Design of Power Supply Service Plan for Electric Company Considering Harmonic Management

Qitian Mu, Jiafeng Ren, Yajing Gao and Yongchun Yang
Department of Electrical Engineering
North China Electric Power University
Baoding 071003, China
ncepugyj@163.com

Fei Wang
State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources (North China Electric Power University), Baoding 071003, China; also with Department of Electrical Engineering, North China Electric Power University, Baoding 071003, China; also with Hebei Key Laboratory of Distributed Energy Storage and Micro-grid (North China Electric Power University), Baoding 071003, China
feiwang@ncepu.edu.cn

Miadreza Shafie-khah
C-MAST, University of Beira Interior
6201-001 Covilhã,
Portugal
miadreza@ubi.pt

João P. S. Catalão
INESC TEC and FEUP, 4200-465 Porto, Portugal;
also with C-MAST/UBI, 6201-001 Covilhã, Portugal;
also with INESC-ID, IST-UL, 1049-001 Lisbon, Portugal
catalao@ubi.pt

***Abstract*—With the deepening of the reform of the power system, the sale companies need to constantly explore new business models and marketing programs. At the same time, the power quality should meet the requirements of the user, in which the harmonic problem is a very important aspect. Based on the service level of the harmonic losses of the application of the evaluation value of governance, the harmonic characteristics of the user put forward the harmonic control scheme of passive and active service, and simulated under PSCAD verification. Based on the analyses of the effectiveness and cost of the above schemes, combined with the profit analysis of the selling companies, a value-added service package containing the harmonic treatment is designed for the users to choose.**

***Index Terms*—power sale company; user suitability evaluation; harmonic governance; power service package.**

I. Introduction

In order to further solve the problems existing in the development of power industry [1,2], the State Council of China's Central Committee of the Communist Party of China promulgated the " Some opinions on further deepening the reform of the electric power system [2015] No.9 [A]." in March 2015, and clearly put forward the power system of "holding the middle and opening the two ends" structure and "steadily promote the reform of sales side, orderly release to the social capital of placing electricity business" approach.

With the development renewable energy integration and economic & social production, such as solar PV systems, a large number of non-linear devices of power users, especially large industrial users, have been put into use, bringing about several very serious problems. For instance, the fluctuant output of renewables like solar PV plants always lead difficulties for the active power balance of bulk power grid, which requires the accurate power forecasting technology [3-6] and active participation like demand response [7-10] to mitigate.

Due to a large number of harmonic currents on the one hand caused a serious loss of electricity, increasing the burden on electricity users[11]; the other hand, caused by the temperature of electrical equipment to speed up insulation aging, making equipment life shortened [12], which make harmonic pollution become another serious problem.

With the deepening of people's understanding of the harm of harmonics, many harmonic control methods have been proposed, which are mainly divided into two types: passive control and active control. Adopting the filter composed of series-parallel connection of RLC passive components to filter out, it is called passive filter. Because it has the advantages of low cost, mature technology, simple structure and easy realization, it has still been widely used [13, 14]. The other is to add a power electronic converter at the load end of the grid to filter out the harmonics. This device is called Active Power Filter (APF). Compared with the passive filter, it has the advantages of good filter characteristics, no resonance and so on. As the power electronics technology advances, the technology also gradually matures [15, 16].

In this paper, according to the power quality requirements of users, firstly, based on the level of harmonic economic loss, the applicability of user harmonic management value-added services is analyzed and evaluated, and the appropriate users are selected. The user harmonic analysis model. Based on the analysis of the harmonic characteristics of the users, the schemes of passive and active user-customized power service are proposed and simulated respectively. Finally, combined with the profit analysis of the sales company and the profit of the value-added service, the power supply service package with harmonic control is designed to provide users with diversified choices.

II. USER SUITABILITY ASSESSMENT BASED ON HARMONIC ECONOMIC LOSS

In the power users to develop service packages, to provide value-added services, the user needs to be assessed. For electric users, users have the need to sign a contract of good power supply package with the sales company only when the power harmonics bring a certain degree of economic loss. Therefore, according to user harmonic economic losses to users of high-quality power supply package evaluation is the first step in the introduction of sales package.

