Intelligent Forecasting Method for Substation Operating Cost of Power Network with Nonstationary Characteristics

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Abstract. With the rapid development of the national economy, the power system has been greatly expanded. The operation cost of power grid substation also presents a trend of sharp increase, which brings great challenges to power system. In order to manage and control the operation cost of substation effectively, the intelligent prediction method of power system operation cost with non-stationary characteristics is proposed. Based on the MCSSD method, this paper extracts the non-stationary features of substation operation information, analyzes the economic load rate of substation, determines the substation capacity, constructs the intelligent forecast model of substation operation cost according to the operation law of substation equipment life cycle, and obtains the forecast result of operation cost, and based on this, formulates the intelligent forecast and control measures of substation operation cost. The experimental data shows that after the method should be proposed, the average time for forecasting the operation cost of substation is 11.6, which is lower than the maximum limit, and the highest prediction accuracy is 83%. The results of the two indicators are in line with the standard, which fully confirms that the proposed method has a better forecasting effect of substation operation cost.

Keywords: Non-stationary characteristics · Power grid · Substation · Operating cost · Intelligence · Prediction

1 Introduction

In recent years, with the rapid development of national economy, the state has accelerated the construction of power facilities. By 2020, the State Power Grid will promote the optimal allocation of power resources in a wide range, complete the cross-regional and cross-provincial power transmission capacity of 605.489 billion kilowatt hours, complete the electricity-sharing tasks for 15,300 households and 4937,000 people without electricity, comprehensively narrow the power supply gap between urban and rural areas, and invest 80.74 billion yuan in completing rural network projects. Power enterprises not only actively fulfill their social responsibility, but also pursue the maximization of economic, social environment and comprehensive value under the requirement of promoting

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sustainable development. Therefore, on the basis of ensuring the safety and reliability of power supply, substation projects should consider not only the initial construction cost of the project, but also the operation and maintenance costs, so as to minimize the investment cost [1].

For a long time, the fierce competition situation has been existing in the power grid construction industry, and the high quality and fast completion of tasks has become an important means for all transformer construction enterprises to participate in market competition. Due to the increase of labor costs year by year, it is difficult to improve the construction operation level to a large extent in a short term, so the profit margin of the whole industry is low [2]. Under the current market situation, the substation construction enterprise can only change the management idea and mode, on the one hand, it can adapt to the demand and change of the power grid project construction to enlarge the market share, on the other hand, it must choose the scientific and effective tools and methods of cost forecast and control, and combine with the actual management to apply, so as to enhance the cost leading competitiveness of the enterprise.

Substation is the process of power transmission through transformers. A transformer is a device that uses the principle of electromagnetic induction to change the alternating voltage. The main components are the primary coil, the secondary coil and the iron core (magnetic core). Therefore, the intelligent prediction of substation operation cost mainly aims at transformer. The collected substation information is non-stationary, which brings great difficulty to the forecast of substation operation cost. Therefore, the research on intelligent forecast method of substation operation cost is proposed. Based on the extraction of non-stationary features of substation information, the substation operating cost can be accurately predicted to provide accurate data support for the control of substation operating cost.

2 Research on Intelligent Forecasting Method of Power Grid Substation Operation Cost

2.1 Nonstationary Feature Extraction of Power Grid Substation Information

In order to accurately predict the operation cost of power grid substation, the first task is to extract the non-stationary characteristics of power grid substation information. According to the above requirements, this research based on Multi-scale Chirplet Sparse Signal Decomposition (MCSSD) method extracts the non-stationary features of power grid substation information as follows:

Based on the theory of MCSSD, it can be found that the multi-scale characteristic of LFM base function makes it match the analysis signal dynamically, and solves the problem of single base function in whole analysis time. The frequency slope information contained in the LFM basis function makes it suitable for analyzing the non-stationary signal whose frequency is curvilinear, and preserves the multi-scale property of the wavelet transform. The multi-scale LFM sparse signal decomposition method can decompose a multi-component signal into a number of single-component signals with physical significance. Multi-modal non-stationary signals in substation can be decomposed into single-modal signals according to frequency, so that non-stationary signals can be decoupled in time domain [3]. The signal results decomposed by the MCSSD method are shown in Fig. 1.

