power loss on transmission line can be equivalent to the increase of transmission line resistance.

2) Transformer

The power losses on transformer include two parts, namely copper loss and iron loss. The copper loss refers to the power loss caused by current passing through transformer windings [24].

The iron loss is the power loss appearing in the iron core. Similar to the power loss on transmission lines, the power losses on transformers are also divided into two parts, namely fundamental loss and harmonic loss. The additional harmonic loss is the k times of the fundamental loss. The additional copper loss multiplier of transformers denoted by k_{cu} is expressed as Eq. (3).

$$k_{cu} = \sum_{n=2}^{h} n HRI_n^2 \tag{3}$$

Transformer iron loss multiplier of transformers is expressed as Eq. (4).

$$k_{\mathrm{Fe}} = \alpha \sum_{n=2}^{h} n^2 HRI_n^2 + \beta \sum_{n=2}^{h} n \; HRI_n^{1.6} \tag{4}$$

where α and β are the ratios of the eddy current loss and the hysteresis loss to the iron loss of the transformer.

B. Power losses caused by the reduction of transformer capacity

Under the influence of harmonics, winding loss and eddy current loss of transformer will significantly increase, leading to the increase of transformer temperature, which makes the transformer cannot work in its rated capacity [25].

The power loss caused by the reduction of transformer capacity is also a non-ignorable part of the economic losses. Let F' be the transformer capacity reduction rate caused by harmonics, which can be calculated by Eqs. (5)-(7).

$$F' = \frac{a}{1 + bF_k} \tag{5}$$

$$F_k = \frac{F}{1 + THDi^2} \tag{6}$$

$$F = \sum_{n=1}^{h} \left(\frac{I_n}{I_1} \right)^2 n^2 = \sum_{n=1}^{h} HRI_n{}^2 n^2 \tag{7}$$

where a=1.15 and b=0.15 (empirical values). THD_i is the total harmonic distortion (THD) of current. According to the value of F' and the rated capacity of transformer, the reduction of transformer capacity can be calculated.

In summary, the economic losses caused by harmonics denoted by y_{loss} mainly consists of three parts: 1) The economic loss due to the additional power loss on transmission line, denoted by y_l; 2) The economic loss due to the additional power loss on transformers, denoted by y_t; 3) The economic loss due to the capacity reduction of transformer. Thus, we have

$$\begin{aligned} y_{loss} &= y_l + y_T + y_F \\ &= Q_{loss}^l \cdot \rho_0 + Q_{loss}^T \cdot \rho_0 + \frac{F' \cdot C_T}{N_T} \end{aligned} \tag{8}$$

where Q_{loss}^l and Q_{loss}^T are the annual electricity loss caused by the additional power loss on the transmission line and the transformer. ρ_0 is the electricity price. C_T is the cost of the transformer. N_T is the service life of the transformer.

III. Cost Analysis of Harmonic Control

A. Harmonic control methods

The presence of harmonics not only reduces the power quality resulting in the decrease of product quality, but also leads to severe economic loss. Therefore, it is essential for those larger industrial customers to conduct harmonic control. Many harmonic control methods have been proposed, which can be classified into two types: passive power filters (PPFs) and active power filters (APFs). PPFs are usually composed of resistors, inductors and capacitors, which do not depend upon an external power supply and do not contain active

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components such as transistors [26]. PPFs have the advantages of low-cost, maturity and simple structure. APFs are a kind of power electronic devices, which are usually an inverter composed of insulated gate bipolar transistors (IGBTs). They are equivalent to a harmonic generator, which generates the required harmonics by controlling IGBT. The basic principle of APFs is to detect the harmonic current from the compensation object, and then generate a compensation current that equal to the harmonic current but the polarity is opposite, so as to filter out the harmonic [27]. Compared to PPFs, APFs show better performance on harmonic filtering, but are usually more expensive than PPFs.

B. *Cost analysis of harmonic control*

1) Equipment purchase cost

The cost of harmonic control denoted by C_{cus} mainly includes two parts，namely equipment purchase cost and maintenance cost. The equipment purchase cost denoted by C_{inv} is an important part of the cost of harmonic control and can be expressed Eq. (9).

$$C_{inv} = \rho_{inv} \cdot S \tag{9}$$

where ρ_{inv} is the unit-price of the harmonic control equipment and S is the capacity of the equipment.

