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An Optimization Method for Reducing Losses in Distribution Networks Based on Tabu Search Algorithm

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Abstract: With the continuous growth of power demand and the diversification of power consumption structure, the loss of distribution network has gradually become the focus of attention. Given the problems of single loss reduction measure, lack of economy, and practicality in existing research, this paper proposes an optimization method of distribution network loss reduction based on tabu search algorithm and optimizes the combination and parameter configuration of loss reduction measure. The optimization model is developed with the goal of maximizing comprehensive benefits, incorporating both economic and environmental factors, and accounting for investment costs, including the loss of power reduction. Additionally, the model ensures that constraint conditions such as power flow equations, voltage deviations, and line transmission capacities are satisfied. The solution is obtained through a tabu search algorithm, which is well-suited for solving nonlinear problems with multiple constraints. Combined with the example of 10kV25 node construction, the simulation results show that the method can significantly reduce the network loss on the basis of ensuring the economy and environmental protection of the system, which provides a theoretical basis for distribution network planning.

Keywords: Distribution network; Loss reduction measures; Economy; Optimization model; Tabu search algorithm

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1. Introduction

Under the background of the continuous growth of electricity consumption in the whole society, the proportion of tertiary industry and residential electricity consumption in the electricity consumption structure is increasing, and the influence of distribution network in the power system is also increasing. According to statistics, the power loss caused by 10kV distribution network accounts for about 50% of the power loss of the entire system [1]. And with the development of smart grid, the addition of distributed power sources also makes the loss distribution of distribution network more complicated. Research on the loss reduction of distribution network can produce good economic and environmental benefits.

At present, distribution network loss reduction studies tend to select loss reduction measures by studying the loss reduction effect of a single measure in the distribution network, ignoring the loss change distribution law and interaction of different loss reduction measures in the network, and have not considered other better measures that may indirectly affect the heavy loss area. The existing research shows that the use of energy-saving wires can reduce the resistance value of the line, to reduce the power loss of the transmission line. At the same time, combined with the analysis of different regions, the application of energy-saving wires has significant economic and social benefits [2]. The particle swarm clustering algorithm with adaptive inertia weight can cluster similar load curve users and classify them for phase optimization adjustment, which can significantly reduce the unbalance of three-phase load and effectively reduce the line loss [3].

One of the important tasks of power enterprise operation is to ensure economy and the rational use of loss reduction measures can improve the economy of power system operation. However, the existing research on loss reduction often fails to comprehensively consider the economic benefits generated by the combination of economic and practical operation of each loss reduction measure. The existing research comprehensively considers the economic operation of the distribution network and the loss reduction measures of the distribution network. By analyzing the economic operation conditions of distribution transformers, the key factors affecting the economic operation of distribution transformers are identified and a reasonable distribution transformer is selected to reduce the loss [4]. According to the loss reduction scheme set formed by different loss reduction measures, the optimal decision model is constructed, which takes into account the comprehensive planning cost and the economic benefit of the lost power, and the optimization algorithm is used to determine the combination scheme of loss reduction measures with the best comprehensive benefit [5]. Existing research is based on the power grid energy efficiency index corresponding to the proposed loss reduction measures. It uses the sum of the total input of loss reduction measures and the loss cost resulting from electricity loss as the objective function. In addition, the research takes into account various constraints, such as voltage deviation, branch transmission capacity, the number of measures, and the total input capital. Finally, through the enumeration method in the optimization algorithm, the measure combination scheme with the best overall benefit is obtained [6].

Optimization algorithm is a way to solve the problem of optimal combination of measures. The combination optimization of loss reduction measures for distribution network can be reduced to discrete and nonlinear programming problems. The available comprehensive optimization algorithms include genetic algorithm, particle swarm algorithm, tabu search algorithm and so on [7]. In the existing research, tabu search algorithm is used in reactive power optimization of power system, and the feasibility and effectiveness of this algorithm are verified by practical cases [8]. At the same time, genetic algorithm is applied to the power supply planning of distribution network and the reactive power reduction optimization of distribution network [9]. In the distribution network model with distributed power access, the optimization model of loss reduction based on genetic algorithm is constructed to solve the line loss of distribution network, and the corresponding loss reduction measures are given [10].

