Research on Energy Performance Contracting mode of demand-side reactive power compensation

Shen Xiao[1, a], Zhicheng Sun[1, b], Yao Rao[1, c], Jianyong Cui[2, *], Ran Zhang[3, d], Wei Guo[4, e], Zheng Liu[1, f]

[1]State Grid Electric Power Research Institute (Nari Group Corporation) State Grid Electric Power Research Institute Wuhan Energy Efficiency Evaluation Company Wuhan, China

[2]Wuhan University Wuhan, China

[3]State Grid Hebei Electric Power Co., Ltd Shijiazhuang, China

[4]State Grid Hebei Marketing Service Center Shijiazhuang, China

* Corresponding Author Email: 929679076@qq.com, [a]seuxsd@163.com, [b]11702816342qq.com, [c]573265092@qq.com, [d]zhangr@he.sgcc.com.cn, [e]guoweidianli@163.com, [f]378010740@qq.com

Abstract. Demand-side reactive power compensation achieves the purpose of saving energy and protecting the environment by improving the efficiency of electricity consumption and optimizing the way of electricity consumption, reducing electricity consumption and power demand while completing the same power consumption function. However, some users are facing the problems of insufficient funds and immature technical means, and cannot independently carry out demand-side reactive compensation. This paper proposes the demand-side reactive power compensation Energy Performance Contracting model, describes in detail the participants and operation modes in this mode, and uses Shapley value theory to distribute the benefits between the energy-saving service company and the user, and obtains the preliminary revenue distribution scheme. Three factors, namely the proportion of input, risk sharing and negotiating position, were adopted to revise it, and revised again in combination with the degree of implementation contribution to make the distribution of benefits more scientific and reasonable.

Keywords: Reactive compensation, Energy Performance Contracting, shapley.

1. Introduction

With the development of China's economy in the direction of green and low-carbon, in addition to meeting people's daily life production needs, higher requirements are also put forward for energy conservation and efficiency of the power system [1-3]. The distribution network line loss accounts for a large proportion of the active loss of the power system, and reasonable demand-side reactive power compensation is of great significance for reducing the distribution network line loss, ensuring the user's power experience, and improving the reliability of the distribution network power supply [4-8]. Demand-side reactive power compensation is to achieve the power management activities carried out by low-cost power services by improving power efficiency and optimizing power consumption methods, reducing power consumption consumption and power demand while completing the same power consumption function, and achieving the purpose of saving energy and protecting the environment[9]. For users with large power consumption, the power grid company proposes an electricity fee assessment system on power factor, and when the user's power factor is too low, they will receive penalties on electricity fees; When the user's power factor is too high, they will be rewarded on the electricity bill. Therefore, users can increase the power factor by investing in reactive power compensation devices, so as to obtain benefits from electricity costs, However, some users are facing the problems of insufficient funds and immature technical means, and cannot independently carry out demand-side reactive compensation. Energy Performance Contracting is a mechanism in which energy-saving service companies and energy-using units sign energy-saving transformation contracts, provide energy-saving transformation services to energy-using units, and recover the initial investment and profits from the energy-saving benefits after energy-saving transformation[10]. This model effectively improves the enthusiasm of energy-using units lacking funds and professional technology to participate in energy-saving transformation projects, so it is widely used in energy-saving transformation projects. However, under this model, the income distribution ratio agreed in the contract directly affects the interests of both parties, so establishing a reasonable income distribution method is crucial to the smooth development of the project

This paper proposes the demand-side reactive power compensation Energy Performance Contracting model, describes in detail the participants and operation modes in this mode, and uses Shapley value theory to distribute the benefits between the energy-saving service company and the user, and obtains the preliminary revenue distribution scheme. Three factors, namely the proportion of input, risk sharing and negotiating position, were adopted to revise it, and revised again in combination with the degree of implementation contribution to make the distribution of benefits more scientific and reasonable.

2. Demand-side reactive power compensation Energy Performance Contracting mode

In the scenario of demand-side reactive power compensation, the stakeholders of the energy performance contracting model include energy-saving, users, service companies, and power companies, and the relationship between energy-saving, users, service companies, and power companies is shown in Fig. 1.