2) Equipment maintenance cost

The maintenance costs of harmonic control equipment denoted by C_{mai} include repair costs, equipment replacement costs, labor costs and other costs.

In summary, the cost of harmonic control denoted by C_{cus} can be expressed as Eq. (10).

$$C_{cus} = \rho_{inv} \cdot S + C_{mai} \tag{10}$$

IV. Electricity Retail Contract Design Incorporating Harmonic Control

A. *Qualitative analysis of costs and benefits for both ERs and customers*

Fig. 2 shows the cost and benefit analysis of ERs before and after the electricity market reform. Utility companies have monopolies in the retail segment before the electricity market reform. They purchase the electricity from power generation companies and sell it to customers. Namely, the profits of utility companies come from the price difference between purchase and sale before the new reforms. After electricity market reform, ERs appear as the brokers between electricity markets and customers. The electricity purchase cost of ERs is equal to the sum of the feed-in tariff charged by power generation companies and T&D price charged by grid companies. The profits of ERs also come from the price difference between the purchase and the sale.

This paper proposes a novel business model in which the harmonic control is incorporated as a value-added service into the electricity retail contract (a contract in which a mutual agreement has been made between the ER and the customer). Specifically, an ER can sign a retail contract with a customer. In the contract, the ER sells electricity to the customer whilst providing harmonic control services. The harmonic control service is achieved by installing harmonic control equipment. The ER is responsible for the investment, installation and maintenance of harmonic control equipment. After installing the harmonic control equipment, the economic loss caused by the harmonic to customers can be saved. Since the harmonic control service also need cost (i.e. equipment investment and maintenance cost), the retail electricity price will increase. However, the cost saving due to the implementation of harmonic control will still exceed the additional cost charged by ERs. In other words, both the ER and the customer can share the cost saving due to harmonic control during the contract period. Thus, the customer can save the electricity cost. The ER can gradually recover the investment cost of the harmonic equipment during the contract period. The proposed business model enhances the competitiveness of the ER (who adopts the proposed business model) in the retail market.

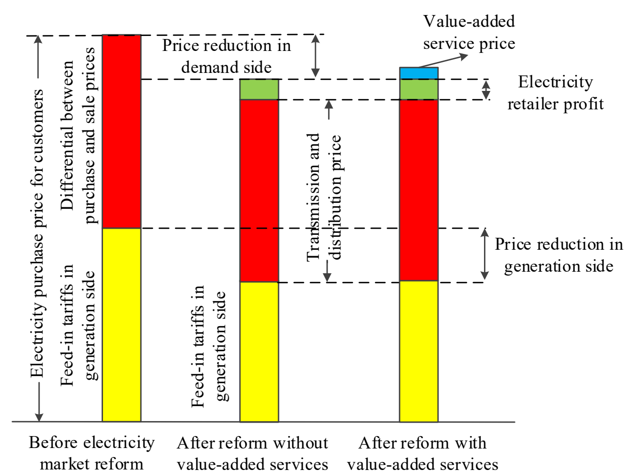

Fig. 2. Cost and benefit analysis for ERs

B. *Design of the electricity retail contract incorporating harmonic control services*

Based on the above analysis, the retail electricity price if there is no value-added service can be calculated by Eq. (11).

$$\rho_{c0} = \rho_{pur} + \rho_{tra} + \rho_{mk} \tag{11}$$

where ρ_{c0} is the retail electricity price when there is no value-added service. ρ_{pur} is the feed-in tariffs in generation side. ρ_{tra} is the transmission and distribution price. ρ_{mk} is differential between the purchase and the sale price, which is the main source of profits for ERs when there is no value-added service.

If the harmonic control service is incorporated into the electricity retail contract, the retail electricity price will increase, which can be calculated by Eq. (12).

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$$\rho_c^p = \rho_{c0} + \rho_{cus} = \rho_{co} + \frac{\alpha \cdot \rho_{inv} \cdot S + C_{mai} \cdot N}{N \cdot Q'} \quad (12)$$

where ρ_{cus} is the additional price charged by ERs due to the harmonic control service. α is the recovery ratio of equipment investment cost for ERs during the contract period. N is the contract period. Q' is the annual electricity amount actually required by the customer after harmonic control.