A. Economic losses caused by harmonics to industrial users

The existence of power harmonics will bring a lot of hazards to power users. The power loss caused by harmonics is mainly reflected in the power loss of transformers and transmission lines. This article will focus on the losses caused by the power harmonics on the distribution network of power consumers and conduct a quantitative assessment [17].

1) Line and Transformer Harmonic Additional Loss Assessment

a. Power lines

When there is harmonic current in the transmission line, the waveform of the current will be distorted. The distortion current expression is:

$$I = \sqrt{I^2{}_1 + I^2{}_2 + \ldots + I^2{}_h} = \sqrt{\sum_{n=1}^{h} I^2{}_n} \tag{1}$$

In equation (1), n is the number of harmonic currents and h is the maximum number of harmonic currents in the line.

THD_i is the harmonic current distortion rate

$$THD_i = \left(\sqrt{I^2{}_2 + I^2{}_3 + \ldots + I^2{}_h} \,/\, I_1\right) \times 100\% \tag{2}$$

HRI_n for each harmonic content, refers to the ratio of the harmonic current and the fundamental current, that is:

$$HRI_n = I_n / I_1 \tag{3}$$

where I_n is the n-th harmonic current, I_1 is the fundamental current.

Take the transmission line as an example, the total loss in the line is:

$$P_{loss} = \sum_{n=1}^{h} I^2{}_n R_n \tag{4}$$

Where R_n is the line resistance at nth harmonic.

It can be seen from (4) that the harmonic current will increase the effective value of the current in the transmission line, thereby increasing the transmission loss of the electric energy.

When considering the skin effect, the line resistance can take the following model:

$$R_n = \sqrt{n} R_1 \tag{5}$$

Therefore, the loss of power transmission lines can be expressed as:

$$\begin{aligned} P_{loss} &= \sum_{n=1}^{h} I^2{}_n R_n \\ &= I_1^2 R_1 + \sum_{n=2}^{h} I^2{}_n R_n \\ &= I_1^2 R_1 (1 + \sum_{n=2}^{h} \sqrt{n} HRI_n^2) \end{aligned} \tag{6}$$

From (6) we can see that the transmission line loss is divided into two parts, one for the fundamental loss, which is generated by the fundamental current; the other part is the harmonic loss, which is generated by the harmonic current and is the fundamental current k_l Times, of which:

$$k_l = \sum_{n=2}^{h} \sqrt{n} HRI_n^2 \tag{7}$$

This shows that under the premise of the fundamental loss of the known line, the power loss due to harmonics can be quantified based on the increase of the resistance under the influence of harmonics.

b. transformer

Transformer losses include copper loss and iron loss in two parts. Among them, the copper loss refers to the current loss through the transformer winding when the power loss. Iron loss is the loss occurred in the iron core. As with the loss of the transmission line, due to the presence of harmonic currents, the transformer losses are also divided into two parts, fundamental loss and harmonic loss [18] .he relationship between harmonic additional loss and fundamental loss is also determined by the function of HRI_n. The same harmonic loss k times the fundamental loss.

The transformer copper loss is expressed as:

$$P_{Cu} = P_{Cu1}\left(1 + \sum_{n=2}^{h} n HRI_n^2\right) \tag{8}$$

Pcu_1 is the copper loss caused by the fundamental current. Thus obtained transformer copper loss additional harmonic multiples:

$$k_{cu} = \sum_{n=2}^{h} n HRI_n^2 \tag{9}$$

Transformer iron consumption expression is:

$$P_{Fe} = P_{h1}\left(1 + \sum_{n=2}^{h} n^2 HRI_n^2\right) + P_{e1}\left(1 + \sum_{n=2}^{h} n HRI_n^{1.6}\right) \tag{10}$$

Among them, P_{Fe} is the iron loss caused by the fundamental current, P_{h1} is the fundamental eddy current loss, and Pe1 is the fundamental hysteresis loss [19]. Transformer hysteresis loss Harmonic additional loss multiples:

$$k_{\mathrm{Fe}} = \alpha \sum_{n=2}^{h} n^2 HRI_n^2 + \beta \sum_{n=2}^{h} n \ HRI_n^{1.6} \tag{11}$$

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

2) Evaluation of Loss Caused by Derating of Transformer under Harmonics

Under the influence of higher harmonics, the power transformer winding loss and eddy current loss will be significantly increased, so that the temperature of the transformer increases, making the transformer cannot work with normal working capacity. This part of the transformer due to harmonic-induced capacity reduction is also an important part of the economic losses caused by harmonics [20].