This paper analyzes the comprehensive benefits of different combinations of loss reduction measures, taking into account the construction cost of each measure and the economic benefits of loss reduction. It establishes an optimization model for distribution network loss reduction, with the ultimate goal of maximizing the comprehensive benefits of loss reduction. The model is solved using the tabu search algorithm. Through the combination and parameter optimization of different measures, The comprehensive loss reduction scheme of distribution network with the best economic benefits is obtained.

2. Establishment of distribution network loss reduction optimization model

Distribution network planning for loss reduction is a multi-objective optimization problem. The decision optimization model should fully consider the comprehensive benefits brought by the implementation of each loss reduction measure to the current distribution network. On this basis, the optimal optimization objective function of comprehensive benefits and the distribution network loss reduction optimization model under different constraints are established. The combined optimization model is as follows:

$$
\begin{aligned}
L_1 \quad & \min F(\lambda,\xi) \\
s.t. \quad & G(\lambda,\xi) \le 0 \\
& H(\lambda,\xi) = 0
\end{aligned}
\tag{1}
$$

In the formula, (1) F- optimization model objective function; (2) G- inequality constraint and; (3) H- equality constraint.

2.1. Optimize the model objective function

Under the current development goal of a low-carbon society, the construction costs, economic benefits of power saving, and environmental benefits of various measures at different transformation levels should be comprehensively considered. In the distribution network loss reduction optimization model, the objective function includes the acquisition costs and other construction costs related to equipment installation and replacement. The comprehensive benefits of distribution network loss reduction mainly account for the direct power benefits generated by reducing electricity loss, as well as the indirect low-carbon environmental benefits resulting from the reduced electricity loss [11]. Therefore, it is proposed that the objective function of distribution network planning loss reduction model is:

$$max\, F = F_1 + F_2 - (F_T + F_L + F_C) \tag{2}$$

In the formula, F_1– the economic benefits directly generated by reducing the loss of electricity, 10,000 yuan/year; F_2– The low carbon environmental benefit indirectly generated by the reduction of power loss, 10,000 yuan/year; F_T – Comprehensive investment cost of replacing different types of transformers, 10,000 yuan/year; F_L – The comprehensive investment cost of replacing different models of distribution lines, 10,000 yuan/year; F_C – ifferent capacity reactive power compensation device comprehensive investment cost, 10,000 yuan/year.

In the objective function of the distribution network optimization model, the calculation methods of different benefits and costs are as follows:

The economic benefits directly generated by reducing the loss of power. F_1 can be obtained by reducing the loss of power multiplied by the corresponding electricity price:

$$F_1 = \left(\sum_{n=1}^{n_{all}} \Delta A_{Tn} + \sum_{m=1}^{m_{all}} \Delta A_{Lm}\right)\sigma \times 10^{-4} \tag{3}$$

In the formula, the power loss reduced by the ΔA_{Tn} , ΔA_{Ln} – n transformer and the m line in one year, kWh; n_{all}, m_{all} –The number of transformers and lines in the distribution network; σ– Local electricity price, yuan.

The low-carbon environmental benefits indirectly generated by the reduction of power loss F_2 can be calculated according to the price per ton of carbon dioxide emission rights in the current carbon trading market and the carbon dioxide emissions reduced by the reduction of power loss:

$$F_2 = \left(\sum_{n=1}^{n_{all}} \Delta A_{Tn} + \sum_{m=1}^{m_{all}} \Delta A_{Lm}\right) \times \beta \times \frac{\rho}{1000} \times 10^{-4} \tag{4}$$

In the formula, β– carbon dioxide emissions reduced by saving per unit of electricity, kg;

ρ– carbon trading market price per ton of carbon dioxide emission rights, yuan.

Annual comprehensive investment cost of reactive power compensation device F_C, according to the distribution network planning to reduce the input of compensation device capacity, unit capacity cost, other installation and construction investment and economic service life:

$$F_C = \frac{1}{N_C}(f_{C1} \cdot Q_C + f_{C2}) \tag{5}$$

From this equation, f_{C1} – reactive power compensation device unit capacity cost, ten thousand yuan; Q_C – Reactive power compensation capacity, kVar; f_{C2} –Other construction expenses of reactive power compensation device, ten thousand yuan; N_C – Economic service life of the reactive power compensation device: years.