The value of α affects the profit of both ERs and customers. If α is set to be less than 1, it means the equipment investment costs cannot be fully recovered within the contract period. Even so, the ER still can recover costs or even get profits by renewing contracts with the customer. Because the customer is willing to renew the contract in this case since she can obtain better services whilst saving electricity costs from the contract. Moreover, the ER can also obtain some indirect benefits (which are difficult to quantify) from the proposed business model. For example, it helps the ER to cultivate customer loyalty, improve customer satisfaction and attract more new customers.

If α is set to be between 1 and a critical value α_0, both ERs and customers will share the benefits due to the cost saving after harmonic control. α_0 can be calculated by (13).

$$\alpha_0 = \frac{[\rho_{co}(Q - Q') - C_{mai}]N}{\rho_{inv} \cdot S} \quad (13)$$

where Q is the annual electricity consumption of customers before harmonic control. If α is set to be more than α_0, the cost saving due to the implementation of harmonic control will be less than the additional cost charged by ERs, thus customers are not willing to sign the contract in this case.

V. Case Study

This paper takes a metallurgical plant in China as an example to illustrate the effectiveness of the proposed business model. The metallurgical plant is a typical large industrial customer with six-pulse rectifier harmonic sources, whose average annual electricity consumption is 20 million kWh. There are two distribution transformers in the metallurgical plant. The capacity and rated voltage of each transformer is 2500 kVA and 10/0.4 kV. The specific parameters of each distribution transformer are listed as follows: the apparent power is 2007kVA, the active power is 1570kW, the reactive power is 1250kVar and the power factor is 0.782. The harmonic contents in the metallurgical plant are typical harmonics. The THD of voltage is 33.81%. The magnitudes of the 5th, 7th, 11st and 13rd harmonic are 610 A, 435 A, 278 A and 234 A, respectively.

A. Results of economic loss caused by harmonics

1) Economic losses due to additional loss on transformer and transmission line caused by harmonics

According to the discussion of the additional harmonic losses, the additional loss multiplier are calculated as: k_l=0.5647, k_{Cu}=0.2125, k_{Fe}=4.4217. The iron loss and copper loss caused by fundamental current of the two transformers in the metallurgical plant are 4.36 kW and 40.24 kW respectively according to the investigation on the electricity data and related equipment parameters of the metallurgical plant. The average running time of the transformers in the metallurgical plant is 6500 hours per year. The power loss ratio on transmission lines caused by fundamental current is 5%. The local electricity price is 0.75 yuan. Hence, the annual economic loss of the metallurgical plant due to power loss on transformers and transmission lines caused by harmonics is 0.558 million yuan.

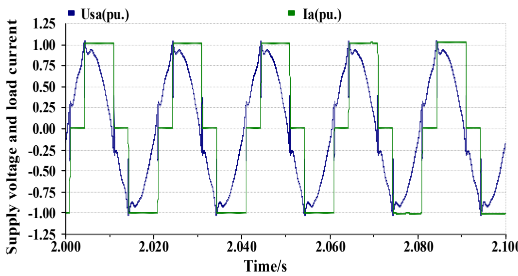
2) Economic losses due to reduction of transformer capacity caused by harmonics

According to the harmonic data of the metallurgical plant, F'=0.6501 is obtained, that is to say, the transformer needs to be reduced to 65.01% of the rated capacity in order to keep the transformer from overheating. The model of the transformer used in this plant is SF9-2500/10/0.4, and the service life of the transformer is 25 years. According to the investment and maintenance cost of the transformer, the metallurgical plant will suffer from the economic loss of more than 36 thousand yuan each year due to the reduction of the transformer capacity caused by harmonics. In summary, the total economic loss caused by harmonic problems to the metallurgical plant is 0.562 million yuan.

