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Cost Analysis of Synchronous Condenser Transformed from Thermal Unit Based on LCC Theory

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Abstract: With the development of large-scale renewable energy consumption and multi-infeed high voltage direct current (HVDC) systems, the demand of a system for the synchronous condensers with a strong dynamic reactive power support capacity and a strong short-time overload capacity is increasing. Meanwhile, with the reuse of a large number of retired thermal units, the most practical and economic way is to transform thermal units into synchronous condensers. The cost difference in the life-cycle of the synchronous condenser transformed from a thermal unit (SCTTU) and the newly established synchronous condenser (NESC) is a key factor that affects the decision-making and construction of the transformation from thermal unit to synchronous condenser. However, the life-cycle cost (LCC) of the synchronous condenser transformed from a thermal unit and the newly established synchronous condenser contains many uncertain factors, which affect the accuracy of the LCC estimation value. In order to quantify the impact of the blind information on the cost of the synchronous condenser station, blind number theory is introduced to establish the blind number model of the LCC of the synchronous condenser transformed from a thermal unit and the newly established synchronous condenser. Additionally, the LCC of the NESC and SCTTU with a different life-cycle under the capacity of 2 $\times$ 300 MVar are estimated. The results show that the cost of the SCTTU with a long service life of more than 15 years is significantly lower than that of the NESC and, thus, the SCTTU has better economic performance. The economic performance of the SCTTU with a life-cycle of less than 15 years is not better than that of the NESC. Compared with the traditional calculation method of a single cost value, the blind number model can obtain the possible distribution interval of LCC and the reliability of the corresponding interval, which makes the estimation results more valuable for practical engineering reference.

Keywords: synchronous condenser transformed from thermal unit (SCTTU); newly established synchronous condenser (NESC); life-cycle cost (LCC); blind number theory

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1. Introduction

Building a novel power system with renewable energy as the main body is an important way for China to achieve the goal of "carbon peaking and carbon neutrality". With the State Grid Corporation further accelerating the construction of a novel power system and fully promoting the realization of the "dual carbon" goal, the dominant position of novel energy power generation with "weak support" will become increasingly prominent. The output space of traditional thermal power units with "strong support" will be limited, the reactive power demand of the power system will rise sharply, and the voltage stability will face great challenges [1–3]. In order to increase the proportion of dynamic reactive power supply, optimize the utilization rate of thermal power units, and improve the stable operation level of the power grid, the new large capacity synchronous condenser has been widely used in HVDC transmission and reception terminals in recent years, and has played an important role in suppressing the DC commutation failure and improving the voltage stability of the system [4]. Up to now, 47 new large-capacity 300 MVar synchronous condensers have been built, and 39 have been put into operation in China. However, the new large capacity synchronous condenser faces a series of problems, such as high cost, high operation and maintenance costs, and great construction difficulties.

Compared with the NESC, there are two advantages in transforming the thermal units into synchronous condensers. One is the advantage of economic cost, and the other is the advantage of improving the utilization rate of thermal units. The SCTTU can save the investment cost of the synchronous condenser unit itself and, at the same time, the retired thermal unit can be reconstructed and reused, which will improve the utilization rate of the thermal units [5]. Therefore, power systems should make full use of the existing retired thermal units, transform them into synchronous condensers, and conduct long-term grid connected operation, which makes use of to its characteristics of strong overload capacity and fast response speed, and provides sufficient dynamic reactive power support for the power grid without occupying active space. In doing so, it is possible to reduce investment and operation costs, improve the utilization rate of thermal units, and solve the survival problems of thermal power plants. This has significant practical value and social and economic benefits [6].

At present, there have been relevant studies on synchronous condensers and synchronous condensers transformed from thermal units. With the large-scale access to HVDC transmission and new energy, the domestic research on the synchronous condensers and the synchronous condensers transformed from thermal units is gradually enriched. Jiang Zhe et al. [6] demonstrated the feasibility of the technical transformation of retired thermal units to synchronous condensers, and took Shandong power grid as an example to verify the ability of the synchronous condensers transformed from thermal units to improve the voltage stability of the power grid and the new energy grid connection characteristics. D. K. Chaturvedi [7] proposed the transformation scheme of transforming a 500 MW retired thermal unit into a 300 MVar synchronous condenser, and demonstrated the ability of SCTTU to provide dynamic compensation, improve system inertia, and improve system power quality. Karan et al. [8] proposed the steps of transforming retired thermal units into synchronous condensers to provide reactive power support for the system, so as to meet the reactive power demand of the Indian power grid under large-scale new energy access. J. An et al. [9] proposed an optimal configuration method for the conversion of thermal power units to synchronous condensers and verified the feasibility of the proposed scheme from the perspectives of technology, economy, and operation mode in combination with engineering cases. J. Kaur and N. R. Chaudhuri [10] put forward the transmission scheme from thermal units to synchronous condensers in the weak interconnection system and analyzed the supporting ability of synchronous condensers transformed from thermal units in the system. In addition, in terms of cost estimation, the China Qaidam converter station 2×300 MVar synchronous condenser project adopts a single value estimation method to estimate the cost of the NESC [11]. The cost estimation of the NESC of the China Jiangsu Taizhou 2×300 MVar synchronous condenser station is also a single value estimation method [12]. Huang Z et al. [13] proposed that the cost estimation of replacing the retired thermal power unit with new energy power station and synchronous condenser also adopts a single value estimation method. Most of the above studies focus on the aspects of technical feasibility, transformation methods, and the improvement of power grid stability after the transformation. Few economic studies are only the estimation of a single value of the cost of synchronous condensers. Therefore, there is still a lack of comprehensive analysis, both in terms of foreign and domestic circumstances, for the cost analysis of synchronous condensers transformed from thermal units.