The annual comprehensive investment cost of distribution line replacement F_L, according to the acquisition cost required to replace the large diameter distribution line, other construction costs and the economic service life of the line:

$$F_L = \frac{1}{N_L}(f_{L1} + f_{L2})L \tag{6}$$

Based on Equation 6, f_{L1} – Purchase cost per unit length of different types of distribution lines, ten thousand yuan; f_{L2} – Other construction costs per unit length of distribution line, ten thousand yuan; L – Distribution line replacement length, km; N_L – Distribution line economic service life, years.

Distribution transformer replacement annual comprehensive investment cost, F_T, according to the replacement of new energy-saving transformer equipment acquisition cost, other construction costs and economic service life:

$$F_T = \frac{1}{N_T}(f_{T1} + f_{T2}) \tag{7}$$

Based on Equation 7, f_{T1} – different types of transformer acquisition cost, ten thousand yuan; f_{T2} – Distribution transformer other construction costs, ten thousand yuan; N_T – Distribution transformer economic applicable life, years.

2.2. Optimization model constraints

In the distribution network loss reduction optimization model, the establishment of constraint conditions mainly includes the following parts:

(1) Power flow equation constraints

$$\begin{cases} P_i = P_{Li} + U_i \sum_j^N U_j (G_{ij} \cos\delta_{ij} + B_{ij} \sin\delta_{ij}) \\ Q_i = Q_{Li} + U_i \sum_j^N U_j (G_{ij} \sin\delta_{ij} - B_{ij} \cos\delta_{ij}) \end{cases} \tag{8}$$

From this equation, node P_i,Q_i – i input active power, reactive power, kW, kVar; U_i,U_j –The voltage amplitude of nodes i and j, kV; P_{Li},Q_{Li} – Active and reactive power absorbed by node i load, kW, kVar; G_{ij},B_{ij},δ_{ij},–Conductance, susceptance, and voltage phase Angle difference of branches between nodes i and j.

(2) Constraint of voltage deviation

In the current power system, the voltage deviation requirement for the 10kV distribution network is $-10\% \leq \Delta U\% \leq +5\%$, and the voltage deviation requirement for the 0.4kV distribution network is $|\Delta U\%| \leq +7\%$, where the voltage deviation calculation formula is:

$$\Delta U\% = \frac{U_i - U_N}{U_N} \times 100\% \tag{9}$$

In the formula, U_i, U_N node operating voltage and rated voltage value, kV.

(3) Line transmission capacity constraints

The actual transmission capacity of the line should not exceed its maximum allowed transmission capacity, transmission capacity is generally expressed by the transmission current:

$$I_j \leq I_{j.max} \tag{10}$$

In the formula, I_j, $I_{j,max}$ The actual current flowing through the branch and the maximum current allowed through, A.

3. Solution of distribution network loss reduction optimization model

3.1. Distribution network loss reduction optimization model solving algorithm

For the solution of distribution network optimization model, its process can be regarded as a combinatorial optimization problem. The methods commonly used to solve combinatorial optimization problems in current research include: genetic algorithm, particle swarm optimization, enumeration, and tabu search algorithm [12–13]. Tabu Search algorithm (Tabu Search) is a kind of optimization algorithm based on the global scope proposed by scholar F. Lover in the 1970s. The basic idea of the algorithm is to search for the extended neighborhood and constantly marking the local optimal solution found in the search process to avoid the problem of roundabout search at the local extreme value and obtain the global optimal solution through continuous optimization [14]. The algorithm is suitable for nonlinear, multi-constraint, and discrete multi-variable global optimization problems, mainly composed of the following seven parameters: tabu object, tabu length, contempt criterion, neighborhood function, evaluation function, memory frequency information, and termination criterion.