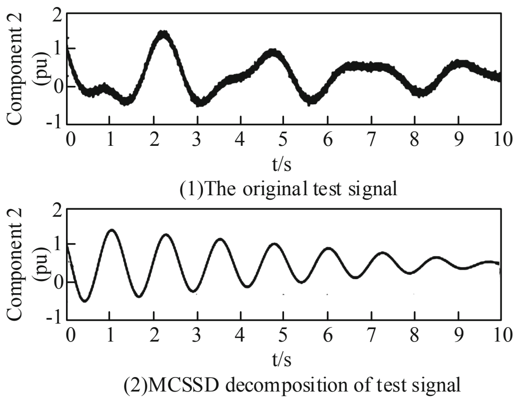

Fig. 1. MCSSD decomposed signal results

In summary, MCSSD is particularly suitable for the decomposition of multimodal coupled nonstationary signals. The power nonstationary signal of power system is essentially a response signal of multimodal time-varying vibration system. Therefore, MCSSD can be used to select single modal vibration component from multimodal nonstationary signals. The single-mode oscillation response can be approximately expressed as a formula (1) by the product of a pure FM signal and an envelope signal.

$$\begin{aligned} x_i(t) &= A_i(t)\cos(\omega_{di}(t)t + \theta_{i0}) \\ &= A_{i0}e^{-\xi_i\omega_i t}\cos\left(2\pi f_i\sqrt{1-\xi_i^2}t + \theta_{i0}\right) \end{aligned} \tag{1}$$

In Formula (1), $A_i(t)$ represents the amplitude envelope of the i substation signal, $A_i(0) = A_{i0}$. $\omega_{di}(t)$ represents the damped modal frequency of the i substation signal. t stands for time. θ_{i0} represents the initial phase of the i substation signal. ξ_i represents the damping ratio of the i substation signal. f_i represents the frequency of the substation signal of the i-th grid.

Take the logarithm of the amplitude envelope of the i substation signal, and get the formula (2).

$$\ln A_i(t) = -\xi_i\omega_i t + \ln A_{i0} \tag{2}$$

The mathematical meaning of the expression (2) is: $\ln A_i(t)$ is a function of time t of the first degree, with a slope of $\xi_i\omega_i$. The $A_i(t)$ and $\omega_{di}(t)$ of the i-decomposed signal can be obtained by MCSSD decomposition. Subsequently, the frequency $f_i(t)$ and the modal damping ratio $\xi_i(t)$ of the i-th decomposed signal are obtained by combining formula (1) and formula (2), respectively, as shown in formula (3).

$$\begin{cases} f_i(t) = \frac{1}{2\pi}\sqrt{\omega_{di}^2(t) + \left(\frac{d \ln A_i(t)}{dt}\right)^2} \\ \xi_i(t) = \frac{\frac{d \ln A_i(t)}{dt}}{\sqrt{\omega_{di}^2(t) + \left(\frac{d \ln A_i(t)}{dt}\right)^2}} \end{cases} \tag{3}$$

It should be pointed out that because of the influence of noise, $\ln A_i(t)$ and time t are not strictly linear relations, $\ln A_i(t)$ approximation is a straight line, can be fitted by the least squares method. Using the relations mentioned above, the oscillation characteristic parameters $f_i(t)$ and $\xi_i(t)$ can be identified and extracted from the component signals derived from MCSSD, which is the non-stationary characteristic of substation signals.

Through the above, the non-stationary characteristics of power system substation signals are extracted, which provides support for the subsequent economic load analysis of substation [4].

2.2 Economic Load Analysis of Substation

The economical load rate of substations is always changing during the whole process from being put into production until it is finally withdrawn from operation, generally showing a law from small to large. The trend of running costs shows a change from large to small and then from small to large. In order to optimize the operation cost of transformer substation, the transformer substation shall operate within a certain load rate range [5]. The study of operation cost is based on reliability, and the relationship between economic load rate and operation cost is shown in Fig. 2.