In this paper, a cost calculation method based on LCC is proposed. At the same time, blind number theory is introduced into the cost calculation model to solve the influence of various uncertain information on the cost of the synchronous condenser project, and the distribution range of the life-cycle cost of the synchronous condenser is obtained. The life-cycle cost of the NESC and the SCTTU with different service life are compared and analyzed. Combined with the operation mode of the reactive power equipment in the market, the reactive power pricing under different operation modes of the NESC and the SCTTU is formed. The analysis results show that the life-cycle cost of the SCTTU with a long life-cycle of more than 15 years is significantly lower than that of the NESC, and the SCTTU has lower market reactive power pricing and better economy. At the same time, the cost range and the corresponding confidence of the SCTTU are obtained. Compared with the single value of the traditional prediction, these results have more engineering reference value.

The remained of this paper is organized as follows. In Section 2, the life-cycle cost model of a synchronous condenser is established. In Section 3, blind number theory is introduced, and the processing and calculation methods of blind information are introduced. In Section 4, the LCC model of the synchronous condenser based on the blind number theory is established. In Section 5, based on the existing market, a reactive power pricing model with coverage cost as the objective is constructed. In Section 6, a detailed case study proves that the proposed SCTTU is economical. In Section 7, several important conclusions are summarized.

2. Life-Cycle Cost Analysis of SCTTU

The connotation of life-cycle cost can be summarized as follows: the generalized life-cycle cost refers to all expenses incurred by all stakeholders, such as producers, consumers, and the public, in the life-cycle of the project from the perspective of the whole society. In a narrow sense, the life-cycle cost refers to the cumulative sum of the costs of the project at each stage of its life-cycle after discounting [14].

This paper is based on the life-cycle cost theory in a narrow sense, and more intuitively reflects the cost of the synchronous condenser project. According to the life-cycle stage, the life-cycle cost of the construction project mainly includes the cost of the decision-making stage, the cost of the design stage, the cost of the construction stage, the cost of the operation and use stage, and the cost of the scrapping and dismantling stage [15]. These are as follows:

(1) Cost of the decision-making stage. The cost in the decision-making stage mainly refers to the expenses incurred in the process of project planning, feasibility studies, market investigation, fundraising, scheme optimization, land acquisition, etc. [3];

(2) Cost of the design stage. The cost in the design stage accounts for a small proportion in the total investment of the project, but the design stage is an important stage in the cost control of the construction project;

(3) Cost of construction stage. The cost of this stage mainly includes labor, materials, equipment, management, and various taxes;

(4) Cost of the operation and use stage. The cost in the use stage refers to various expenses that the user needs to pay in the process of using the project, mainly including energy consumption expenses, maintenance expenses, management expenses, etc. [6];

(5) Cost of scrapping and dismantling stage. The scrapping and dismantling stage is the last stage of the project life-cycle. In this stage, the demolition of the project and the disposal of wastes are mainly carried out, and the costs are mainly demolition costs and cleaning costs.

The change in the life-cycle cost of the construction project at different stages is shown in Figure 1. Life-cycle cost analysis is an auxiliary tool for investment decision-making. Its core aim is to identify the cost items at each stage of the life-cycle, and to conduct quantitative estimation and analysis of the cost according to a certain cost estimation model and method. Finally, the Life-cycle cost of the project is obtained, and the project decision is made on this basis.

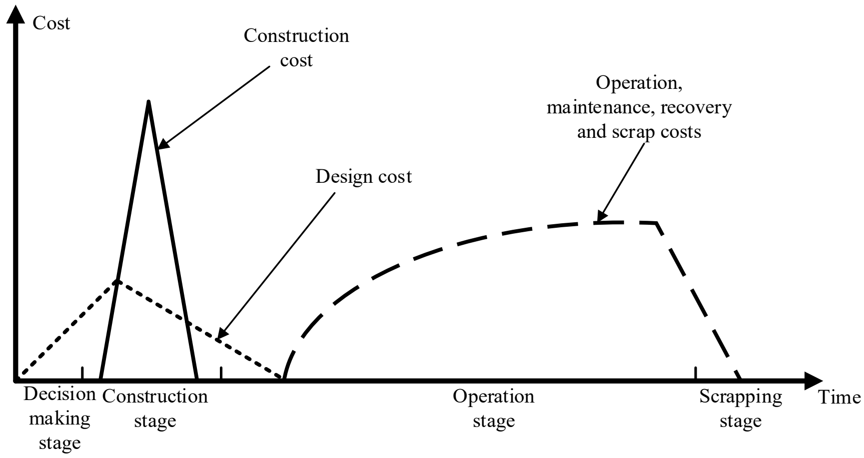

Figure 1. Diagram of cost trend at each stage of the life-cycle.

2.1. Life-Cycle Cost Analysis of SCTTU and NESC

According to the stage division of the construction project based on the life-cycle theory, combined with the engineering characteristics of the synchronous condenser, this paper brings the design decision into the construction cost. Considering that, in addition to operation and maintenance costs, overhaul and technical transformation costs, as well as market penalty costs caused by power failure, are not able to be included in operation and maintenance costs during the operation phase of the SCTTU and the NESC, they are calculated separately. The final scrapping stage is the residual value cost of the equipment. Since the residual value of the equipment is the residual value of the project, its cost calculation is negative. Therefore, the life-cycle cost of the SCTTU and the NESC can be divided into five parts.

The present value of the initial construction cost S_b (i.e., the total construction investment from year 0 to year k) is expressed as follows:

$$S_b = \sum_{t=0}^{k} \frac{S_{bt}}{(1+i)^t} \tag{1}$$

where S_{bt} is the construction investment in the year t, and i is the discount rate.

Assuming that the operation cost is generated from the year l, the present value expression of the operation and maintenance cost is as follows:

$$S_u = \sum_{t=l}^{T} \frac{S_{ut}}{(1+i)^t} \tag{2}$$

where S_{ut} is the operation and maintenance cost of the year t, and T is the service life of the synchronous condenser.

Assuming that the overhaul cost is generated from the year m, the present value expression of the overhaul and technical transformation cost is:

$$S_r = \sum_{t=m}^{T} \frac{S_{rt}}{(1+i)^t} \tag{3}$$

where S_{rt} is the overhaul and technical transformation cost of the year t.

Assuming that the penalty cost is generated from the year x, the present value expression of the penalty cost is as follows:

$$S_p = \sum_{t=x}^{T} \frac{S_{pt}}{(1+i)^t} \tag{4}$$

where S_p is the penalty cost incurred in the year t.