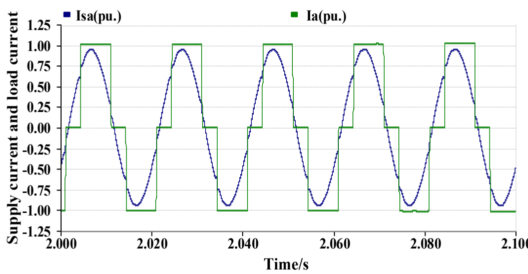
B. Simulation analysis of harmonic control

1) Harmonic control by PPFs

If the PPF is used to conduct the harmonic control for the metallurgical plant, we need to install the 5th, 7th, 11st and 13rd PPF. If the power factor is improved to 0.95 by reactive power compensations, the fundamental wave compensation capacity should be designed as 735 kVar. Considering the harmonic capacity and certain margin, the capacity of each PPF should be designed as 1800 kVar. Based on the above designed parameters, the simulation model is built in PSCAD. Fig. 3 shows the power supply voltage and load current after harmonic control. It can be seen that there are considerable harmonic contents in the load current before harmonic control. We can see the waveform of load current has been greatly improved after filtering harmonics. Fig. 4 presents the Fast Fourier Transform (FFT) analysis results of the power supply current before and after harmonic control. It can be seen that the 5th, 7th, 11st and 13rd harmonics are significantly reduced. Simulation analysis shows that the PPF can effectively filter out those typical harmonics so that the harmonic content of the power supply side decreases significantly. The THDs of voltage and current are reduced to 2.4% and 1.38%. Specifically, the 5th, 7th, 11st and 13rd harmonic currents are reduced to 35 A, 16 A, 8 A and 7 A, respectively. The power factor is improved to 0.939.

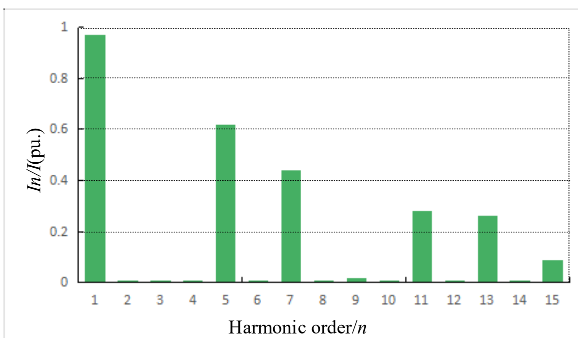


(a) Power supply voltages and load currents after harmonic control

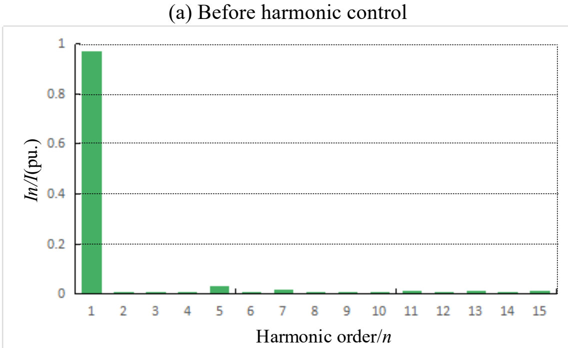


(b) Power supply currents and load currents after harmonic control

Fig. 3. The harmonic control performance of the PPF.



(a) Before harmonic control

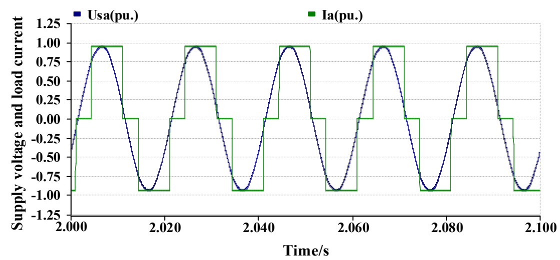


(b) After harmonic control

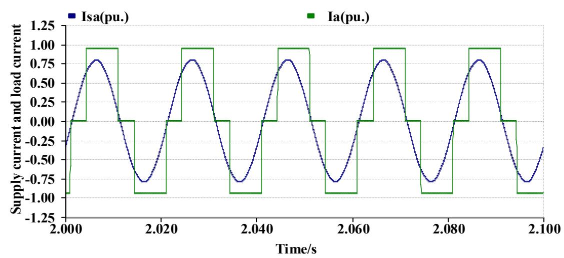
Fig. 4. Harmonic contents of the power supply current before and after harmonic control