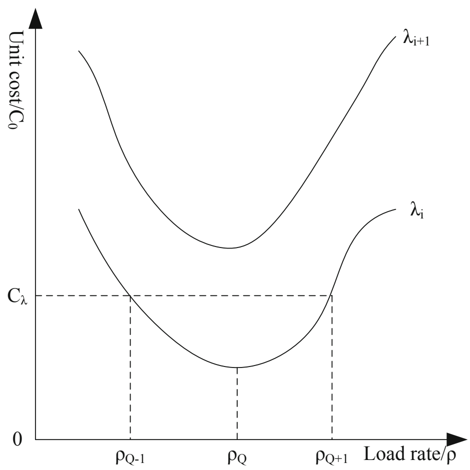

Fig. 2. Relationship curve between economic load rate and operating cost

As shown in Fig. 2, unit cost C_0 increases with the increase of reliability; under certain conditions of reliability λ_i, there exists load rate ρ_Q, making unit cost C_0 lowest and substation operation cost optimal; when load rate from 0 to ρ_Q gradually increases, unit cost C_0 gradually decreases; when load rate exceeds ρ_Q, unit cost C_0 gradually increases with the increase of load rate; within acceptable unit cost C_λ, economic load rate has a certain optimization range, the lower limit of economic load rate can prevent excessive waste of resources, and the upper limit can guarantee the safe and reliable operation of equipment [6].

The formula for calculating the economic load rate of power grid substation shall be:

$$\rho_Q = \sqrt{\frac{P_0 T + k_Q Q_0 T}{P_k \tau_{\max} + k_Q Q_k \tau_{\max}}} \tag{4}$$

In Formula (4), ρ_Q refers to the economical load rate of the power grid substation; P_0 refers to the no-load loss of the main transformer; T refers to the operation cycle; k_Q refers to the economic equivalent of reactive power, wherevers to the coefficient of converting the reactive power loss into active power loss according to the economic cost. In practical calculation, reactive power economic equivalent k_Q can be simply calculated as the ratio of reactive power price to active power price; Q_0 means reactive power no-load loss; P_k means load loss of main transformer; $\tau_{\max}$ means annual loss hours; Q_k means reactive power load loss.

According to the design requirements of the main transformer capacity in the Electrical Design Manual of Power Engineering, the capacity of other transformers should be 70%–80% of the total capacity when one main transformer is out of service. The load rate of the main transformer determined according to the design requirements is called safe operation load rate [7]. In general, for a substation with several transformers of the same capacity, if the load rate of the remaining transformers does not exceed 130% after a main transformer is switched off due to failure, the load rate of each transformer shall be:

$$\rho_a = \rho_k \times N/N - 1 \tag{5}$$

In Formula (5), ρ_a represents the safe operating load rate; ρ_k represents the short-time allowable overload rate; and N represents the number of transformers.

Through the above process, the calculation of the economic load rate of the power grid transformation is completed, and sufficient data support is provided for the subsequent determination of the power transformation capacity.

2.3 Determining Process of Substation Capacity

For the substation operation cost forecast, it mainly aims at the component main transformer. The capacity and the number of main transformers have a significant impact on the grid structure, power supply security and reliability and economy. The selection of the capacity and number of main transformers generally depends on the nature of the load in the planning area, the level of demand for reliability of power supply, the rate of growth, the capacity of the next higher grid or power plant to provide the load and the technical and performance indicators of the distribution devices connected thereto, the cost per unit capacity and the system short-circuit capacity and transport and installation conditions [8].