The present value expression of the residual value at the end of the year T is as follows:

$$S_q = S_{qt}/(1+i)^T \tag{5}$$

where S_{qt} is the residual value at the end of the year T.

Therefore, we can obtain the calculation formula of the life-cycle cost of the synchronous condenser project as follows:

$$S_{\mathrm{LCC}} = S_b + S_u + S_r + S_p + S_q \tag{6}$$

2.2. Uncertainty Analysis of Cost in Each Stage

(1) Uncertain influencing factors of initial construction cost S_b.

Here,S_b is the costs and expenses incurred in the process of planning, design, implementation, and the completion of project construction of a synchronous condenser or a synchronous condenser transformed from a thermal unit. At present, most Chinese assets are estimated according to industry regulations, and the traditional quota is used as the pricing basis. Now, the estimation theory is relatively mature, the cost change range is not large, and the influence of uncertain factors on it is not great. Therefore, this model mainly considers the uncertain factors of operation and maintenance in the calculation. Here, S_b is determined by the budget estimate of the corresponding project and treated as a deterministic factor.

(2) Uncertain influencing factors of operation and maintenance cost S_u.

Here, S_u corresponds to the annual cycle cost, which is the cost that will occur every year in the research cycle. Most of the daily operation and maintenance costs are related to the functions and custody services of the equipment in the synchronous condenser, mainly including energy consumption costs, maintenance costs, labor costs, environmental costs, etc. The energy consumption cost refers to the energy consumption required by the operation of the project equipment. Maintenance cost refers to the cost of maintenance, overhaul, and the replacement of parts for the project equipment. Labor cost refers to the labor cost generated by the operation and management of a synchronous condenser. Environmental cost refers to the cost required to establish the equipment operation environment. According to the above analysis, among the influencing factors of S_u, personnel factors constitute the main uncertain factors, resulting in large changes in maintenance and operation management costs.

(3) Uncertain influencing factors of overhaul and technical transformation cost S_r.

Here, S_r is divided into overhaul cost and technical transformation cost. It corresponds to the non-annual cycle cost, which is not a cost that will occur every year. Overhaul cost refers to the cost of major maintenance measures that must be taken to maintain the normal operation of equipment. The cost of technological transformation is the cost incurred by introducing advanced technology, equipment, and materials to improve, update and transform the existing backward production equipment and supporting auxiliary facilities. The costs of these two parts will be affected by the environment or the development of social technology and economy, with strong uncertainty. The occurrence of overhaul cost is a random probability event, while the occurrence of technical transformation cost is a kind of unknown information and grey information, which makes it difficult to accurately estimate a certain value in actual work. This paper will introduce blind number theory to solve this problem.

(4) Uncertain influencing factors of penalty cost S_p.

Here, S_p is the power shortage cost on the demand side and the direct economic reflection of the power supply reliability level of the power grid. Its magnitude is related to the outage probability, outage duration, average outage power, and maintenance cost after outage. The empirical value shall be adopted according to the actual station operation.

(5) Uncertain influencing factors of equipment residual value S_q.

Residual value S_q is the residual value of the equipment or the whole project at the end of the analysis period. Unlike other costs mentioned above, S_q can be a positive cost or a negative value. There is a strong subjective uncertainty in the estimation of S_q, but because of its small proportion in the total cost, it is often ignored or estimated as a percentage of the initial construction investment. The uncertainty is ignored here and is estimated as a function of initial construction cost.

From the above analysis, it can be seen that S_u, S_r, and S_p are all regarded as functions of the running time of the synchronous condenser in the calculation equation (6) of the synchronous condenser LCC. This expression is inaccurate and does not conform to the actual situation. Because S_r and S_p do not occur every year, their occurrence is affected by many uncertain factors. Later, blind number theory is introduced into Equation (6) and corrected to reasonably deal with the uncertain information in the cost analysis.

3. Blind Number Reliability Model

Objective uncertainty information may be expressed in two or more forms of uncertainty. Complex information with the above four forms of uncertainty at most is called blind information. For such uncertain information, blind number theory can be used to express and process it.

3.1. Definition of a Blind Number

Let $\alpha_i \in g(I)$, where $g(I)$ is an interval grey number set, $\alpha_i \in [0,1]$, $\quad i = 1, 2 \ldots, n$, $f(x)$ is a grey function defined on $g(I)$, and $f(x)$ is the following:

$$f(x) = \begin{cases} \alpha_i, & x = x_i (i = 1, 2, 3, \ldots, n); \\ 0, & x = other \end{cases} \tag{7}$$

When $i \neq j$, $x_i \neq x_j$, $\sum\limits_{i=1}^{n} \alpha_i = \alpha \leq 1$, then function $f(x)$ is called a blind function.

In the expression of the blind function $f(x)$, α_i is the reliability of x_i value, α is the total reliability of $f(x)$, and n is the order of $f(x)$ [16].

3.2. Operation of Blind Numbers

Let * denote four operations (add, subtract, multiply, and divide) of blind numbers, and set the blind numbers as A and B. The four operations for defining blind numbers are as follows:

$$\begin{aligned} A = f(x) &= \begin{cases} \alpha_i, & x = x_i (i = 1, 2, 3, \ldots, m); \\ 0, & x = other \end{cases} \\ B = g(y) &= \begin{cases} \beta_j, & y = y_j (j = 1, 2, 3, \ldots, n) \\ 0, & y = other \end{cases} \end{aligned} \tag{8}$$

Then, the following can be calculated:

$$\begin{array}{c c} \begin{matrix} x_1 \\ \vdots \\ x_i \\ \vdots \\ x_m \end{matrix} & \begin{bmatrix} x_1 * y_1 \cdots x_1 * y_i \cdots x_1 * y_n \\ \vdots\vdots\vdots \\ x_i * y_1 \cdots x_i * y_i \cdots x_i * y_n \\ \vdots\vdots\vdots \\ x_m * y_1 \cdots x_m * y_i \cdots x_m * y_n \end{bmatrix} \\ & y_1 \quad y_i \quad y_n \end{array} \tag{9}$$

Equation (9) is called the matrix of the confidence band edge product of A with respect to B, $\alpha_1, \alpha_2, \ldots, \alpha_\mathrm{m}$, and $\beta_1, \beta_2, \ldots, \beta_\mathrm{n}$ are the confidence sequences of A and B, respectively. The $m * n$-order matrix is called the confidence product matrix of A on B, which is referred to as the confidence product matrix for short. The element $x_i * y_i$ in the possible value *matrix of A with respect to B and the element $\alpha_\mathrm{i} * \beta_\mathrm{i}$ in the confidence matrix of A with respect to B are called corresponding elements, and their positions are called corresponding positions [17].

