A Collaborative optimization approach for grid equipment overhaul/retirement strategy considering system effectiveness and risk

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Abstract. In order to improve the science of grid equipment overhaul and decommissioning decisions, a collaborative optimization method of equipment overhaul/decommissioning strategy considering system effectiveness and risk is proposed. The interaction effect between overhaul and decommissioning is analysed from the perspective of system effectiveness, and 2 attributes of integrated cost input and system reliability improvement are proposed, and then a prospect model with cost/benefit attributes is established based on the prospect theory. Then, with the maximum integrated prospect value as the optimization objective, a collaborative optimization model of overhaul/decommissioning strategy is established with the system risk level as the constraint. Finally, the effectiveness of the proposed method is verified by taking the transformer equipment of an urban area distribution network as an example.

Keywords- Power; grid equipment; maintenance strategy; equipment replacement; system effectiveness; prospect theory.

1. Introduction

Energy structure change has given rise to further deepening of power market reform, energy change and security make asset scale and investment demand increase, at the same time to ensure economic development and livelihood stability, the lack of investment and cost conduction ability under tariff control, double pressure to the grid enterprise asset management brings serious challenges, as an asset-intensive enterprise, how to develop equipment overhaul and decommissioning strategy has become the focus of the industry.

The maintenance of power grid equipment has gone through three stages: post-event maintenance, periodic maintenance and condition maintenance. With the development of condition monitoring technology, power grid enterprises gradually enter the condition overhaul stage, and based on condition detection information, research on overhaul interval, overhaul time and overhaul mode has been carried out [1]. For example, literature [2] established equipment state transfer model based on Markov chain and added maintenance parameters such as inspection rate and maintenance rate to get the impact of various maintenance parameters on failure rate, and then assessed the impact of equipment failure on system reliability index, and then transformed reliability index into outage loss to optimize inspection interval and maintenance strategy with the goal of optimal overall system economy.

The experts and scholars have conducted a lot of research on the decision of grid equipment decommissioning and renewal, and there are roughly three kinds of decision ideas at present. One is the asset equipment state evaluation method, based on the operating parameters of the equipment, reliability parameters and other state quantity comprehensive judgment whether to carry out the decommissioning renewal [3]. Second is the equipment asset whole life cycle cost method, the equipment operation before and in the middle of the failure rate is low, and the initial investment cost is large, the whole life cycle cost decreases year by year, when the operation to the later stage, the equipment performance becomes worse, maintenance cost, operation cost, failure loss cost is increasing, the whole life cycle cost will increase year by year, therefore, the equipment whole life cycle cost curve trend as the basis for judgment, the lowest point of the curve is The best decommissioning time [4][5]. Third, the equipment renewal cost and benefit comparison method compare the costs and investment returns generated by the equipment before and after renewal during its service life, and thus determines the optimal decommissioning renewal plan [6].

In summary, there are 2 problems in the current study when deciding equipment decommissioning: one is to pay attention to the economics of individual equipment and its

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impact on system reliability, ignoring the impact of decommissioning on other performance such as system cost; the second is that overhaul can improve equipment performance and extend service life, and thus the interaction between decommissioning decision and overhaul decision occurs, and the two independent decisions cannot obtain the global optimal solution.

In order to solve the above problems, this paper defines power system effectiveness as the ability to meet the requirements of power supply service and safe and reliable operation under specified conditions, considers the contribution of equipment to system effectiveness, and proposes a collaborative optimization method for equipment overhaul/retirement strategy. Firstly, we extract two types of attributes related to system effectiveness, namely, comprehensive cost input of equipment and system reliability; then, we analyze the influence of equipment overhaul and decommissioning time on each index and introduce the prospect theory to propose a model for calculating the prospect value of cost and reliability attributes under the determination of overhaul and decommissioning time; finally, we integrate the prospect value calculation model of the two types of attributes, take overhaul and decommissioning time as the optimization variables, and take the annual Finally, we integrated the prospect value calculation models of the two types of attributes, took the overhaul and decommissioning time as the optimization variables, took the acceptable risk level of the system as the constraint, and took the maximum integrated prospect value of each attribute as the goal to establish the cooperative optimization model of equipment overhaul/decommissioning strategy.

2. Collaborative optimization model for overhaul/decommissioning strategy considering effectiveness and risk

2.1 Problem Analysis

System effectiveness refers to the ability of the system to meet the given quantitative characteristics and service requirements under the specified conditions, which is expressed in the power system as the ability to meet the requirements of power supply service and safe and reliable operation under the specified conditions. Power equipment is the smallest unit to realize the efficiency of power system. When deciding on equipment replacement and retirement, we should consider how to maximize the system efficiency with minimum cost, instead of making decision only from the economic perspective of a certain equipment.