At present, there is no specific provision on the selection of the number and capacity of transformers in the power grid system in China, which is usually carried out in accordance with the relevant rules and regulations and in combination with the experience of designers. Based on the application of the prediction theory of operating costs, the following circumstances shall be considered:

(1) The capacity of the main transformer is determined according to the nature of the planned load and the grid structure. The planned capacity of newly-built substation transformer should meet the demand of 5–10 years planning load development of power supply area, and avoid unnecessary expansion and capacity increase. In order to avoid the waste of resources when the initial load of a substation is relatively small, the time to put several main transformers into operation may be arranged according to the demand for load growth [9].
(2) Where there are important users in the planned power supply area of a substation, the power supply load of the first and second grade users shall be guaranteed within the allowable time for overload of other transformers under the condition that one main transformer is overhauled or fails. For a substation with normal load, any outage of a transformer shall ensure that 70%–80% of the total load of the power supply is not affected.
(3) The capacity of a single transformer should not be too large or too small, and the space for expansion due to load increase should be reserved. And in order to ensure the power supply mode of operation convenient, should consider the use of multiple transformers.
(4) Although the loss of large capacity main transformer is lower than the cost of unit capacity, but the requirement of matching equipment is also high, it may be difficult to compensate for the increased investment. Therefore, the economic operation mode of the main transformer should be calculated when the transformer capacity is selected, and the operation cost of the main transformer and its supporting devices should be considered. The reasonable design scheme of the main transformer capacity and the number of units is chosen to control the load rate at the economical load rate.
(5) The reasonable design scheme of the main transformer capacity and the number of units is chosen to control the load rate within a certain range of the economic load rate. A lower limit value of economic load rate can prevent excessive waste of resources caused by low load rate of main transformer, and determine the upper limit value to ensure the safe and stable operation of the system.

In this paper, a more economical selection method is proposed based on the reliability of operation and the theory of life cycle cost. The flow chart is shown in Fig. 3.

Use the process shown in Fig. 3 to determine the substation capacity and make intelligent predictions for the subsequent substation operating costs.

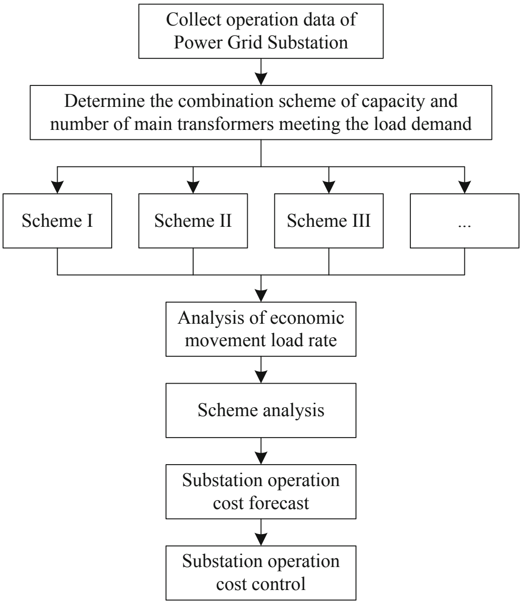

Fig. 3. Flow chart for determination of substation capacity

2.4 Intelligent Prediction of Substation Operating Cost

According to the operation law of the equipment life cycle, the standard operating status and key control points are the focus of the whole process management, according to the life cycle cost theory and the relevant expenses of the substation equipment, an intelligent prediction model of the substation operation cost can be constructed. Which is:

$$LCC = IC + OC + MC + FC + DC \tag{6}$$

In formula (6), LCC represents the total operating cost of the substation equipment during the entire life cycle; IC represents the initial investment cost, which mainly includes equipment purchase costs, installation engineering costs, land acquisition costs, etc.; OC represents Operating costs, mainly including equipment energy costs, status inspection costs and labor costs, etc.; MC represents maintenance and overhaul costs, including daily maintenance costs, planned overhaul costs and personnel training costs, etc.; FC represents failure costs, including power outages Loss costs, troubleshooting costs and penalty costs, etc.; DC shows equipment scrap processing costs, including equipment decommissioning processing costs and equipment residual value.

Among them, operating costs are mainly variable costs of substation engineering projects, which mainly include three aspects, operating costs, overhaul and maintenance costs, and failure costs.

n-year operating costs = annual daily inspection costs + n-year equipment energy costs = annual inspection labor costs + n-year equipment energy costs;

Overhaul and maintenance costs = periodic disassembly and overhaul costs + various types of periodic overhaul and maintenance costs;

Failure cost = Troubleshooting costs + Failure cost.

The above process completes the intelligent prediction of substation operation cost, and provides accurate data support for substation operation cost control.