If A, B, and C are blind numbers, and the operation between blind numbers satisfies the following properties [18]:

$$\begin{array}{l} A+B=B+A \\ A\times B=B\times A \\ (A+B)+C=A+(B+C) \\ (A\times B)\times C=A\times(B\times C) \\ (A+B)\times C=A\times C+B\times C \end{array} \tag{10}$$

3.3. Mean Value of Blind Number

Define a and b as real numbers, and $a \le b$, $(a+b)/2$ is the center of rational grey number $[a,b]$, denote $\odot[a,b]$=$(a+b)/2$, and it is a first-order unascertained rational number, then the following is true:

$$E(f(x)) = \begin{cases} \alpha, & x = \frac{1}{\alpha}(\odot)\sum\limits_{i=1}^{n}\alpha_i x_i \Big) \\ 0, & x = other \end{cases} \tag{11}$$

Here, $E(f(x))$ is the mean value of blind number $f(x)$, which reflects the average value of blind number $f(x)$ [19].

If the blind numbers $f(x)$ and $g(y)$ are known, the mean value of the blind numbers has the following properties:

$$\begin{array}{l} E(f(x)+g(y)) = E(f(x))+E(g(y)) \\ E(f(x)-g(y)) = E(f(x))-E(g(y)) \\ E(f(x)\cdot g(y)) = E(f(x))\cdot E(g(y)) \end{array} \tag{12}$$

4. Life-Cycle Cost of SCTTU and NESC Based on Blind Number Theory

After collecting and sorting out the actual data of the previous synchronous condenser projects, we can know that in the actual construction of the synchronous condenser project, the estimation method and theory of the initial construction cost S_b are very mature, so S_b can be expressed by the first-order blind number $S_b(x)$. The residual value S_q is usually expressed as a percentage of the initial construction cost, so the blind number expression of S_q is also first-order and can be expressed as $S_q(v) = rS_b(x)$, where r is the percentage of the residual value in the initial construction investment. The operation and maintenance cost S_u is related to the service life T of the synchronous condenser and is a continuous cost that occurs every year. Therefore, it can be expressed by the cost $S_u(y)$ that occurs every year. As for the overhaul and technical transformation cost S_r and the penalty cost S_p, they do not occur every year. In order to express them more scientifically and rationally, two variables f and n_m are introduced, where f represents the frequency of occurrence of S_r in the life-cycle T of the synchronous condenser, and n_m represents the number of occurrences of S_p in the full life-cycle T. Thus, the blind number expression of each cost can be obtained.

The initial construction cost can be obtained as follows:

$$S_b(x) = \sum_{t=0}^{k} \frac{S_{bt}(x)}{(1+t)^t} \tag{13}$$

The operation and maintenance cost can be obtained as follows:

$$S_u(y) = \sum_{t=l}^{T} \frac{S_{ut}(y)}{(1+i)^t} \tag{14}$$

The overhaul and technical transformation cost can be obtained as follows:

$$S_r(z) = \sum_{t=1}^{T/f} \frac{C_{rt}(z)}{\left(1+i_f\right)^t} \tag{15}$$

Where $i_f = (1+i)^{1/f} - 1$, which represents the actual discount rate of the overhaul and technical transformation cost.

The penalty cost can be obtained as follows:

$$S_p(w) = \sum_{t=1}^{n_m} \frac{S_{pt}(w)}{(1+i_m)^t} \tag{16}$$

where $i_{\mathrm{m}} = (1+i)^{T/n_m}$, which represents the actual discount rate of penalty cost.

The residual value can be obtained as follows:

$$S_q(v) = \frac{rS_q(x)}{(1+i)^T} \tag{17}$$

Thus, the blind number expressions of the SCTTU and the NESC are obtained as follows:

$$S_{(LCC)} = S_b(x)\left[1 - \frac{r}{(1+i)^T}\right] + S_u(y) + S_r(z) + S_p(w) \tag{18}$$

5. Reactive Power Pricing Mechanism Based on Cost of Synchronous Condenser

5.1. Reactive Power Quotation Mechanism of Synchronous Condenser

To establish the reactive power market, all reactive power participants shall provide their quotation curves to the independent system dispatcher. The synchronous condenser can obtain the corresponding economic compensation when its quotation curve is basically consistent with the comprehensive cost curve. Therefore, the life-cycle cost of the synchronous condenser needs to be subdivided to obtain the reactive power quotation. China's reactive power market is not complete. By analogy with the cost curve of generator reactive power generation participating in market auxiliary services [20], the reactive power cost curve of the synchronous condenser can be obtained, as shown in the Figure 2.

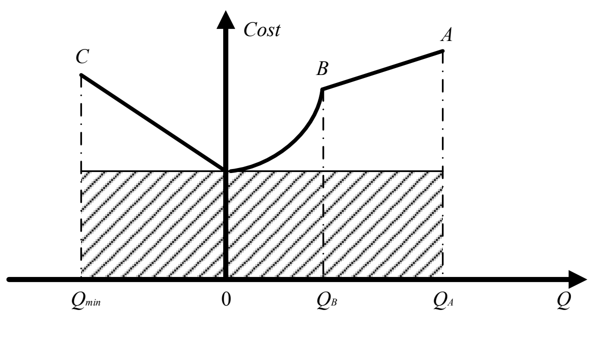

Figure 2. Comprehensive cost curve of the synchronous condenser.