2) Harmonic control by APFs

The output current of APF is 2200 A, considering the margin, the capacity of each APF is designed to be 1750 kVar. The simulation results are shown in Fig. 5 and Fig. 6. It can be overserved that the APF can effectively filter out typical harmonics, so that the harmonic content of the power supply side decreases substantially, and the power factor can also be significantly improved. The *THDs* of voltage and current are 2.2% and 1.05%, respectively. Specifically, the 5th, 7th, 11st and 13rd harmonic currents are reduced to 16 A, 25 A, 6 A and 4 A, respectively. The power factor is improved to 0.998.

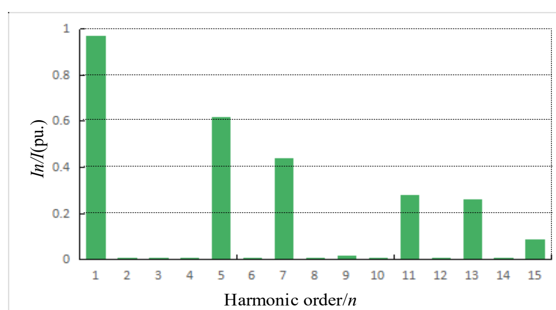


(a) Power supply voltages and load currents after harmonic control

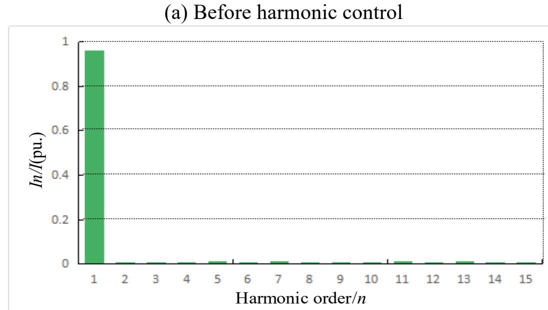


(b) Power supply currents and load currents after harmonic control

Fig. 5. The harmonic control performance of the APF.



(a) Before harmonic control



(b) After harmonic control

Fig. 6. Harmonic content of load current and power source current of active solution

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C. *Comparison between the electricity retail contracts with and without harmonic control services*

At present, the unit-price of the PPF is about 300 yuan per kVar and the unit-price of the APF is about 1000 yuan per kVar. Since there are two transformers in the metallurgical plant, and each of them needs to install a PPF with the capacity of 1800 kVar or an APF with the capacity of 1750 kVar to perform the harmonic control. If we perform the harmonic control using the PPF, the equipment investment cost will be 1.08 million yuan. If we perform the harmonic control using the APF, the equipment investment cost will be 3.52 million yuan. The annual operation and maintenance costs of the PPF and the APF are considered as 3% and 1% of the equipment investment cost. In this section, α is set to be 70%, we analyze the relationship between the retail electricity price and the contract period, given in Fig. 7.

It can be found that for both contracts, the electricity purchase price for the customer decreases with the increase of contract period. This is because ER is willing to provide beneficial price to customers if the customers are willing to sign long-term contracts with the ER.

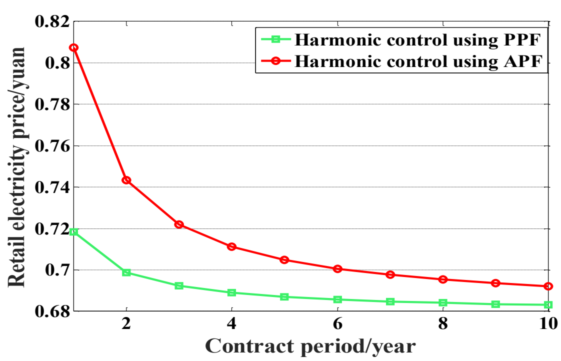

Fig. 7. The relation between retail electricity price and contract period.

Compared to the PPF, if customers choose the APF to perform harmonic control, the electricity price will be higher, because the investment cost of the APF is more expensive than the PPF. However, the harmonic control performance of the APF is better than the PPF, namely the economic loss avoided by the APF is more than the PPF. Therefore, the retail electricity prices in these two contracts become close with the increase of the contract period.