For the harmonic loss of economic losses caused by the transformer capacity, the transformer derating rate of the formula:

$$F' = \frac{a}{1 + bF_k} \tag{12}$$

where $a = 1.15$ and $b = 0.15$ are empirical values.

$$F_k = \frac{F}{1 + THDi^2} \tag{13}$$

where THD_i is current harmonic distortion rate.

$$F = \sum_{n=1}^{h} \left(\frac{I_n}{I_1} \right)^2 n^2 = \sum_{n=1}^{h} HRI_n{}^2 n^2 \tag{14}$$

According to Equations (12), (13), and (14), the derating rate F' of the transformer can be obtained from the use of each harmonic current.

According to the price of the transformer parameters can be caused by the harmonic loss of transformer capacity to quantify the assessment.

B. User value-added service fitness assessment

Based on the reasonable assessment of user harmonic economic loss, it is necessary to determine a reasonable evaluation index, evaluate the power user's fitness, and judge whether the user is accustomed to the value-added service package according to the calculation result [21].

Definition of harmonic economic loss rate L:

$$L = \frac{y_{loss}}{y} \tag{15}$$

where y_{loss} is the cost of harmonic losses in the assessment period; y is the total electricity expenditure in the assessment period; and the assessment period is generally taken as 1 year.

According to the discussion of harmonic economic loss in A, y_{loss} mainly consists of three parts: the loss of electric energy of lines caused by harmonics(y_l), the loss of electric energy of transformers (y_t)and the loss of capacity of transformer(y_F), that is:

$$\begin{aligned} y_{loss} &= y_l + y_T + y_F \\ &= Q_{loss}^l \cdot \rho_0 + Q_{loss}^T \cdot \rho_0 + \frac{F' \cdot C_T}{N_T} \end{aligned} \tag{16}$$

Q_{loss}^l and Q_{loss}^T, respectively, due to the loss of electricity caused by the harmonic power, ρ_0 for the price, C_T for the transformer price, N_T for the transformer service life.

Harmonic loss cost yloss can be obtained according to equation (16), then the annual electricity consumption of the user is determined to be y, then obtain the user's harmonic economic loss rate L.

According to L, user fitness is divided into two levels: applicable ($L_m \le L \le 1$), not applicable ($0 \le L < L_m$). L_m is a constant reflecting the level of fitness evaluation.

III. HARMONIC SOLUTION SELECTION AND COST ANALYSIS

The cost of harmonic control program The main equipment investment and operation and maintenance costs in two parts.

A. Equipment investment C_{inv}

The investment in equipment is mainly related to the type and capacity of custom power equipment.

Equipment investment is an important part of the cost of harmonic management solutions and can be expressed as:

$$C_{inv} = \rho_{inv} \cdot S \tag{17}$$

Where ρ_{inv} is the unit price of custom power equipment (yuan /kvar) and S is the capacity of the equipment (kvar).

B. Operation and maintenance costs C_{mai}

This part of the cost mainly reflects the operation and maintenance costs of customized power equipment, including operating costs, maintenance costs, equipment replacement costs, maintenance costs and other personnel.

As shown above, the cost of a custom power service, C_{cus}, can be expressed as:

$$C_{cus} = \rho_{inv} \cdot S + C_{mai} \tag{18}$$

IV. POWER COMPANY HIGH-QUALITY POWER SUPPLY PACKAGE DESIGN

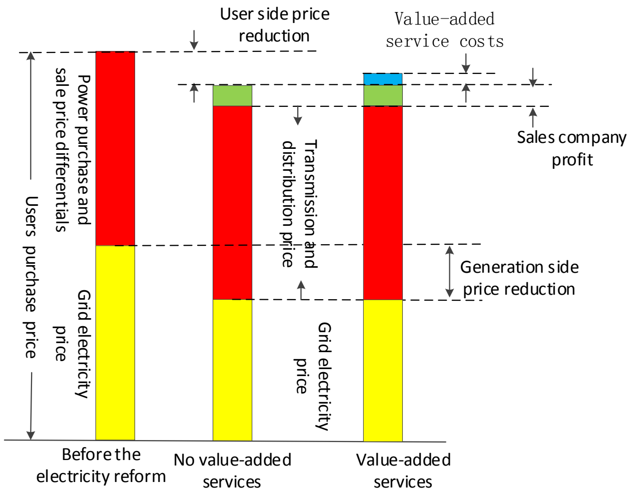

Fig.3 Analysis of electricity price before and after the sale of electricity

Based on equipment investment costs and user contract years for different value-added service packages, the electricity purchase price for each solution is calculated. First calculate the power company does not provide custom power services when the user purchase price, the power company and the user sharing power generation sharing.