The comprehensive cost curve of the synchronous condenser can be divided into three sections, as follows:

(1) In order to maintain the system voltage, the generator in this area operates in the leading phase to absorb reactive power. Similar to the generator, a certain proportion of the reactive power and quantity of the synchronous condenser can be compensated. Since the leading phase operation will cause great damage to the generator and affect the service life of the generator, the absolute value of the slope in this section is larger than that of sections Q_A to Q_B;

(2) Different from the traditional generators, the reactive power output of the section from 0 to Q_B is relative to the installed capacity of the synchronous condenser. Most of its capacity will be used as cold and hot standby, and there is no actual output. Therefore, the cost slope is larger than that of the Q_A to Q_B sections with normal output, and the rising speed is faster. Therefore, appropriate economic compensation is required;

(3) The section from Q_B to Q_A belongs to the normal output section of the synchronous condenser. The slope of the cost curve is small and the cost increases linearly. A certain proportion of the generator can be paid for.

According to the above analysis of the comprehensive cost curve of the synchronous condenser, the reactive power quotation curve of the reactive power participant is shown in Figure 3.

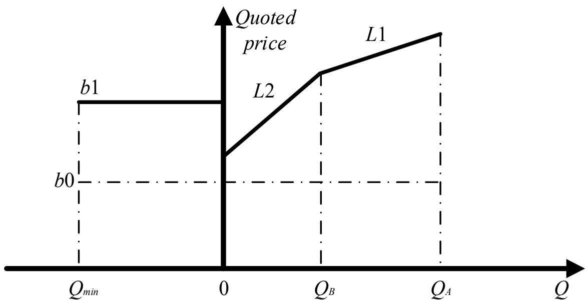

Figure 3. Reactive power quotation curve of the synchronous condenser.

It can be seen from Figure 3 that $b0$ compensates the reactive power investment cost of the synchronous condenser to encourage it to invest in reactive power and ensure that the system has sufficient reactive power sources. Here, $(b1 - b0)$ is the compensation for the leading phase operation of the synchronous condenser, and *L2* and *L1* are the reactive power quotations under two conditions when the synchronous condenser normally generates reactive power.

5.2. Reactive Power Market Pricing Mechanism

At present, there are the following two kinds of electricity price models: two-part electricity price and single electricity ladder electricity price. The two-part electricity price consists of the basic electricity price (capacity electricity price) and the electricity price. The basic electricity price is calculated based on the customer's electricity capacity or maximum demand, and the electricity price is calculated based on the customer's actual monthly electricity consumption. The electricity charges calculated by the two kinds of electricity prices are added together, and the electricity charges adjusted by the power factor are all the fees payable by the customer. The single step electricity price divides the monthly electricity consumption of urban and rural residents into several levels, and the electricity price is increased by levels [21]. Aiming at the cost recovery method of reactive power compensation device, combined with the electricity price recovery mode of different power grid equipment, it is proposed that reactive power compensation device can recover the cost in the following three ways [22].

(1) Unified operation of power grid. The dynamic reactive power compensation device is not an independent entity, and its asset ownership and operation right belong to the power grid company. The power grid uniformly bears the costs, principal and interest repayment, profits and taxes of the reactive power compensation device, and performs unified dispatching and unified operation. Under this management mode, the cost of the synchronous condenser is recovered by incorporating it into the transmission and distribution electricity price.

(2) Independent operation. As an independent entity, the asset ownership and operation right of the reactive power compensation device belong to the dynamic reactive power compensation device company, and the company will uniformly bear the cost, interest

payment, profit, tax and other expenses of the reactive power compensation power station, and conduct unified dispatching and unified operation. The power grid company pays for the reactive service by purchasing it, and the operation and maintenance expenses can be recovered by the reactive service expenses paid by the power grid company. Under this management mode, the dynamic reactive power compensation device recovers the cost through two modes of single electricity price and two-part electricity price [23].

Under the single electricity price mode, the government competent department verifies the feed-in tariffs of the dynamic reactive power compensation device, and the power grid company uniformly pays its costs and profits, and is responsible for the repayment of principal and interest. The power station is only responsible for operation according to the power grid dispatching requirements, and the operating income of the power station is realized through the electricity price during the operation period [24]. The capacity price is:

$$P_{ca} = \frac{P_a \times \alpha + C_f}{(1 - \eta_z \times (\eta_c + \eta_e)) \times E_o} \tag{19}$$

where P_a is the total investment, α is the capital utilization rate, C_f is the fixed cost, η_z, η_c and η_e are value-added tax rate, urban construction maintenance tax rate and education additional tax rate, E_o is the total online capacity.

Under the two-part electricity price mode, reactive power compensation price is the sum of average cost price (capacity price) and marginal cost price (electricity price) [25]. As shown in Equation (20).

$$P_e = \frac{C_k}{(1 - \eta_z \times \eta_f)) \times F_o} \tag{20}$$

where P_e is the electricity price, C_k is the variable cost, η_f is the additional tax rate, and F_o is the on grid electricity.

(3) Lease operation. The established dynamic reactive power compensation device operating company leases the equipment to the power grid company or other operating entities for operation, so as to collect the lease fee to ensure its own principal and interest repayment and appropriate profit [22], and its calculation method is similar to the calculation method of electricity price during the operation period.

6. Case Study

6.1. Case Data

This paper takes 2 × 300 MVar SCTTU and NESC as examples. The service time of the generator after the transformation is calculated according to the transformation level and the unit capacity in three cases of 20, 15, and 10 years. According to the engineering experience, the ending residual value is 5% of the initial construction cost. The overhaul and technical transformation period are generally 4–6 years according to the generator maintenance regulations, and the period for the main transformer is generally 10 years. Since the generator is to be reconstructed, the interval of 4 years is taken. The fault rate is taken as the engineering experience value of 0.643 times/year, from which the number of occurrences of penalty cost are 13, 10, and 7. According to the provisions on the social discount rate in the 'Economic evaluation methods and parameters of construction projects (Third Edition)' issued by the National Development and Reform Commission and the Ministry of Construction in 2006, the benchmark discount rate is set as $i = 8\%$ in this paper.