2.5 Cost Control of Substation Operation

Based on the forecast data of substation operation cost, the paper controls the substation operation cost by earned value method, so as to ensure the normal operation of substation project, minimize the operation cost and increase the competitiveness of substation enterprises.

The steps of substation operation cost control are as follows:

Step 1: Run work structure decomposition

Work structure decomposition is of great importance in project earned value management. Scientific and reasonable work structure decomposition is the basic criterion of operation plan, and also optimizes the allocation of resources to improve the work efficiency. The work breakdown structure decomposes the project level by level according to the scope of the construction project and optimizes it layer by layer [10].

The first floor of the substation operation project consists of six parts: earthwork, foundation works, tower works, wiring works, accessory installation and acceptance. The earth and stone works mainly aim at some basic civil engineering works; the basic works mainly include some basic works, such as digging, digging, pouring, maintenance and backfilling; the tower pole works mainly focus on the tower pole assembly, mainly aim at the tower pole selection, tower pole transportation, tower pole component, lightning protection, grounding device and the selection of relevant equipment; the wire erection works mainly include the selection of conductors and ground wires, the wear of conductors, the construction and placement of hydraulic tubes and the selection and configuration of metal tools; the acceptance link is relatively simple, mainly to check whether the whole project conforms to relevant standards.

Step 2: Operation schedule

In order to better achieve the specific requirements of operating cost control, the operation management department has made the overall planning of the operation schedule according to the requirements of construction period and production efficiency. Considering the natural conditions, social conditions, weather conditions, the working efficiency of the builders and the unpredictable emergencies, it is necessary to refine and decompose the target of the operation in order to ensure the smooth development and implementation of the operation.

Step 3: Analysis of operating cost control process

The cost control of substation operation needs to consider all kinds of factors comprehensively and meticulously. The operating cost and schedule deviation of earned value method are explained in detail and systematically, which has overall control over the operation and implementation situation. Through collecting and sorting out the deviation data in the course of actual operation, we can supervise and manage the construction period, the cost, the quality of the operation and so on according to the specific situation of the operation deviation, and finally find out the basic reasons of the deviation of all parties in the operation, and optimize the scheme of the operation on this basis, so as to achieve the expected final effect of cost control.

In order to achieve the ultimate goal of cost control, the implementation parties of substation operation have made a concrete analysis according to the actual operation situation before the project construction, and made a detailed cost control plan, as well as the corresponding emergency measures and solutions. In the operation cost control plan, the investment arrangement should not only accord with the actual situation of the operation, but also consider the unexpected situation. In the development of operating cost control plan should be refined to the month, or even in some operational links need to be refined to the day, such a cost control plan is more reasonable.

The main methods for monitoring operating cost expenditure and progress include routine monitoring and regular monitoring. Day-To-Day monitoring is the observation and recording of aspects of the day-to-day state of operations. It relates not only to the commencement time, completion time, duration and actual cost expenditure of the operations, but also to the specific allocation of human, material and financial resources. Regular monitoring is mainly in a fixed date for a certain period of time to monitor the state of operation. Regular monitoring is based on routine monitoring but is more systematic and standardized. In the combination of daily monitoring and regular monitoring of statistical data formed on the basis of a greater authority and scientific nature, more in line with the actual situation.

Through the above process, the intelligent prediction and control of the operation cost of the power grid substation is realized, which provides effective support for the stable operation of the substation. It also reduces costs for the overall operation of the power grid, boosts the overall development of the power system, and provides residents with better power supply.

3 Experiment and Result Analysis

3.1 Experiment Preparation Stage

Table 1. Power demand forecast table for planning area

Year	Average growth rate	Maximum load
2015	5%	265 MV
2016	5%	278 MV
2017	6%	290 MV
2018	8%	301 MV
2019	9%	310 MV
2020	8%	338 MV

In order to verify the application performance of the proposed method, the experimental objects are selected and their basic conditions are introduced, as follows:

A 220 kV substation is planned to be constructed, with a safe operation life of 30 years, a base load of 35MW and an annual load growth rate of $\gamma(t)$. The electricity demand forecast for the planning area is shown in Table 1.