System efficiency is accomplished by the work of the equipment, and there are differences in the efficiency of the individual equipment. During the period of system performance, equipment undergoes a series of operating conditions from operation, maintenance, failure, overhaul to decommissioning and replacement, and the cost investment and reliability loss caused by different operating conditions are also different. Therefore, this paper selects "comprehensive cost input" and "system power supply reliability" to reflect the influence of equipment operation status on system performance. Among them, "comprehensive cost input" covers five economic indicators, including equipment investment cost, operation and maintenance cost, failure cost, maintenance cost and depreciation loss; "system power supply reliability" is expressed by the indicator of expected energy not supplied (EENS).

2.2 Optimized strategy for power grid improvement plan

The optimization of overhaul/decommissioning strategy considering system performance includes both economic and reliability indicators, and the planner's requirements for economy and system reliability are usually subjective, therefore, the optimization of equipment overhaul/decommissioning strategy considering the planner's subjective preference is more consistent with the original planning intention. In this paper, we introduce the prospect theory and use the prospect value instead of the traditional expected value to build a collaborative optimization model of equipment overhaul/decommissioning strategy based on the prospect theory, with the maximum integrated prospect value in the equipment planning cycle as the optimization objective, and establish the optimization model as shown in the following equation. In which, considering the inconsistency of each attribute's scale, the reliability attribute is converted into an economic index, and the scale of each attribute is unified into "yuan".

$$\max V = \omega_1 V_{\cos t} + \omega_2 V_{rel}$$
$$\text{s.t.} \quad \begin{aligned} & t_0 < t_m < t_r \le T \\ & EENS_t < EENS_{ref} \end{aligned}$$

Where: V is the integrated prospect value of the grid company's decision equipment maintenance and decommissioning strategy; V_{cost} is the prospect value of the integrated cost input of equipment in the planning cycle; V_{rel} is the prospect value of the system power supply reliability improvement in the planning cycle; $\omega_1$and ω_2 denote the importance of the prospect of the two attributes, which are usually given by the decision maker and satisfy$0\le\omega_1$, $\omega_2\le1$, $\omega_1+\omega_2=1$; t_0 is the study is the service age of the equipment at the beginning of the cycle; T is the design life of the equipment as the upper limit constraint of the study cycle; t_{m} is the overhaul time; t_{r} is the decommissioning time; EENS_t is the annual system expected outage power supply; $EENS_{ref}$is the value of the system acceptable expected outage power supply.

The calculation model of each prospect value is as follows.

2.2.1 Equipment comprehensive cost prospect model

The cost input of the equipment in the planning cycle belongs to the expenditure, when the cost is greater than the reference value, the decision maker's heart perceives it as a loss, and when it is less than the reference value, it is perceived as a gain, and the specific expression of the prospect value V_{cost} is.

$$V_{\cos t} = \pi^{+}\left(p_{\cos t}\right)v^{+}\left(E_{\cos t}\right) + \pi^{-}\left(p_{\cos t}\right)v^{-}\left(E_{\cos t}\right)$$

$$\begin{cases} v^{+}\left(E_{\cos t}\right) = \left(E_{\cos t.0} - E_{\cos t}\right)^{\alpha}, E_{\cos t} \le E_{\cos t.0} \\ v^{-}\left(E_{\cos t}\right) = -\lambda\left(E_{\cos t} - E_{\cos t.0}\right)^{\beta}, E_{\cos t} > E_{\cos t.0} \end{cases} \begin{cases} \pi^{+}\left(p_{\cos t}\right) = p_{\cos t}{}^{\gamma} \Big/ \left[p_{post}{}^{\gamma} + \left(1-p_{\cos t}\right)^{\gamma}\right]^{1/\gamma} \\ \pi^{-}\left(p_{\cos t}\right) = p_{\cos t}{}^{\delta} \Big/ \left[p_{\cos t}{}^{\delta} + \left(1-p_{\cos t}\right)^{\delta}\right]^{1/\delta} \end{cases}$$

Where: V_{cost} is the prospective value of the comprehensive cost of equipment; $\pi^{+}(p_{cost})$ and π^{-} (p_{cost}) denote the weight functions of the decision maker's perception of equipment cost input as gain and loss, respectively; $v^{+}(E_{cost})$and v^{-} (E_{cost}) denote the value functions of the decision maker's perception of cost input as gain and loss, respectively; E_{cost} is the comprehensive cost of equipment in the planning cycle, expressed as equal annual cost; E_{cost}.0 is the decision maker's expectation of cost; α and β denote the risk appetite and risk aversion coefficient, respectively; λ is the loss aversion coefficient. cost is the integrated cost input of the equipment in the planning cycle, expressed as equal annual value cost; $E_{\text{cost.0}}$ is the decision maker's expectation of cost; α and β denote the risk preference and risk avoidance coefficient respectively, generally $0<\alpha,\beta<1$; λ is the loss avoidance coefficient, generally $\lambda>1$; γ and δ denote the decision maker's risk attitude when facing "gain" and "loss" respectively. γ and δ denote the risk attitude coefficients of decision makers when facing "gain" and "loss" respectively, and the two coefficients indicate the degree of gain preference and risk aversion of decision makers.

