The Two-layer Optimization Model Design of "Source-Network-Charge-Storage" Coordination for a New Power System Considering Integrated Cost

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Abstract. The widespread adoption of renewable energy plays a crucial role in achieving the Sustainable Development Goals of a low carbon power system. To effectively manage and control the distribution network system and promote integrated coordination, a two-layer optimization model is proposed. This model is based on the coordination of "source-network-charge-storage" within the framework of the new power system. With the lowest annual integrated cost as the upper optimization objective and the optimal load variation as the lower optimization objective, quantum genetic algorithm was used to conduct simulation analysis, and the results showed that the model proposed in this paper could not only save the integrated cost of active distribution network, but also improve the proportion of new energy consumption and improve the comprehensive benefits of distribution network system.

Keywords. "Source-net-Load-Storage" collaboration; Two-layer optimization model; Quantum genetic algorithm

1. Introduction

At present, the global consensus is focused on the efficient development and utilization of renewable energy. However, the unpredictable and fluctuating power output from renewable sources poses new challenges for the secure and stable operation of power systems, particularly when integrated into large-scale grids. Furthermore, the ongoing reforms in national transmission and distribution pricing, heightened scrutiny over state-owned assets and enterprises, comprehensive planning and management of power grid companies, and limited investment capacity have necessitated strict cost control measures. To ensure the efficient operation of the power system, the integration of source, network, load and storage emerged at the historic moment. As one of the system, the research on the coordinated optimal scheduling of new power system is of great significance.

ICIDC 2023, June 02-04, Nanchang, People's Republic of China

DOI 10.4108/eai.2-6-2023.2334665

The emergence of smart grid makes it possible to coordinate the interaction of "source-net-charge-storage". Chen Z.X. et al. (2023) proposed a comprehensive planning and analysis method for multi-energy complementary collaborative development based on the Global Clean Energy Resource Evaluation Platform and production simulation. [1] Pu T.J. et al. (2015) conducted a detailed analysis on the construction and application of urban energy Internet based on energy supply, consumption, transport carrier and multi-power cooperative optimization. [2] Based on the energy Internet theory, a large number of scholars have studied the coordinated optimization of "source-network-charge-storage" in power system. Zhao Z. et al. (2022) proposed the "source-net-charge-storage" multi-energy complementary system architecture of regional energy internet. [3] TIAN H. et al. (2021) studied the relationship between the mapping elastic potential energy power angle security index and the path load balance through the trend theory. [4] Yang X.Y. et al. (2020) proposed an integrated source-storage-network planning method considering flexible supply-demand balance. [5]

Based on the above research and the optimization objective of the comprehensive coordinated operation of "source-network-charge-storage" in the active distribution network system, the optimization model of the coordinated operation of "source-network-charge-storage" is proposed. The results of optimization examples show that the model and method in this paper can provide corresponding optimization suggestions for the system regulation of distribution network, power trading decision-making and other behaviors, which has positive significance for improving the consumption level of renewable energy and system operation efficiency.

2. A two-layer optimization model of "source-network-charge-storage" collaboration

In the collaborative optimization problem of "source-network-charge-storage", not only integrated cost and stability, but also reliability should be considered. Therefore, a two-layer model of "source-network-charge-storage" collaborative optimal scheduling is established to optimize the load characteristic curve as far as possible, so as to optimize the overall economic benefits and reliability of the system. The two-layer optimization model of "source-network-charge-storage" coordination is shown in Figure 1.

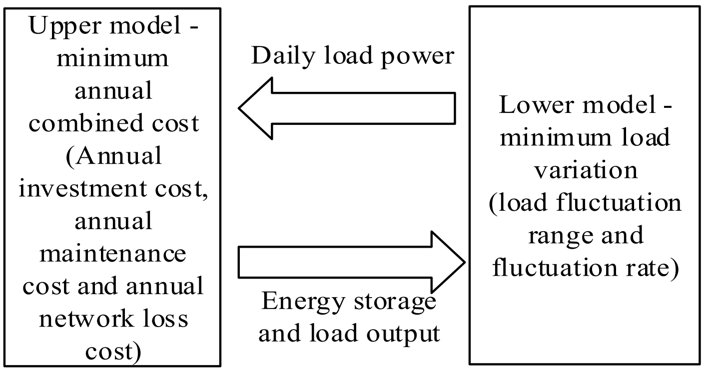

Figure 1. A two-layer optimization model of "source-network-charge-storage" collaboration

2.1 The objective function

2.1.1 Upper model.

The upper model aims for the lowest annual integrated cost, the objective function is shown in Equation (1).

$$\min f = C_{inv} + C_m + C_{loss} \tag{1}$$

Where: annual investment cost is denoted by C_{inv}, annual maintenance cost is denoted by C_m, annual network loss cost is denoted by C_{loss}. The calculations are shown in equations (2) ~ (4).