Taking the five-year contract period as an example, the retail electricity prices in different electricity retail contracts are shown in Table I. We calculate the actual annual electricity amounts needed to be purchased by customers and the annual electricity bill before and after harmonic control. The results are shown in Table II.

Since the harmonics lead to the electricity loss of customers, the actual electricity amounts that are actually needed by customers will significantly reduce after harmonic control.

TABLE I. COMPARISON OF RETAIL ELECTRICITY PRICES BETWEEN DIFFERENT ELECTRICITY RETAIL CONTRACTS

Electricity retail contract	Retail electricity price (yuan/kWh)
No harmonic control services	0.6775
Harmonic control services using PPFs	0.6883
Harmonic control services using APFs	0.6915

TABLE II. COMPARISON OF ANNUAL ELECTRICITY BILL FOR CUSTOMERS BETWEEN DIFFERENT ELECTRICITY RETAIL CONTRACTS

Electricity retail contract	Electricity loss ($\times10^4$ kWh)	Annual electricity purchase amount ($\times10^4$ kWh)	Annual electricity bill ($\times10^4$ yuan)
No harmonic control services	74.39	2000.00	1335.00
Harmonic control services by PPFs	0.21	1925.82	1325.54
Harmonic control services by APFs	0.16	1925.77	1331.67

From Table II we can see that compared with the electricity retail contract without harmonic control services, both contracts with harmonic control services can help customers to save annual electricity bills. Moreover, the PPF-based harmonic control method can save more money for customers because of its lower equipment investment cost. However, it should be noted that the above conclusions are drawn when α is set to be 70% and the contract period is five years. There are some other indirect benefits for ERs such as the improvement of the customer loyalty that are difficult to quantify.

D. *Advantages of utility-owned ERs on performing harmonic control*

Compared to those privately-owned ERs, utility-owned ERs have more information about the distribution network topology structure and customer harmonic pollution. In this section, we will present a case to demonstrate the unique advantage of utility-owned ERs on performing the proposed business model.

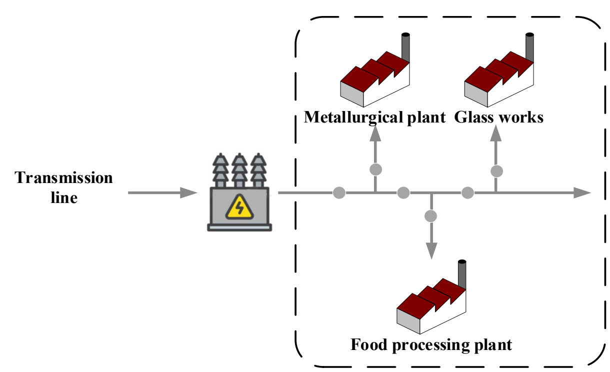

Fig. 8. A part of distribution network topology structure in a certain region

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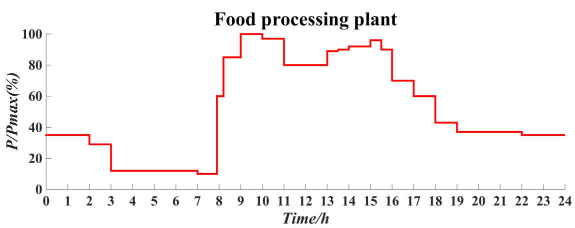
Fig. 8 shows a part of distribution network topology structure in a certain region. There are three large industrial customers under the same feeder, namely a food processing plant, a glass works and a metallurgical plant. The electricity consumption and harmonic pollution information of the three customers is shown in Table III. The electricity consumption characteristics of the three customers are quite different. The electricity load of the food processing plant is mainly concentrated in the daytime. On the contrary, the electricity load of glass works is mainly concentrated at night.