Then, the cost of the different scheme harmonic control devices and the value-added service costs are allocated to the user-side electricity prices, and the electricity purchase price of each program is calculated. Figure 3 shows the profit analysis of power sales companies before and after power sales reform.

According to the above analysis results, no value-added services, electricity users purchase price can be calculated by the following formula：

$$\begin{aligned}\rho_{c0} &= \rho_{pur} + \rho_{tra} + \rho_{mk} \\ &= \rho_{pur} + \rho_{tra} + k_r \cdot \Delta\rho\end{aligned} \tag{19}$$

Among them, ρ_{c0} for no value-added services when the user purchase price (yuan/kWh), ρ_{pur} for generation-side feed-in tariffs, ρ_{tra} for transmission and distribution tariff. ρ_{mk} is the electricity price that reflects the profit of the sales company, which is converted into a ratio of the price of power generation side $\Delta\rho$ to the sales company, k_r is the proportional coefficient.

Passive control scheme user price can be calculated by the following formula:

$$\begin{aligned}\rho_c^p &= \rho_{c0} + \rho_{cus}^p \\ &= \rho_{c0} + \frac{\alpha \cdot \rho_{inv}^p \cdot S + C_{mai}^p \cdot N}{N \cdot Q}\end{aligned} \tag{20}$$

ρ_{pus}^p is the price increase of passive governance (yuan/kWh), α is the recovery ratio of equipment investment cost of the sales company during the contract period (%), N is the contract life (year), Q is the annual trading volume, ρ_{inv}^p is passive power filter unit price (yuan/kvar), S is device capacity (kvar), C_{mai}^p is passive filter annual operation and maintenance costs. Active treatment package price is calculated as follows:

$$\begin{aligned}\rho_c^a &= \rho_{c0} + \rho_{cus}^a \\ &= \rho_{c0} + \frac{\alpha \cdot \rho_{inv}^a \cdot S + C_{mai}^a \cdot N}{N \cdot Q}\end{aligned} \tag{21}$$

ρ_{pus}^a to reflect the active control of the price increase (yuan/kWh), ρ_{inv}^a active power filter unit price (yuan / kvar), C_{mai}^a for the active filter annual operation and maintenance costs.

V. CASE STUDY

Taking a metallurgical enterprise as an example, it is a typical six-pulse rectified harmonic source power user with an average annual electricity consumption of 20 million kWh and two distribution transformers with a single capacity of 2500 kVA and a rated voltage of 10 / 0.4 kV.

The typical data of each transformer with variable load is apparent power 2007kVA, active power 1570kW, reactive power 1250kvar, power factor 0.782, voltage total harmonic distortion rate is 33.81%.

Harmonic content is mainly typical characteristic harmonic source, of which 610A is 5 times, 435A is 7 times, 278A is 11 times, 234A is 13 times.

A. Analysis of Applicability of Customer Value Added Service

1) Estimation of Harmonic Additional Loss in Transformer and Transmission Line

According to the discussion of the additional harmonic losses, calculate the harmonic additional loss multiples as:

$$k_l = 0.5647,\quad k_{Cu} = 0.2125,\quad k_{Fe} = 4.4217$$

Through the history of the metallurgical plant data survey and related equipment to understand the parameters of the two sets of transformer fundamental iron loss of 4.36kW, copper loss of 40.24kW fundamental.

The metallurgical plant transformer operates for an average of 6,500 hours a year, and the basic power loss of the metallurgical plant line is calculated at 5%.According to the local catalog price of 0.75 yuan, the user's annual economic loss due to harmonics caused by harmonics is 557,900 yuan.

2) Losses due to derating of power transformers due to harmonics

According to the discussed formula for transformer derating under harmonics, according to the pre-harmonized harmonic data given by the harmonics, $F' = 0.6501$ is obtained..