The main equipment for power grid transformation is a transformer, as shown in Fig. 4.

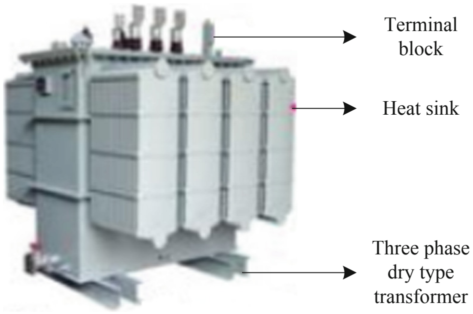

Fig. 4. Transformer schematic

Based on the above-mentioned prepared data and objects, the intelligent prediction experiment of power grid substation operation cost is carried out, and the application effect of the proposed method is shown through the prediction time and accuracy.

3.2 Forecast Time Analysis

Table 2 shows the estimated time of power grid substation operation cost obtained through experiments.

Table 2. Time for forecasting the operation cost of power grid substation

Number of transformers	Forecast time	Maximum limit
10	6.56 s	8.56 s
20	7.04 s	9.12 s
30	9.50 s	10.45 s
40	10.01 s	12.40 s
50	11.45 s	13.52 s
60	12.08 s	14.58 s
70	13.44 s	15.00 s
80	14.03 s	15.95 s
90	15.89 s	16.47 s
100	16.00 s	17.80 s

As shown by the data in Table 2, compared with the maximum prediction time, the prediction time of running cost obtained by the proposed method is lower. The average prediction time of the method in this paper is 11.6 s, which indicates that the proposed method has better real-time prediction.

3.3 Forecast Accuracy Analysis

Based on the experimental environment set up in Sect. 3.1, the prediction accuracy of the method in this paper, the substation cost prediction method based on the improved BP neural network (method 1) and the substation cost prediction method based on the least squares support vector machine (method 2) is compared.. The experimental results are shown in Fig. 5.

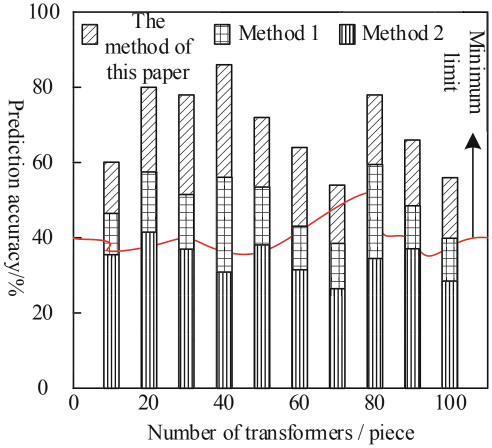

Fig. 5. Prediction accuracy of power grid substation operation cost

As shown in the data in Fig. 5, compared with the minimum limit of prediction accuracy, the prediction accuracy of operating cost obtained by the proposed method is higher, and the highest accuracy is 83%. The prediction accuracy of the method in this paper is higher than the two compared methods, indicating that the proposed method has higher prediction accuracy.

The above-mentioned experimental data shows that after the method should be proposed, the prediction time and prediction accuracy of the power grid substation operation cost are in line with the standard, which fully proves that the proposed method has a better substation operation cost prediction effect.

4 Conclusion

In order to effectively manage and control the cost of substation operation, a research on the intelligent prediction method of substation operation cost of power grid with non-stationary characteristics is proposed. The MCSSD method is used to extract the non-stationary characteristics of the power grid substation information, analyze the substation economic load rate, and determine the substation capacity. According to the relevant expenses of substation equipment, an intelligent prediction model of substation operation cost is constructed, and the prediction result of operation cost is obtained. Based on this, the control measures of substation operation cost are formulated. It is verified by experiments that the proposed method greatly shortens the running cost prediction time, and the average prediction time is 11.6s. At the same time, the method improves the prediction accuracy of operating cost, and the highest prediction accuracy is 82%. It provides more effective support means for substation operation, and also provides some reference and reference for cost forecasting research.

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