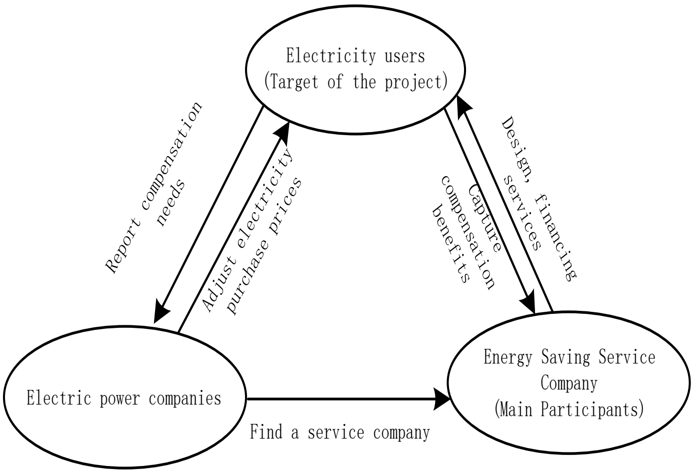

Fig. 1 A three-way relationship in the Energy Performance Contracting model

Power companies: According to the electricity consumption policy and the power factor of the user, the electricity purchase price of the user is adjusted, but it is an important driving force to promote the demand-side reactive power compensation of the user.

Energy-saving service company: with technical credibility, the main work includes formulating reactive power compensation plans for users, technical support, realizing the docking between equipment manufacturers and users, and promoting high-quality power investment by users.

Users: If there is a demand for reactive power compensation but insufficient economic strength, the Energy Performance Contracting model transfers the initial investment pressure to the energy-saving service company, avoiding the problem of large investment and high risk in the traditional user-borne model. The user does not need to bear the life-cycle operation and maintenance costs of the reactive power compensation equipment, and the energy saving service company is responsible for the operation and maintenance of the equipment during the contract period, which reduces the burden on the user.

The specific implementation path of the Energy Performance Contracting model is shown in Figure 2.

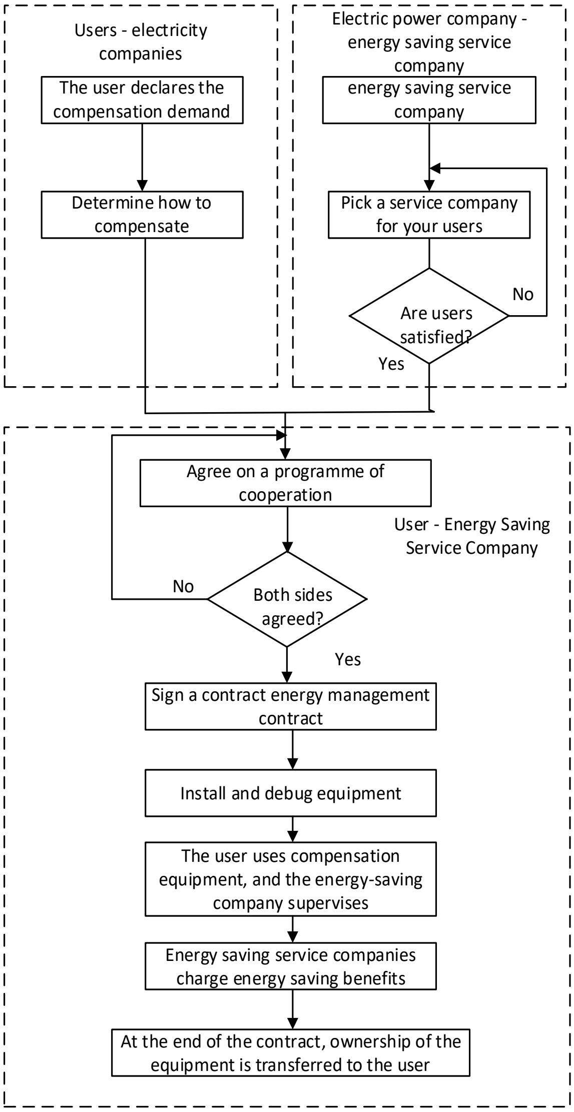

Fig. 2 The specific implementation path of the Energy Performance Contracting model

1) The user reports the compensation demand to the power company, and the power company actively seeks the appropriate energy-saving service company to negotiate the service plan with the user.