The model of the transformer chosen in this article is SF9-2500/10/0.4. The transformer life is calculated according to 25 years. Combined with the transformer cost and maintenance cost, the user will pay about 0.36 million yuan more for harmonics each year.

3) Harmonic Economic Loss Level L Evaluation

L_m takes the empirical value of 0.02 here. The user needs extra expenses of 561,500 yuan due to power harmonic problems. Combined with the user's annual electricity consumption and other information, it can be concluded that the user's annual electricity expenditure is about 15 million yuan. So the harmonic economic loss level L is:

$$L = 56.15 / 1500 = 0.374$$

L> 0.02, so the user is suitable for value-added service packages, it is necessary to launch high-quality power supply packages for the user.

B. Harmonic control scheme simulation analysis

1) Passive scheme

In the example shown in the rectifier type harmonic source of power users typically, using passive filtering scheme, by adding 5th, 7th, 11th, 13th filters, and improve the power factor to 0.95 as the fundamental design of reactive power compensation, available fundamental compensation capacity is 735 kvar, considering the harmonic capacity and a certain margin, the total capacity of device design for 1800kVar.

Based on the above design parameters, the simulation model is built in PSCAD, and the simulation results are shown in Figure 4-Figure 6. Figure 4 is the supply voltage and load current after the compensation. It can be seen that there is a great harmonic content in the load current, Figure 5 comparing the waveform of the supply current with the load current, the supply current has been greatly improved after the filter, Figure 6 is the histogram of the current FFT analysis before and after the filtering. It can be seen that the 5th, 7th, 11th and 13th harmonic contents are obviously reduced.

Simulation analysis shows that the passive power filter can effectively filter out typical harmonics, so that the harmonic content of the power supply side decreases greatly. The THD of voltage is 2.4%, and the harmonic content is mainly typical characteristic harmonic, among which 5th harmonic current is 35A, the 7th harmonic current is 16A, the 11th harmonic current is 8A, the 13th harmonic current is 7A, and the power factor is 0.939.

2) Active Scheme

The output current of the active power filter is 2200 A, considering the margin, the device capacity is 1750 kvar, the results of the simulation verification in PSCAD are shown in Figure 7 - Figure 9 the electrical meanings of each map are consistent with the passive filtering scheme.

Through the waveform, the APF can effectively filter out typical harmonics, so that the harmonic content of the power supply side decreases greatly, and the power factor can also be greatly improved.