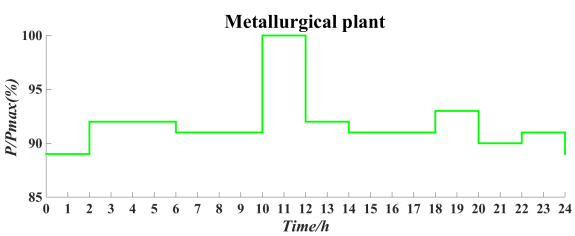
TABLE III BASIC INFORMATION OF THREE CUSTOMERS

Customer type	Annual electricity consumption （kWh）	Distribution transformer capacity （kVA）	THD	Compensation capacity needed （kVar）
Food processing plant	10 million	2000	26.42%	800
Metallurgical plant	20 million	5000	33.81%	1800
Glass works	40million	8000	32.16%	3200

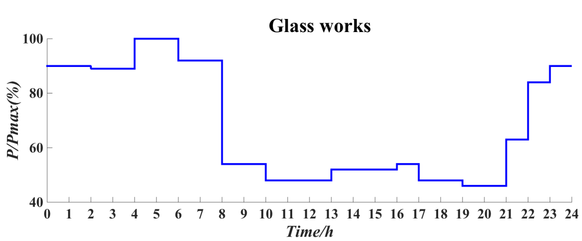
Due to the continuity requirement of production process, the metallurgical plant maintains a high load throughout the day. Fig. 9 shows the typical normalized daily load curves of the three customers.



(a)Food processing plant



(b) Metallurgical plant



(c) Glass works

Fig. 9. Typical normalized daily load curve of three customers.

The peak load denoted by P_{max} of the food processing plant, metallurgical plant and glass works is 1600 kW, 3800 kW, and 6500 kW, respectively. From Fig. 8 we can see that the daily load curves of the glass work and the food processing plants fluctuate greatly during the whole day, and the load is less than the 60% of the peak load in most of the time. The rated capacity of the harmonic control equipment should be designed according to the peak load of the customer, which means the equipment cannot be fully utilized in most of the time for those customers with large fluctuations in the load. Let us define the utilization ratio [28, 29] of the harmonic control equipment η, which is expressed as Eq. (14).

$$\eta = \int_0^T \frac{C_n(t)}{C_R} dt / T \tag{14}$$

where C_R is the rated compensation capacity of the filter. $C_n(t)$ is the actual compensation capacity required by customers, which varies with time t. T is the evaluation time period. In this paper, T is set to be 24 hours. We calculate the utilization ratio for the three customers. The η of the metallurgical plant, food processing plant and glass works are 82.75%, 47.11% and 65.19%, respectively.

Typically, privately-owned ERs have little knowledge about the topology structure of the distribution network. Therefore, they are more likely to perform the harmonic control for each customer separately in this case, as shown in Fig. 8. Namely, they need to install the harmonic control equipment at Nodes 2, 4 and 6, respectively. As such, the harmonic control equipment with the total capacity of 5800kVar is required. Instead, utility-owned ERs can obtain abundant information about the power grid operation, such as topology structure and power quality data, from utility companies. They can just install the harmonic control equipment with the capacity of 4800kVar at the public node 1 to achieve the same harmonic control effect. Hence, the utilization rate of the harmonic control equipment can be improved to 83.27%. The harmonic control capacity needed can be reduced, thus the investment cost can be significantly saved.

VI. CONCLUSION

With the deepening of the electricity market reform, many privately-owned ERs are permitted to engage in electricity retail business, intensifying the competition in the electricity retail market. This paper proposes a novel business model for utility-owned ERs that incorporates the harmonic control as a value-added service into electricity retail contracts. Simulation results have demonstrated the effectiveness of the proposed business model. Furthermore, the unique advantage of utility-owned ERs compared to privately-owned ERs on performing harmonic control has also been verified in a case study. Considering the influence effects of multiple impact factors on the customers' electricity consumption including the penetration rate of distributed solar PV generation [30], the electricity price [31], the incentive-based residential demand response and the residential customized feedback interventions [32], the harmonic pollution levels of the customer probably would change in different specific cases from time to time such as multiple microgrids [33-35]. Therefore, more specific quantitative analysis regarding the impacts on the value-added service package under various scenarios with different harmonic pollution levels of customers and the optimal design principle for the price tariff should be conducted based on the current works [36-43] in the future work.

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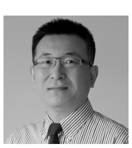

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