The overhaul and decommissioning behaviours divide the planning cycle into three stages: before overhaul, after overhaul and after decommissioning and replacement. Considering the time value of money, the cost input of the equipment in the planning period is converted into equal annual value cost, and at year T the final value of the total cost of the equipment is:

$$C_{all}\left(T\right) = C_{CI} + C_{CO} + C_{CF} + C_{CM} + C_{MV}$$

Conversion of final value of cost to equivalent annual value cost:

$$E_{\cos t} = C_{all}\frac{i}{(1+i)^{T}-1}$$

The specific expressions for each cost are as follows.

(1) Initial investment C_{CI}

$$C_{CI} = C_{CI}^{new}(1+i)^{T-t_r}$$

Where: C_{CI}^{new} is the investment cost of new equipment to be replaced after the old equipment is retired to still ensure the power supply capacity of the system; i is the discount rate; $(\mathrm{T}-t_r)$ is the operating life of the new equipment in the planning cycle.

(2) Operation and maintenance costs C_{CO}

$$C_{CO} = \sum_{t=t_0}^{t_m} C_{CO}^{old1}(1+i)^{T-t} + \sum_{t=t_m+1}^{t_r} C_{CO}^{old2}(1+i)^{T-t} + \sum_{t=t_r+1}^{T} C_{CO}^{new}(1+i)^{T-t}$$

Where: p_0 is the no-load loss of transformer per hour in kW/h; P_E is the electricity price in Yuan/(kW-h); N_k is the total number of load levels; α_k is the proportion of transformer's kth load level in one year time; $p_{f,k}$ is the load loss of transformer per hour in kW/h under the corresponding kth load level; γ_t is the percentage coefficient of transformer's annual maintenance cost to its initial investment cost before overhaul, and the size of its value is related to the failure rate.

(3) Failure cost C_{CF}

$$C_{CF} = \sum_{t=t_0}^{t_m} \mathrm{F}\left(t\right)C_1(1+i)^{T-t} + \sum_{t=t_m+1}^{t_r} \mathrm{F}'\left(t\right)C_1(1+i)^{T-t} + \sum_{t=1}^{T-t_r} \mathrm{F}''\left(t\right)C_2(1+i)^{T-t}$$

Where: C_{CF} is the cost of repairing equipment after a failure incident in the planning cycle, which is related to equipment reliability. $\mathrm{F}(t)$ is the cumulative probability of life of old equipment before overhaul; $\mathrm{F}'(t)$ is the cumulative probability of life of old equipment after overhaul; $\mathrm{F}''(t)$ is the cumulative probability of life of new equipment; C_1 is the failure repair cost of old equipment; C_2 is the failure repair cost of new equipment.

(4) overhaul cost C_{CM}

The cost of overhauling equipment during the planning cycle depends on whether or not overhaul actions occur.

$$C_{CM} = \omega_t C_m\left(1+i\right)^{T-t_m}$$

Where: ω_t indicates whether the equipment is serviced at moment *t*. If serviced, $\omega_t = 1$; otherwise, $\omega_t = 0$; C_m is the cost required to service a single piece of equipment.

(5) depreciation loss C_{MV}

Depreciation loss during the planning cycle is the depreciable cost of old equipment lost, obtained by subtracting the accumulated depreciation expense from the initial investment, and is related to the decommissioning time t_r.

$$C_{MV} = \left[C_{IN}^{old} - \sum_{i=1}^{t_r} C_i\right]\left(1+i\right)^{T-t_r}$$

Where: $\sum_{i=1}^{t_r} C_i$is the accumulated depreciation cost of the old equipment from year 1 to the time of decommissioning.