The service time of the 2 × 300 MVar NESC can be up to 40 years or even 60 years, and the general service time is 30 years. From the engineering experience, the ending residual value is 5% of the initial construction cost. The overhaul and technical transformation period are based on the generator maintenance regulations, and the interval of 5 years is taken as the intermediate value. The fault rate takes the engineering experience value of 0.433 times/year, from which the number of occurrences of penalty cost is 13. The benchmark discount rate is $i = 8\%$.

According to the engineering calculation, the cost corresponding to the NESC and the SCTTU with different service life after transformation is shown in Table 1.

Table 1. Life-cycle cost of the NESC and the SCTTU with different service life.

Construction Type	Construction Cost/10^4 Yuan	Operation and Maintenance Cost/10^4 Yuan		Overhaul and Transformation Cost/10^4 Yuan		Penalty Cost/10^4 Yuan	
		Reliability	Cost Range	Reliability	Cost Range	Reliability	Cost Range
Newly established	26,002	0.15 0.65 0.2	2058.5–2166.8 2166.8–2383.5 2383.5–2708.5	0.25 0.65 0.1	736.7–758.3 758.3–780 780–801.7	0.23 0.55 0.22	541.7–563.4 563.4–585 585–650
Transformed (20 year service life)	4802	0.15 0.75 0.1	1874.4–2003.7 2003.7–2040.6 2040.6–2273.5	0.3 0.55 0.15	884.1–909.9 909.9–936.2 936.2–962.1	0.13 0.68 0.19	650–676.1 676.1–702 702–780
Transformed (15 year service life)	4523	0.2 0.6 0.2	1780.68–1903.5 1903.5–1938.5 1938.5–2159.8	0.13 0.76 0.11	928.3–955.3 955.3–983 983–1,010.2	0.1 0.85 0.05	656.5–682.8 682.8–709 709–787.8
Transformed (10 year service life)	4039	0.05 0.8 0.15	1593.2–1703.2 1703.2–1734.5 1734.5–1932.5	0.18 0.7 0.12	946–973.6 973.6–1,001.7 1001.7–1029.5	0.25 0.57 0.18	663.1–689.7 689.7–716.1 716.1–795.7

Taking a city in China as example, the electricity consumption of the whole society is 98.385 billion kWh, the electricity price level is 0.4 yuan/kWh, the value-added tax rate is 13%, the urban construction and maintenance tax rate is 7%, the education additional tax rate is 3%, the on-line capacity of the synchronous condenser is subject to the rated capacity, and the on-line capacity is calculated as 80% of the occupied capacity per hour.

6.2. Result Analysis

The costs of NESC and the SCTTU with different service life are brought into the calculation formula of blind number cost in the life-cycle, and the 27th order blind number expression (reliability band edge product matrix) of the four life-cycle costs of NESC and the SCTTU with different service life can be obtained from Equation (18). Take the SCTTU with a service life of 20 years as an example, and the results are shown in Equation (19).

$$\begin{array}{cc} \begin{array}{c} 0.0242 \\ 0.1268 \\ 0.0354 \\ 0.0964 \\ 0.5045 \\ 0.1410 \\ 1.0093 \\ 0.0488 \\ 0.0136 \end{array} & \left[\begin{array}{ccc} 28,083.0-29,501.9, & 28,107.8-29,526.6, & 28,132.5-29,600.8 \\ 28,206.7-29,628.9, & 28,232.5-29,653.6, & 28,257.2-29,727.8 \\ 28,333.7-29,754.1, & 28,359.5-29,778.8, & 28,384.2-29,853.0 \\ 29,351.4-29,864.2, & 29,377.2-29,888.9, & 29,401.9-29,963.1 \\ 29,476.1-29,991.2, & 29,501.9-30,015.9, & 29,526.6-30,090.1 \\ 29,603.1-30,116.4, & 29,628.9-30,141.1, & 29,653.6-30,215.3 \\ 29,713.7-32,150.8, & 29,739.5-32,175.5, & 29,764.2-32,249.7 \\ 29,838.4-32,277.8, & 29,864.2-32,302.5, & 29,888.9-32,376.7 \\ 29,965.4-32,402.8, & 29,991.2-32,427.5, & 30,015.9-32,501.7 \end{array} \right] \\ & \begin{array}{ccc} 0.13 & \qquad 0.68 & \qquad 0.19 \end{array} \end{array} \quad (21)$$

The 27th order blind number expressions of the NESC and the SCTTU with different service life are optimized and calculated, and the results are shown in Figure 4.

Furthermore, the blind number mean value of annual average cost of NESC and the SCTTU with different service life can be obtained, as shown in Figure 5.

From the above results, it can be seen that the reference average value of the project cost of the NESC and the SCTTU is obtained based on the life-cycle cost analysis of the dimmer based on blind number theory, and the reliability of each interval is given. Compared with the deterministic single value obtained by the deterministic algorithm, it gives the project decision-makers greater reference value.