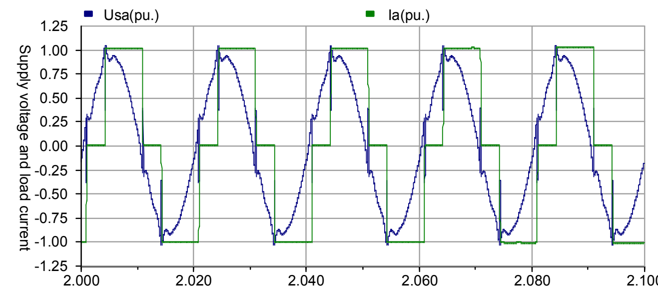

Fig.4 Supply voltage and load current

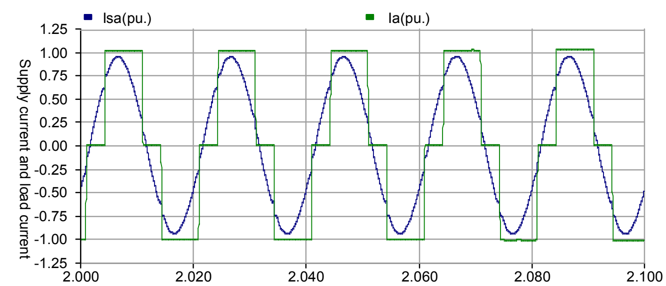

Fig.5 Supply current and load current

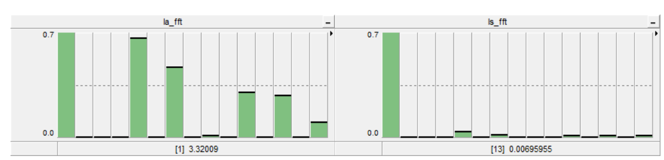

Fig.6 The harmonic content of the load current and the supply current

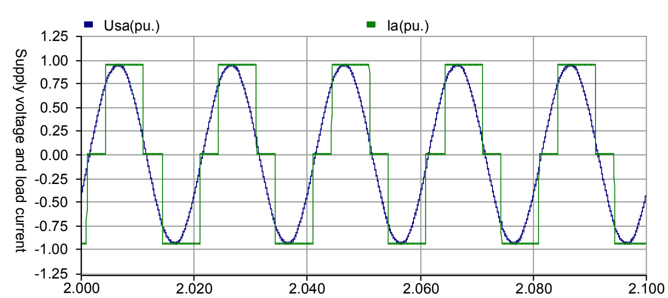

Fig.7. Supply voltage and load current

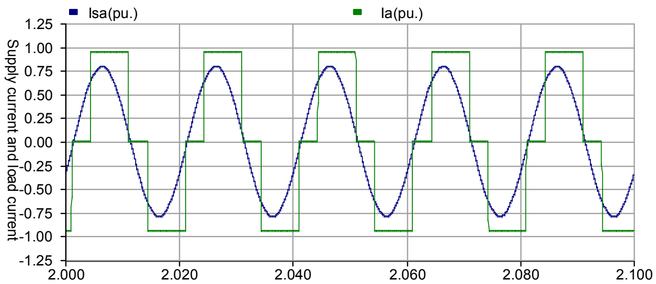

Fig.8. Supply current and load current

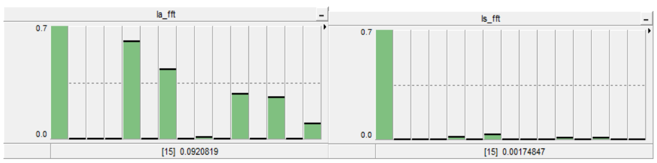

Fig.9. The harmonic content of the load current and the supply current

The *THD* of voltage is 2.2%, and the harmonic content is mainly typical characteristic harmonic, among which 5th harmonic current is 16A, the 7th harmonic current is 25A, the 11th harmonic current is 4A, the 13th harmonic current is 6A, and the power factor is 0.998.

3) User-quality power supply value-added service package design

At present, the passive filter is about 300 yuan /kvar, and the active filter is about 1000 yuan /kvar. Passive filter and active filter prices were 1.08 million yuan and 3.52 million yuan respectively.

The passive power filter annual operation and maintenance costs are considered in terms of 3% of the total cost of the equipment, and the active power filter is considered as 1% of the total cost of the equipment. K_r take 50%, α take 70%. Analyzing the relationship between the user's purchase price and the contractual year when the user's contract with the power sales company is different, which is shown in Figure 10.

Through the above analysis, it is found that the rate of decline in the purchase price of electricity for users after five years of contract has been slow. Taking into account the needs of users and power sales companies, taking the five-year contract period as an example, high quality power supply packages are calculated as follows in Table I.

TABLE I
THE QUALITY SERVICE PACKAGE OF THE ELECTRIC COMPANY

Electricity price package	No value-added services (A)	Passive scheme (B)	Active Scheme (C)
Electricity price(yuan/kWh)	0.6775	0.6883	0.6915

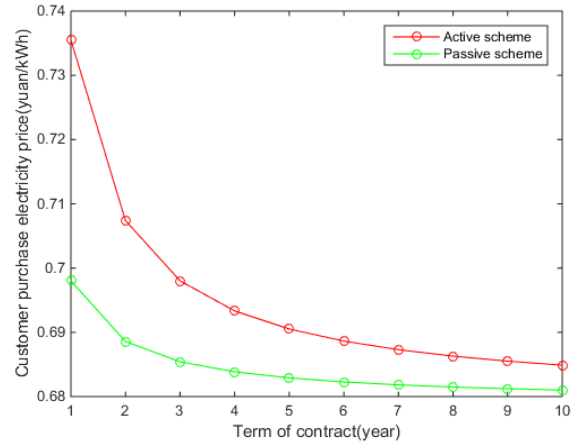

Fig.10 The relation curve between the purchase price of the user and the length of the contract

4) Comparison of Annual Electricity Charges Before and After Using Premium Power Packages

Combining with the PSCAD simulation results, the actual electricity consumption of the users before and after the use of the high-quality electricity supply package is calculated and compared, and the results in Fig12 are obtained.