2) The energy conservation service company signed the Energy Performance Contracting Contract with the energy-consuming customers to determine the energy saving and benefit distribution scheme that can be achieved.

3) The energy-saving service company signs the Equipment Purchase Contract with the equipment supplier to obtain the ownership of the equipment and provide equipment for the project.

4) Energy-using customers use equipment, energy-saving service companies supervise projects, share energy-saving benefits and gain their own profits in the process.

6) At the end of the project cycle, the ESCO will transfer the ownership to the customer.

3. Benefit distribution method of Energy Performance Contracting mode

During the contract period, the ownership of the compensation equipment belongs to the energy saving service company; The energy-saving service company will operate and maintain the equipment, and extracts part of the reduced electricity expenses after reactive power compensation as income. After the installation of the compensation equipment, the annual income B from reducing the electricity bill can be calculated as follows.

$$B=\sum_{i=1}^{12}(k_{\theta i}-k_{\phi i})\cdot\varepsilon\cdot P_i-C_s \tag{1}$$

The above formula ε is the electricity price of users; C_s is the maintenance cost per year; P_i is the reactive energy used by the user in the ith month $k_{\theta i}$ 、 $k_{\phi i}$ respectively refer to the corresponding adjustment proportion of electricity charge before and after compensation in the ith month.

After the end of the contract period, the energy conservation service company will hand over the equipment to the user, and the user will operate and maintain the equipment by himself to obtain income. During the whole life cycle of reactive power compensation equipment, the interests of all parties are calculated as follows:

$$\begin{gathered}
B_e=\sum_{i=1}^{T_c}\frac{B\cdot\beta-C_s}{(1+r)^i}-C_e\\
B_u=\sum_{i=1}^{T_c}\frac{(1-\beta)\cdot B}{(1+r)^i}+\sum_{i=T_c+1}^{T}\frac{B-C_s}{(1+r)^i}-C_u\\
NPV=\sum_{i=1}^{\mathrm{T}}\frac{B\text{-}C_s}{(1+r)^i}-C_u-C_e
\end{gathered} \tag{2}$$

In the above formula, B_e and B_u are the net present value of the user's income in the whole life cycle of the equipment of the energy-saving service company; NPV is the total net present value of the income of the project in the whole life cycle of the equipment, meeting $NPV=B_e+B_u$; B refers to the electricity expense reduced by the user due to reactive compensation every year; C_s is the maintenance cost per year; C_e and C_u are the initial investment of energy conservation service companies and users respectively; T is the service life of the equipment; T_c is the duration of the contract; It refers to the proportion of energy-saving service companies in saving electricity; R is the discount rate, taken as 0.05. It can be seen from the above formula that different values of T_c and T_c will affect the distribution of benefits between energy-saving service companies and users.

According to the theory of Shapley value method, each participant in energy-saving transformation will make a certain contribution to the project during the implementation of energy-saving transformation project, that is, marginal contribution, and its allocation quota is the average of its marginal contribution.

(1) Shapley value of energy-saving service company. The formula is as follows:

$$\begin{aligned}
Y_E(V)&=W(|S|)[V(S)-V(S\setminus E)]\\
&=\frac{V(E)}{2}+\frac{[V(E,U)-V(U)]}{2}
\end{aligned} \tag{3}$$

(2) Shapley value of the user. The formula is as follows:

$$\begin{aligned}
Y_u(V)&=W(|S|)[V(S)-V(S\setminus U)]\\
&=\frac{V(E)}{2}+\frac{[V(E,U)-V(U)]}{2}
\end{aligned} \tag{4}$$

In the above formula, $W(|S|)$ is the weighting factor, taking 0.5; $V(E)$ is the benefit when only energy-saving service companies participate in the implementation of the project, but no users are used as the carrier of transformation, so 此$V(E)=0$; $V(U)$ refers to the user's income when the energy user independently carries out the transformation work; $V(E, U)$ refers to the total income of users and energy-saving service companies when they participate together.