2.2.2 System power supply reliability outlook model

When the equipment is overhauled or replaced with new equipment, the failure rate is significantly reduced, which can effectively improve the system reliability. The system power supply reliability property is expressed as certainty, and the value $v(E_{rel})$ of improving power supply reliability is the prospective value V_{rel} of improving system reliability, and the specific expression is:

$$V_{rel} = \pi^{+}\left(p_{rel}\right)v^{+}\left(E_{rel}\right) + \pi^{-}\left(p_{rel}\right)v^{-}\left(E_{rel}\right)$$

$$\begin{cases} v^{+}\left(E_{rel}\right) = \left(E_{rel} - E_{rel.0}\right)^{\alpha}, E_{rel} \ge E_{rel.0} \\ v^{-}\left(E_{rel}\right) = -\lambda\left(E_{rel.0} - E_{rel}\right)E_{rel}{}^{\beta}, E_{rel} < E_{rel.0} \end{cases} \begin{cases} \pi^{+}\left(p_{rel}\right) = p_{rel}{}^{\gamma} \Big/ \left[p_{rel}{}^{\gamma} + \left(1-p_{rel}\right)^{\gamma}\right]^{1/\gamma} \\ \pi^{-}\left(p_{rel}\right) = p_{rel}{}^{\delta} \Big/ \left[p_{rel}{}^{\delta} + \left(1-p_{rel}\right)^{\delta}\right]^{1/\delta} \end{cases}$$

In this paper, the expected outage power supply EENS is selected as the system reliability assessment index, and the analytical method is used to calculate.

$$E_{rel}\left(t_m, t_r\right) = \sum_{t=t_m}^{t_r} \Delta EENS_m \cdot \left(f_{sell} + f_{comp} \cdot R_{IEA}\right) + \sum_{t=t_r}^{T} \Delta EENS_r \cdot \left(f_{sell} + f_{comp} \cdot R_{IEA}\right)$$

Where: $\Delta EENS_m$ is the difference of system EENS before and after overhaul; $\Delta EENS_r$ is the difference of system EENS before and after decommissioning and replacement; f_{sell} is the average price per unit of electricity sold on the grid; f_{comp} is the electricity production ratio per unit of power shortage; R_{IEA} is the customer evaluation coefficient.

3. Case Analysis

In this paper, the proposed model is verified by using a 110 kV transformer in a class A regional distribution network of a city as an example. The transformer model to be optimized is SFSZ11-31500/110. The current actual life is 10 years, and the expected life is assumed to be 20 years, i.e., the equipment life optimization space is 10 years, and the relevant parameters are shown in Tables 1 and 2. The method proposed in this paper is used to make a synergistic optimized configuration of the transformer's overhaul time and decommissioning replacement time.

Table 1. Equipment parameters of transformer.

Transformers	SFSZ11-31500/110	SS11-31500/110
Equipment capacity (kVA)	31500	31500
Design life (year)	20	20
No-load loss (kW)	32.2	29.4
Load loss (kW)	149.2	149.2
No-load current (%)	0.39	0.36

Table 2. Economic related parameters.

Economic parameters	Values and units
Old transformer purchase cost	250 (million)
New transformer purchase cost	300 (million)
Unit loss of electricity costs	54.828 (yuan/kW)
Integrated tariff	0.8 (yuan/kWh)
Social discount rate	8%
Residual value rate	5%

The relevant parameters in the prospect theory model are "α=0.88", "β=0.88", "λ=2.25", "γ=0.61", "δ=0.69". Let each attribute be equally important "$\omega_1=\omega_2=0.5$", and set the reference points of comprehensive cost expenditure and benefit of improving system reliability to 900,000 yuan and 35,000 yuan, respectively. In the optimization constraint, the system risk level constraint $EENS_{ref}$ is set to 40 MW.

Based on the above parameters to carry out simulation calculations, when using genetic algorithm to solve, the maximum number of iterations is taken as 100, and 60 iterations can be converged, and the results of collaborative optimization of overhaul/retirement strategy, cost/benefit and total benefit of each attribute, prospect value, and comprehensive prospect value are shown in Table 3.

Table 3. Optimized configuration results.

Co-optimization results	Overhaul time t_m	Retirement time t_r
	11	17
Property cost/benefit	Comprehensive cost of equipment E_{cost} (million)	Reliability enhancement gain E_{rel} (million)
	300.098	126.843
Property foreground values	Comprehensive cost of equipment V_{cost} (10^4)	Reliability enhancement gain V_{rel} (10^4)
	7.5203	5.4327
Integrated prospect V (10^4)	6.4765	

From the above table, the result of the synergistic optimization of the overhaul/decommissioning strategy is that the overhaul time tm=11 and the decommissioning time tr=17, with a combined cost value of $3,000,098,000. The reliability improvement benefit is $1,268,430,000. Since the cost input is an expense, when the comprehensive cost of the equipment is less than the reference point, the decision maker's psychological perception is "gain", and the prospect value of the corresponding attribute is positive; the reliability gain is greater than the reference point, so the prospect value of the corresponding gain attribute is positive.

4. Conclusion

In this paper, we propose a collaborative optimization method of grid equipment overhaul/retirement strategy considering system efficiency and risk to address the problem that grid equipment overhaul and retired can only be decided independently of each other. After analysis and validation, the results show that the co-optimization of equipment maintenance/decommissioning strategy considering system efficiency can ensure the optimal system economy and reliability at the same time.

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