The user's annual electricity payment comparison is shown in Figure 12.

From Fig.12, it can be seen that, compared with the power purchase scheme without value-added services, the passive scheme and the active scheme both make the user's annual payment of electricity significantly reduced.

For power sales companies, the introduction of power supply packages reduces the company's electricity bill revenue, but it can attract and retain large power users and sign long-term stable power supply contracts with them. This is a great advantage in the increasingly fiercely competitive environment of the power-supply side. In addition, through the introduction of high-quality power supply packages, the user's harmonic power loss is reduced, which is in line with the national concept of energy saving and consumption reduction.

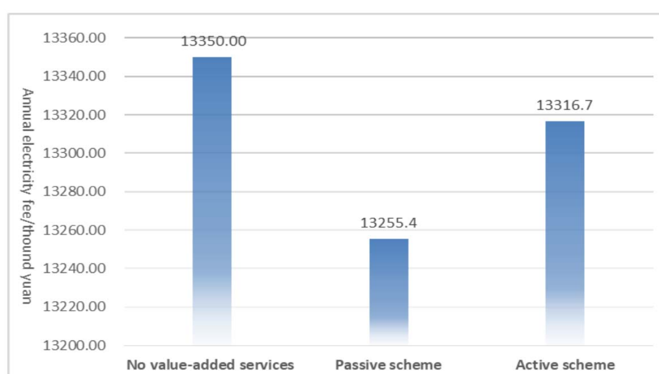

Fig.12. All kinds of packages pay the electricity bill

VI. CONCLUSION

In view of the issue of upgrading the competitiveness of power sales companies under the new power transformation situation, and taking into account the power quality control needs of users, this paper aims to provide users with differentiated high-quality power supply value-added services. Based on the analysis and evaluation of the economic losses caused by users' harmonics, a differentiated power supply service plan is proposed, and the control effect and cost of the solution are analyzed to provide users with different power sale plans.

ACKNOWLEDGMENT

This work was supported by the National Key R&D Program of China (2018YFB0904200), the National Natural Science Foundation of China (51577067), the Beijing Natural Science Foundation of China (3162033), the Hebei Natural Science Foundation of China (E2015502060), the State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources (LAPS18008), the Headquarters Science and Technology Project of State Grid Corporation of China (SGCC)(NY7116021), the Open Fund of State Key Laboratory of Operation and Control of Renewable Energy & Storage Systems (China Electric Power Research Institute) (5242001600FB), the Fundamental Research Funds for the Central Universities (2018QN077). J.P.S. Catalão acknowledges the support by FEDER funds through COMPETE 2020 and by Portuguese funds through FCT, under Projects SAICT-PAC/0004/2015 - POCI-01-0145-FEDER-016434, POCI-01-0145-FEDER-006961, UID/EEA/50014/2013, UID/CEC/50021/2013, UID/EMS/00151/2013, and 02/SAICT/2017 - POCI-01-0145-FEDER-029803, and also funding from the EU 7th Framework Programme FP7/2007-2013 under GA no. 309048.

REFERENCES

[1] X Kong, P Li, Z Yan, et al. "Stress testing on electricity market with retail transactions opened", Power System Technology, vol. 40 No.11 pp. 3279-3286, 2016,

[2] Y Meng, X Ai, L Tang, et al. "Optimal Trading Strategy in Balancing Market for Electricity Retailer Considering Risk Aversion", Power System Technology, vol.40 No.11 pp. 3300-3308, 2016.

[3] F. Wang, Z. Zhen, Z. Mi, H. Sun, S. Su, and G. Yang, "Solar irradiance feature extraction and support vector machines based weather status pattern recognition model for short-term photovoltaic power forecasting," Energy Build., vol. 86, pp. 427–438, 2015.

[4] F. Wang, Z. Mi, S. Su, and H. Zhao, "Short-term solar irradiance forecasting model based on artificial neural network using statistical feature parameters," Energies, vol. 5, no. 5, pp. 1355–1370, 2012.