The Shapley value method is used to distribute the energy saving benefits. Taking into account the marginal contribution of energy conservation service companies and users in the alliance, the benefits of each participant can be obtained through the characteristic function, which has certain guiding significance for the implementation of actual projects. However, this method does not take into account the impact of the investment proportion, risk sharing and negotiation status of the project on the income distribution, which is a problem that all participants attach great importance to. Therefore, the above results will be revised according to these factors.

Negotiation status. Due to the different price sensitivities of the participants in the project, they usually get the income distribution proportion in line with their psychological expectations based on the project characteristics and previous experience. In the process of negotiation between the two parties, if there is only a slight difference between the two parties in the expected distribution ratio, the project can continue to advance under the distribution ratio. If the psychological expectation is not met, that is, there is a large difference between the two parties in the expected distribution ratio, the project implementation may not proceed smoothly. Generally, the project participants choose to use the Delphi method to propose the most ideal income distribution ratio for each party. Through psychological game, both parties make concessions continuously under the condition of meeting their psychological expectations, until the difference between the two is reduced to an acceptable range. In this paper, the revision coefficients v_{11} and v_{21} of energy-saving service companies and users in terms of negotiation status are 0.61 and 0.39 respectively.

Risk sharing. Due to the large time span of the whole life cycle of the energy-saving project, the fluctuation of the price of energy, equipment and materials and the progress of energy-saving transformation technology will affect the project cost and the final energy-saving effect, thus bringing the risk of economic loss to the energy-saving service companies and users; From the perspective of final energy saving benefits, the project participants share the risk of energy saving benefits. From the perspective of project design, early diagnosis, evaluation of energy saving amount and design of energy saving plan will directly affect the implementation of energy saving projects, thus affecting energy saving benefits. On this basis, the analytic hierarchy process and fuzzy comprehensive evaluation method are comprehensively used to obtain the respective risk correction coefficients, and the income distribution quota is revised. The risk correction coefficients of energy-saving service companies and users are v_{12} and v_{22} respectively.

$$\begin{cases} v_{13} = \dfrac{C_e + \mathrm{T_c} \cdot C_s}{C_u + C_e + \mathrm{T} \cdot C_s} \\ v_{23} = \dfrac{C_u + (\mathrm{T} - \mathrm{T_c}) \cdot C_s}{C_u + C_e + \mathrm{T} \cdot C_s} \end{cases} \tag{5}$$

Where, v_{13} is the correction coefficient of the proportion of energy saving service companies; v_{23} is the correction coefficient of the proportion of user input; C_s is the maintenance cost per year; C_e and C_u are the initial investment of energy conservation service companies and users respectively; T is the service life of the equipment; T_c is the duration of the contract.

$J=\{j\}$, $j=1,2,3$ are defined as the revised set of the above influencing factors, where 1 represents the negotiation status, 2 represents the risk sharing, and 3 represents the investment proportion. Assume that the correction coefficient of the ith participant for the jth element is v_{ij}, so as to establish the correction analysis matrix as shown in Table I.

Table 1. Correction analysis matrix

	Negotiation status	Risk bearing	Proportion of investment
Energy-saving service company	v_{11}	v_{12}	v_{13}
user	v_{21}	v_{22}	v_{23}

The correction matrix of the factors affecting the income distribution of the project is:

$$V = \begin{bmatrix} v_{11} & v_{12} & v_{13} \\ v_{21} & v_{22} & v_{23} \end{bmatrix} \tag{6}$$

Let w_n be the weight of the nth (n=1,2,3) factor, and. $w_1+w_2+w_3=1$ Combined with the preliminary income distribution and the correction coefficient, the income distribution of energy-saving service companies and users can be obtained as follows:

Investment proportion. Generally, the more participants invest in the project, the greater the expected reward. The energy conservation service companies and users can be measured by the total investment. The input proportion correction coefficient is the proportion of each participant's input to the total input, and the specific formula is as follows:

$$\begin{aligned} B_e &= Y_E(V)+(\sum_{i=1}^{3} w_i\cdot v_{1i}-0.5)\cdot NPV \\ B_u &= Y_u(V)+(\sum_{i=1}^{3} w_i\cdot v_{1i}-0.5)\cdot NPV \end{aligned} \tag{7}$$

During the term of the contract, the proportion of energy conservation service companies to take from the reduction of electricity charges β can be calculated as follows:

$$\beta=\frac{B_e+C_e+\sum_{i=1}^{T_C}\frac{C_s}{(1+r)^i}}{\sum_{i=1}^{T_C}\frac{B+C_s}{(1+r)^i}} \tag{8}$$

4. Example analysis

The average monthly active power consumption of a cement plant is 792870kwh, and the average monthly inactive power consumption is 505218kwh; The comprehensive electricity charge is 0.493 yuan/kwh, and the power factor is 0.84. It is now considered to increase the power factor to 0.95 through reactive compensation. After calculation, the reactive power compensation capacity to be installed by the user is 350kvar, the market unit price of static var generator is 700 yuan/kvar, the annual maintenance cost is 5000 yuan, and the initial investment of the user is 100000 yuan. According to the estimated six-year contract period, the power grid company will apply to the power grid company to provide services for the user.

The reactive power equivalent is 0.06kwh/kvar [11] calculated according to the adjustment proportion of industrial users' electricity charges. If the compensation is only funded by the users themselves, the power factor can only be compensated to 0.88, and the annual reduction of electricity charges is 93800 yuan, and the annual reduction of network loss is 25600 yuan; After the Energy Performance Contracting mode is adopted, the power factor can be compensated to 0.95, and the annual electricity payment can be directly reduced by 87400 yuan. According to the calculation, when the user compensates himself, the net present value of the income within the life cycle of the equipment is $V(U)$=615800 yuan. When the energy performance contracting mode is adopted, the total net present value of the project is $V(E, U)$=1074600 yuan, and the income for sharing is 458800 yuan.

The revision coefficient of negotiation status is v_{11}=0.61 and v_{21}=0.39. Using the analytic hierarchy process and fuzzy comprehensive evaluation method, the risk correction coefficients v_{12}=0.658 and v_{22}=0.342 were obtained. The investment ratio v_{13} and v_{23} are calculated as follows:

$$\begin{cases} v_{13}=\dfrac{C_e+T_c\cdot C_s}{C+T\cdot C_s} \\ v_{23}=\dfrac{C_u+(T-T_c)\cdot C_s}{C+T\cdot C_s} \end{cases} \tag{9}$$

Get v_{13}=0.593, v_{23}=0.407. In addition, the weight of the three factors of negotiation status, risk bearing and investment proportion in the allocation is taken as w_1=0.146、w_2=0.288、w_3=0.566 respectively.

According to the above data and the modified model shown in equations (7) and (8), it is found that during the six-year contract period of the project, the net present value of the total income of the energy-saving service company is 352300 yuan, and the net present value of the total income of the user is 722300 yuan, and the energy-saving service company takes 58.54% of the electricity saved by the user as the income every year.

As shown in Table 2, the demand-side reactive power compensation Energy Performance Contracting model proposed in this paper is compared with the traditional user direct purchase model in various aspects. It can be seen that under the mode of joint investment between users and energy-saving service companies, the investment scale of users has been effectively expanded, and users can obtain higher income than their own investment in the life cycle of the equipment. At the same time, energy-saving service companies can recover costs and create profits within the contract period. The increase of reactive power compensation capacity can also lead to the reduction of network loss on the incoming network side, which ensures the interests of the three parties.

The adjustment proportion of industrial users' electric charge is shown in Table 2, and the reactive equivalent is 0.15 kw/kvar [15]. According to the analysis in Table 2, after adopting reactive power compensation, the electric charge will be directly reduced by 1.3144 million RMB per year, and the network loss will be reduced by 1.4695 million RMB per year.