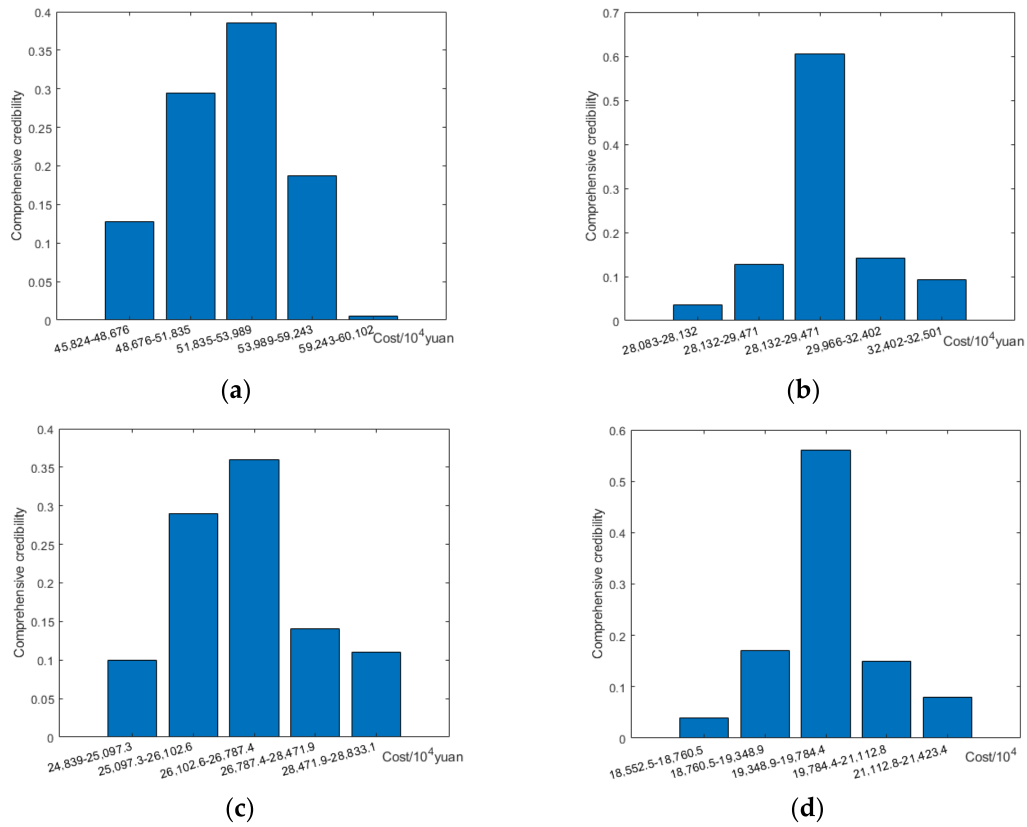

Figure 4. Life-cycle cost of NESC and the SCTTU with different service life: (**a**) NESC (30 year service life); (**b**) SCTTU (20 year service life); (**c**) SCTTU (15 year service life); (**d**) SCTTU (10 year service life).

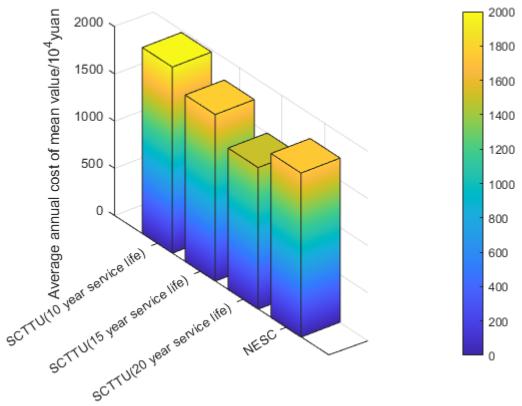

Figure 5. Blind number mean value of annual average cost of NESC and SCTTU.

The average 30 year total cost of the NESC with the same capacity is 5213.86 $\times$ 10^4 yuan, with an annual average of 1737.95 $\times$ 10^4 yuan. The average total cost of the SCTTU (20 year service life) is 2998.78 $\times$ 10^4 yuan, with an annual average of 1499.39 $\times$ 10^4 yuan; the average total cost of the SCTTU (15 year service life) is 2646 $\times$ 10^4 yuan, with an average annual average of 1764.7 $\times$ 10^4 yuan; the average total cost of the SCTTU (10 year service life) is 19,711.6 $\times$ 10^4 yuan, with an annual average of 1971.2 $\times$ 10^4 yuan. Although the service life of the four units is different, it can be seen from the average annual cost and the cost of each stage that the average annual cost of the SCTTU (20 year service life) is significantly lower than that of the NESC, meaning that the SCTTU has better economic efficiency. However, it is not certain that the entirety of the SCTTU is economical. As can be seen from Figure 5, the average annual cost of the SCTTU increases with the reduction in the service life. The average annual cost of the SCTTU with a 15 year service life is basically the same as that of the NESC. The average annual cost of the SCTTU with a 10 year service life is significantly higher than that of the NESC.

In order to analyze the reasons for the cost difference, this paper analyzes the following four aspects: investment cost (excluding residual value cost), operation cost, overhaul and technical transformation cost, and penalty cost.

We start with the annual average cost. It can be seen from Table 1 that the investment cost of the NESC is 2602 $\times$ 10^4 yuan, which is significantly higher than that of the SCTTU with the following three service lives: 4802 $\times$ 10^4 yuan, 4523 $\times$ 10^4 yuan, and 4039 $\times$ 10^4 yuan. However, the investment cost of the three types of SCTTU will gradually increase with the increase in the longevity of the service life, but the difference is in the order of one million yuan, which has advantages over the new established one. The average value of operation cost, overhaul and technical transformation cost, and penalty cost is shown in Figure 6.

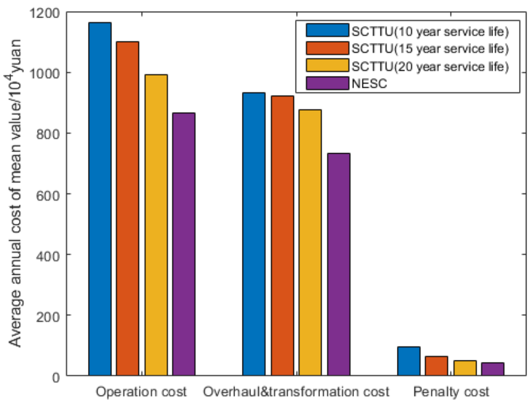

Figure 6. Average annual cost comparison of three costs between NESC and SCTTU.

It can be seen from Figure 6 that the three costs of the NESC are lower than those of the SCTTU. However, due to the high investment cost, the annual average of the life-cycle cost is higher than that of the SCTTU (20 year service life). With the increase in the service life of the transformed one, the operation cost, overhaul and technical transformation cost, and penalty cost decreases. In view of this result, this paper compares the annual change curves of the three costs, as shown in Figures 7–9.