[5] Y. Sun, F. Wang, B. Wang, Q. Chen, N. A. Engerer, and Z. Mi, "Correlation Feature Selection and Mutual Information Theory Based Quantitative Research on Meteorological Impact Factors of Module Temperature for Solar Photovoltaic Systems," Energies, vol. 10, no. 1, p. 7, Dec. 2016.

[6] F. Wang, Z. Zhen, C. Liu, Z. Mi, B. Hodge, M. Shafie-khah, and J. P. S. Catalão, "Image phase shift invariance based cloud motion displacement vector calculation method for ultra-short-term solar PV power forecasting," Energy Convers. Manag., vol. 157, pp. 123-135, Jan. 2018, DOI:10.1016/j.enconman.2017.11.080

[7] Q. Chen et al., "Dynamic Price Vector Formation Model Based Automatic Demand Response Strategy for PV-assisted EV Charging Station," IEEE Trans. Smart Grid, pp. 1–1, 2017.

[8] F. Wang, L. Zhou, H. Ren, X. Liu, S. Talari, M. Shafie-khah, and J. P. S. Catalão, "Multi-Objective Optimization Model of Source-Load-Storage Synergetic Dispatch for a Building Energy Management System Based on TOU Price Demand Response," IEEE Trans. Industry Applications, 2018, 54(2):1017-1028. doi: 10.1109/TIA.2017.2781639

[9] F. Wang, K. Li, C. Liu, Z. Mi, M. Shafie-Khah and J.P.S Catalão, "Synchronous Pattern Matching Principle Based Residential Demand Response Baseline Estimation: Mechanism Analysis and Approach Description," *IEEE Trans. Smart Grid*, April 2018, Early Access. doi: 10.1109/TSG.2018.2824842.

[10] F. Wang, K. Li, N. Duic, Z. Mi, B.M. Hodge, M. Shafie-Khah and J.P.S Catalão, "Association Rule Mining Based Quantitative Analysis Approach of Household Characteristics Impacts on Residential Electricity Consumption Patterns," Energy Convers. Manag., 2018, vol. 171, pp. 839-854. doi.org/10.1016/j.enconman.2018.06.017

[11] XY Xiao, YQ Ma, WX Mo, et al. "Premium power based value-added service model for power supply company under the opening electricity retail side", Journal of Electric Power Science and Technology, vol.31 No.4 pp. 4-10, 2016.

[12] C Hu, SH Du, J Su, et al. "Preliminary research of trading approach and management modes of Chinese electricity retail companies under new electricity market reform" , PowerSystem Technology, vol.40 No.11 pp. 3293-3299, 2016.

[13] ZA Wang, JJ Liu. "Harmonic suppression and reactive power compensation (third edition)", Beijing: China Machine Press, 2016.

[14] ZL Xiao, RX Gong, S Chen, et al. "Detection of harmonics in power system based on modified S-transform", Dianli Xitong Baohu Yu Kongzhi/power System Protection & Control, 43(3):84-90, 2015.

[15] D Klemen "Predictive Direct Control Applied to AC Drives and Active Power Filter", IEEE Transactions on Industrial Electronics vol.56 No.6 pp. 1884-1893, 2009.

[16] R Gavagsaz-Ghoachani, M Phattanasak, JP Martin, et al. "A Lyapunov function for Switching command of dc-dc power converter with an LC input filter", IEEE Transactions on Industry Applications, PP. 99, 2017

[17] JL Zhang. "A Practical Computing Method of Harmonic Loss", Electric Switchgear, vol.49 No.4 pp. 45-47, 2011.

[18] SM Liu, H Shi, L Feng. "Transformer harmonic loss model considering skin effect and proximity effect", Electric Power Automation Equipment, vol.35 No.3 pp. 133-139, 2015.

[19] SY Ge, JL Dong, FC Liu, et al. "Empirical Method of Harmonic Control Loss Reduction Effect in Distribution Network", Proceedings of the CSU-EPSA, vol.27 No.03 pp. 1-4, 2015.

[20] LH Zhao, ZS Feng, YC Zhang, et al. "Study on dry-type transformer derating based on harmonic losses", Electrical Measurement & Instrumentation, vol.54 No.06 pp. 93-99, 2017.

[21] S Tao, XN Xiao. "Infrastructure of the power quality assessment system of power systems", Diangong Jishu Xuebao(Transactions of China Electrotechnical Society), vol.25 No.4 pp. 171-175, 2010.