Table 2. Comparative analysis of different service modes

business model	Compensation capacity (kvar)	Net present value of total income during equipment operation	Net user income during equipment operation	Sampling proportion of energy-saving companies during the contract period	Energy-saving company Total income	Reduce network loss
Direct purchase	100	615800	615800	0	0	25600 per year
Energy Performance Contracting	350	1074600	722300	58.54%	352300	87400 per year

5. Conclusion

This paper proposes an energy performance contracting mode for reactive power compensation on demand side. Power grid companies and energy conservation service companies jointly serve customers. The Shapley value theory is used to distribute the income between the energy-saving service company and the user, and the preliminary income distribution scheme is obtained. The three factors of input proportion, risk sharing and negotiation status are adopted to revise it, and the implementation contribution is combined to revise it again to make the income distribution more scientific and reasonable. Finally, an example is given to prove that the method in this paper can achieve the balance of interests of multiple parties. In other words, with the compensation capacity is increased, the revenue is increased, and the interests of users are greater. The method in this paper has certain theoretical value and practical significance for the further promotion of demand side reactive power compensation.

Acknowledgments

This work was supported by the State Grid Corporation of China Headquarters Science and Technology Project (Project Name: Key technology research and demonstration application of demand-side reactive power service market supporting new power system; Project Number: 1400-202213424A-2-0-ZN).

Reference

[1] Li Xiaopeng, Cheng Xiaolei, Cai Wenbin, Wang Peng, Lv Haixia. Comprehensive evaluation method of power grid energy conservation and emission reduction and operation efficiency under the carbon neutral target [J]. Electrical technology, 2022,(02): 15-17.

[2] Li Chaorui, Zhang Aimin, Deng Yixing, Wen Yuelong. Multi objective layered energy conservation planning method for smart grid under dual carbon constraints[J]. Energy and environmental protection, 2022, 44(03): 188-193.

[3] Li Min, Jiang Xiaotao, Ma Shuguang, Hu Qianqian, Meng Qinglin, Sun Yue. Research on online monitoring system of power grid energy conservation and environmental protection dispatching based on the Internet of Things[J]. Energy and environmental protection, 2021, 43(10): 170-176.

[4] Q. Tao, L. Zhu, X. Zhao, Z. Ni, J. Li and Z. Huang, "A Method for Optimizing Reactive Power Compensation Configuration Scheme Based on New Energy Low Voltage Ride Through Safety Assessment," 2021 IEEE 5th Conference on Energy Internet and Energy System Integration (EI2), 2021, pp. 1364-1367.

[5] W. Li, W. Wei and Z. J. Yong, "Design of Reactive Power Compensation for Low Voltage Distribution Network Based on Intelligent Control Switch," 2021 IEEE 6th International Conference on Cloud Computing and Big Data Analytics (ICCCBDA), 2021, pp. 591-595.

[6] V. Jurák, Z. Bukvišová, M. Ptáček, D. Topolánek and J. Orságová, "Compensation of reactive power in LV network and its impact on reactive power flow through distribution grid," 2020 21st International Scientific Conference on Electric Power Engineering (EPE), 2020, pp. 1-5.

[7] J. Seo and H. Cha, "A New Reactive Power Compensation method for Voltage regulation of Low Voltage Distribution Line," 2021 IEEE Applied Power Electronics Conference and Exposition (APEC), 2021, pp. 2681-2685.

[8] A. Dhaneria, "Grid Connected PV System with Reactive Power Compensation for the Grid," 2020 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), 2020, pp. 1-5.

[9] Liu Chang, Yao Jianggang, Yao Wenfeng, et al. Determination and analysis of time-of-use electricity price based on DSM [J]. Relays, 2005, 33(15): 57-61.

[10] GBT24915-2010. General Principles of Contract Energy Management Technology [S]. 2010.

[11] Pan Youquan, Yang Shengli. Economic Benefit Analysis of Reactive Power Compensation in Distribution Network [J]. Electronic Components and Information Technology, 2020, 4(01): 105-10.