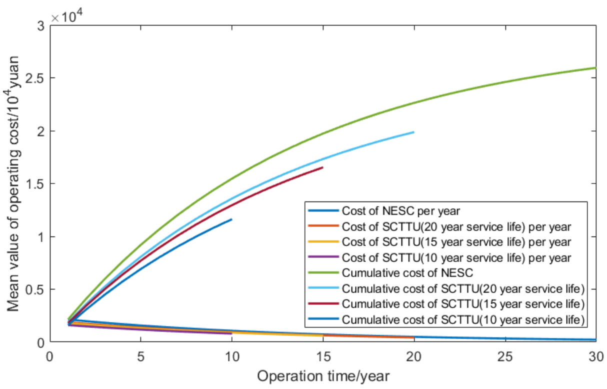

Figure 7. Comparison of operation cost curve between NESC and SCTTU.

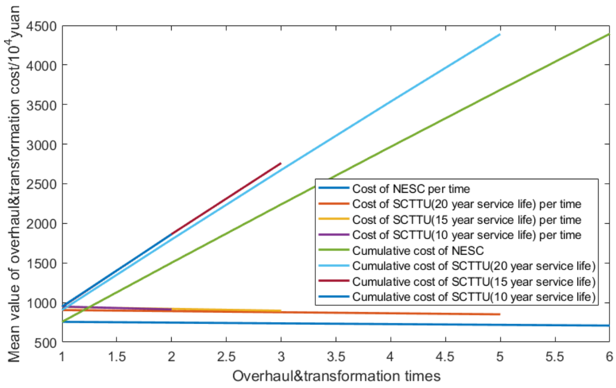

Figure 8. Comparison of overhaul and technical transformation cost curve between NESC and SCTTU.

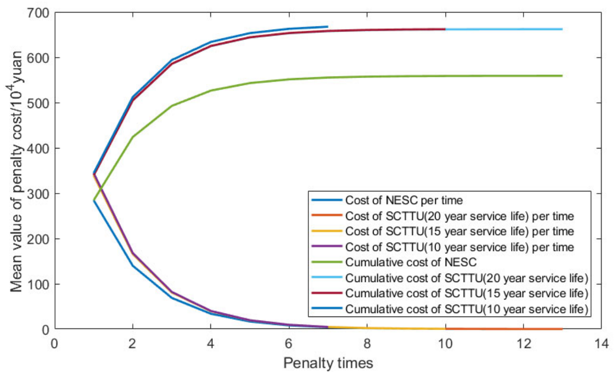

Figure 9. Comparison of penalty cost curve between NESC and SCTTU.

It can be seen that with the increase in the service year after the transformation, the average annual operation cost, and the average penalty cost decrease at the speed of the negative exponential function, resulting in the gradual increase in the accumulated cost, which largely averages the life-cycle cost. However, the overhaul and technical transformation cost has little impact on the average annual operation cost due to the low frequency of occurrence. From this, it can be concluded that, the longer the operation life-cycle of the transformed one, the better its economy. In this paper, the 20-year-old SCTTU has the best economy. It can be inferred that after 15 years of service life, the SCTTU has better economy than the NESC.

Combining the quotation curve and the market pricing mechanism, the pricing results can be obtained, as shown in Table 2.

Table 2. Price summary for unified operation, independent operation, and lease operation (yuan/(kVarh)).

Management Model	Unified Operation of Power Grid	Independent Operation		Lease Operation	
Price form	Increment price	Electricity price	Capacity price	Electricity price	Capacity price
NESC	0.000530	0.0416	55.871	0.0161	92.34
SCTTU (20)	0.000459	0.0341	47.167	0.0129	77.06
SCTTU (15)	0.000547	0.0425	58.495	0.0131	93.85
SCTTU (10)	0.000672	0.0521	67.323	0.0143	97.46

From the quotation of the three management modes, the quotation change trend and cost change trend of the four kinds of synchronous condensers are similar. Due to its cost advantage, the SCTTU with a 20 year service life has the lowest quotation in the vertical comparison of the three management modes, which once again proves the economic advantage of the SCTTU with a 20 year service life.

7. Conclusions

In this paper, a cost calculation method based on the life-cycle cost of the synchronous condenser is proposed, and the blind number theory is introduced into the cost calculation model to solve the influence of various uncertain information on the cost of the synchronous condenser project. The distribution range of the life-cycle cost of the synchronous condenser is also obtained. At the same time, the life-cycle cost of the newly established synchronous condenser is compared with that of the synchronous condenser transformed from thermal units with different service life, the reactive power pricing based on the market mechanism is calculated for the established synchronous condenser and the synchronous condenser transformed from thermal unit, and the following conclusions are obtained:

(1) Under the "dual carbon" background, for the large-scale grid connection of new energy and HVDC transmission with power electronic converter equipment, and with the reuse of a large number of retired thermal units, the synchronous condenser transformed from a thermal unit can provide sufficient dynamic reactive power support for the power grid. According to the analysis of the life-cycle cost, it can be concluded that a synchronous condenser transformed from a thermal unit can reduce investment and operation costs, and improve the utilization rate of the retired thermal units, which has significant practical value and social and economic benefits.

(2) Compared with the traditional single value cost estimation method, the life-cycle cost calculation method based on the blind number theory proposed in this paper gives the cost interval range and its confidence of the synchronous condenser. Combined with engineering cases, the calculation results are reasonable and reliable. This method can help investors summarize the expected costs, help investors identify the probability risks of different costs, and more clearly estimate the cost–return cycle. The clear cost interval range and corresponding reliability provide more valuable reference for the decision-making and construction of the project.

(3) By comparing the life-cycle cost of the newly established synchronous condenser with that of the synchronous condensers transformed from thermal units with different service life, it can be concluded that the life-cycle cost of the synchronous condenser transformed from a thermal unit with a long service life of more than 15 years is lower than that of the newly established synchronous condenser, so its economy is better. In this paper, the 20-year-old transformed thermal unit has the best economy, which proves the economic feasibility of the construction of the synchronous condenser transformed from a thermal unit.

(4) Three types of management pricing are obtained in four different operation modes for the cost recovery of synchronous condenser. Through the comparison of management modes, the impact of management modes on reactive power price can give investors a clearer reference and help investors grasp the lowest price of cost recovery under the corresponding mode. Through the comparison of pricing of a synchronous condenser with four operation modes, it is confirmed that SCTTU with a long service life of more than 15 years has a lower reactive power pricing, and better economy and competitiveness.

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