3.2. Solution steps of distribution network loss reduction optimization model

The tabu search algorithm is used to solve the optimization model and realize the combination and parameter optimization of the distribution network planning loss reduction scheme. The implementation steps are as follows:

(1) Read the distribution network line information, load data, distribution transformer information and other network parameters, operation data parameters and equations, inequality constraint parameters;

(2) According to the preliminary collection of loss reduction measures, generate a combined loss reduction scheme set of different loss reduction measures, and establish a neighborhood structure;

(3) According to the set of combined loss reduction schemes, input algorithm parameters, place tabu table $TL = \varnothing$, calculate the objective function of the initial scheme, and take the scheme $X^{best} = X^0$ as the current optimal scheme;

(4) Generate a neighborhood scheme according to the changes of parameters in the neighborhood structure, pay attention to only considering the change of a single parameter when the parameters change, and do

not take the scheme in the tabu table as the neighborhood scheme;

(5) To judge whether the constraint conditions in each neighborhood scheme are satisfied, subtract the penalty function of maximum value from the objective function of the neighborhood scheme that does not meet the constraint conditions;

(6) Calculate the objective function value of the neighboring scheme and compare it with the current optimal solution. If it is better than the current optimal solution, take the neighboring scheme as the current optimal scheme $X^{best}=X^0$;

(7) Determine whether the termination conditions are met. If the termination requirements are met, output the current optimal scheme as the distribution network loss reduction measures optimization specific implementation scheme; if not, add one iteration number and return to step (4) to continue the iterative calculation.

4. Analysis of numerical examples

In this paper, the 25-node radial distribution network of 10kV as shown in **Figure 1** is used as an example, and four loss reduction measures including 23-node reactive power compensation, L-1 trunk line replacement wire model, 12-node reactive power compensation, and 23-node replacement distribution transformer are selected to form the primary measure set of the comprehensive loss reduction scheme of the distribution network. In the combination optimization of loss reduction measures, there are 15 kinds of combination measure loss reduction schemes randomly generated in the set of primary measures. The specific selection of measures for each scheme is shown in **Table 1**.

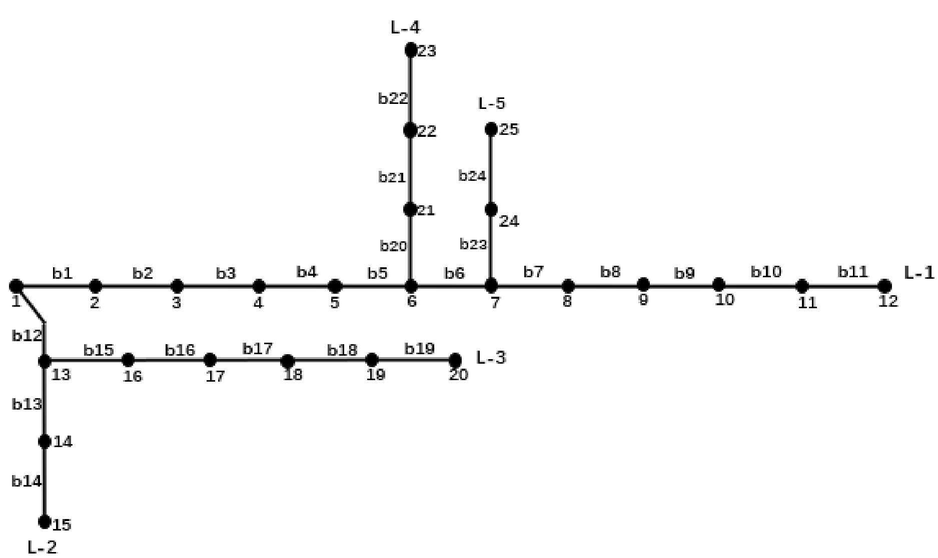

Figure 1. 25-node rural distribution network model

Table 1. Loss reduction measures portfolio options

Loss reduction measures portfolio options	Loss mitigation measures			
	23-node reactive power compensation	L-1 trunk replacement wire model	12-node reactive power compensation	23-node replacement of distribution transformer
Option 1	√			
Option 2		√		
Option 3			√	
Option 4				√
Scheme 5	√	√		
Option 6	√		√	
Scheme 7	√			√
Scheme 8		√	√	
Scheme 9		√		√
Option 10			√	√
Option 11	√	√	√	
Scheme 12	√	√		√
Scheme 13	√		√	√
Scheme 14		√	√	√
Scheme 15	√	√	√	√

In the parameter optimization of loss reduction measures, there are mainly the following options:

(1) In view of the replacement of the main line L-1 wire model loss reduction plan, considering the requirements of future distribution network development transmission capacity, LGJ-150 model is no longer selected on the basis of the original LGJ-120 wire of the branch road, and directly choose to replace the model LGJ-185 or LGJ-240 transmission wire to ensure the future load change requirements;

(2) For 12 nodes, 23 nodes to install reactive power compensation device loss reduction program, the study found that the higher the compensation power factor is not the higher the benefit, in order to make the best comprehensive benefit usually control the power factor of the distribution network at about 0.95, while the current distribution network reactive power compensation usually requires a power factor greater than 0.9 [16]. Therefore, when reactive power compensation is selected, the load power factor reaches 0.9 or 0.95 compensation capacity;

(3) For the replacement of 23-load node distribution transformer loss reduction scheme, on the basis of the original selection to replace the current more used S11 or S13 energy-saving new transformer parameters optimization.

In consideration of parameter optimization, there are hundreds of comprehensive loss reduction schemes for the distribution network, and manual sorting with fewer schemes will produce a large amount of calculation. It is necessary to combine the parameter cost of each measure and use tabu search algorithm to optimize the combined parameter calculation. The optimization price of each measure parameter is shown in **Table 2**.

Table 2. Cost optimization of loss reduction measures parameters

Measures	Voltage rating (kV)	Replacement parameters	Engineering comprehensive cost	Units	Other construction expenses	Units
Replacement of transmission wires	10	LGJ-185	1.700	RMB /km	1	Million yuan /km
		LGJ-240	2.400			
Replacement distribution transformer	10	S11-630	5.570	RMB/set	0.3	Ten thousand yuan/set
		S13-630	7.039			
Reactive power compensation mounting	0.38	-	0.011	RMB /kVar	0.94	Yuan/place

In the objective function calculation of the optimization model, a power purchase price of 0.7 yuan/kWh is used, while the transmission line and distribution transformer costs are based on an economic service life of 15 years. Additionally, the costs of the installed reactive power compensation device are calculated based on an economic service life of 10 years, considering the comprehensive costs of various measures and other construction expenses. The tabu search algorithm is used to obtain the annual economic benefits generated by different combination of measures and parameter optimization in different loss reduction schemes. The tabu step size is 4, and no change in the optimal objective function in 10 iterations is taken as the termination criterion. The specific measures for the top three comprehensive economic benefits in the optimization model are shown in **Table 3**.

Table 3. Optimization results of distribution network loss reduction scheme model

Scheme No.	Specific measures and parameter optimization results	Annual comprehensive benefit / 10,000 yuan
1	23-node reactive power compensation to cos = 0.95, 12-node reactive power compensation to cos = 0.95, 23-node load distribution transformer replaced to S13-630.	3.311
2	23-node reactive power compensation to cos = 0.95, 12-node reactive power compensation to cos = 0.95, 23-node load distribution transformer replaced to S11-630.	3.196
3	23-node reactive power compensation to cos = 0.95, 12-node reactive compensation to cos = 0.95.	3.167

According to the results obtained by the optimization algorithm, the specific loss reduction scheme and optimization parameters for the loss reduction planning of the distribution network are obtained. From the analysis in **Table 3**, it can be found that the more loss reduction measures taken, the better comprehensive benefits will not be produced. When the power supply department carries out practical application, the possibility of implementing measures should be considered comprehensively in combination with economic benefits.

5. Conclusion

This paper starts with the combination and parameter optimization of loss reduction measures in distribution network, establishes an objective function combining the comprehensive cost and the comprehensive benefit of the implementation of each loss reduction measure in distribution network, and optimizes the combination and parameter optimization of the measures concentrated on primary measures through optimization algorithm under certain constraints. Considering that there are many comprehensive measures schemes, tabu search algorithm is used to solve the optimization model. The combination of loss reduction measures and parameter scheme with the best comprehensive benefits are obtained. The following conclusions can be drawn through the analysis of numerical examples:

(1) Under the comprehensive consideration of various operating constraints, the optimized scheme can significantly reduce network loss and improve the economy and environmental protection of the system.

(2) Tabu search algorithm can effectively avoid the defect that the traditional optimization algorithm is easy to fall into the local optimal, and shows a good global optimization ability in the loss reduction optimization of distribution network.

Disclosure statement

The authors declare no conflict of interest.

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