$$C_{inv} = \frac{r+1+r^y}{1+r^y-1} * \sum_{DG}(c_{PV}S_{PV} + c_{WT}S_{WT}) + \sum_{ES} c_{ES}SOC_{ES} \tag{2}$$

$$C_m = \sum_{DG}(\mu_{PV}S_{PV} + \mu_{WT}S_{WT}) + \sum_{ES}\mu_{ES}SOC_{ES} \tag{3}$$

$$C_{loss} = \sum_{k=1}^{N_{SYS}} n_k \sum_{t=1}^{T_{tol}} \alpha \Delta t P_{losst}^k \tag{4}$$

Where, $\frac{r+1+r^y}{1+r^y-1}$ is the annual conversion factor, r is the discount rate and the value is 0. 052, the life cycle of distributed generation and energy storage is denoted by y ,the annual investment cost of photovoltaic is denoted by C_{PV}, S_{PV} is photovoltaic installed capacity, the annual investment cost of wind power is denoted by C_{WT}, S_{WT} S_{WT} is installed capacity of wind power, μ_{PV} μ_{PV} is the annual maintenance cost per unit capacity. μ_{WT} μ_{WT} is the annual maintenance cost of wind power per unit capacity. the annual maintenance cost of an energy storage system per unit capacity is denoted by μ_{ES}, the installed capacity of energy storage system SOC_{ES}, the total number of scenarios is denoted by N_{SYS}, the number of days per year for each scenario is denoted by n_k ,the number of simulated cycles in a day is denoted by T_{tol}, is the electricity price is denoted by α, refers to the network loss of the system during the period t in scenario k.

2.1.2 Lower model.

The lower model optimizes the load variation as the objective function, and the evaluation index is the fluctuation range and fluctuation rate of the comprehensive load on the side of the grid, which reflects the power supply reliability of the distribution network.

$$\lambda = \frac{\max \left| P_g(t+1) - P_g(t) \right|}{\bar{P}_g} \tag{5}$$

$$\min f = \eta_1 \frac{P_{g\max} - P_{g\min}}{\bar{P}_g} + \eta_2 \frac{P_{g\max} - P_{g\min}}{\bar{P}_g} \tag{6}$$

Where: the average daily load is denoted by P_g, the load fluctuation rate is denoted by λ, the time values of daily load are denoted by $P_g(t+1)$ and $P_g(t)$, η_1 and η_2 are the weight coefficients of evaluation indexes, η_1 is 0.23, η_2 is 0.73, $P_{g\max}$ and $P_{g\min}$ are the maximum and minimum values of the daily load power.

2.2 Constraints

2.2.1 Constraints on system power balance.

$$\begin{aligned}&\sum_m Q_F^m + \sum_u Q_X^u + \sum_g Q_{PV}^g + \sum_f Q_W^f + \\ &\sum_i r_k^i - Q_{LOSS} = D_{total} - Q_d(i,t)\end{aligned} \tag{7}$$

Where, the output power of thermal power unit is denoted by Q_F^m, rotary standby unit is denoted by Q_X^u, photovoltaic power unit and wind power unit is denoted by Q_{PV}^g and Q_W^f respectively. Q_{LOSS} is power loss in transmission and distribution. The total system load is denoted by D_{total}.

2.2.2 Constraints on the active power output of distributed power sources.

$$P_{DG.\min} \le P_{DG}(t) \le P_{DG.\max} \tag{8}$$

Where: $P_{DG.\min}$, $P_{DG.\max}$ is the minimum and maximum value of distributed power output active power, The variable $P_{DG}(t)$ represents the actual output active power of the distributed generation within the distribution network.

2.2.3 Constraints on energy storage device.

$$\sum_{i=1}^{N_{ES}} Q_i = Q_D, Q_{i.\min} \le Q_i \le Q_{i.\max} \tag{9}$$

Where, the output power of the energy storage device i in operation is denoted by Q_i, the total energy storage required in the new mode is denoted by Q_D. The minimum and maximum output power of energy storage device i is denoted by $Q_{i.\min}$ and $Q_{i.\max}$.

2.3 Optimization solution

The Quantum Genetic Algorithm (QGA) is an intelligent algorithm that combines quantum computation with genetic algorithms. Traditional genetic algorithms may suffer from a high number of iterations and slow convergence rate if not properly implemented. [6-9]In this study, we introduce the concept of the quantum state vector expression into the genetic coding process. By utilizing quantum logic gates, the evolution and updating of chromosomes are performed, enabling optimization and solving of the target problem. This approach aims to enhance the efficiency and effectiveness of the genetic algorithm. The algorithm flow chart is shown in Figure 2.

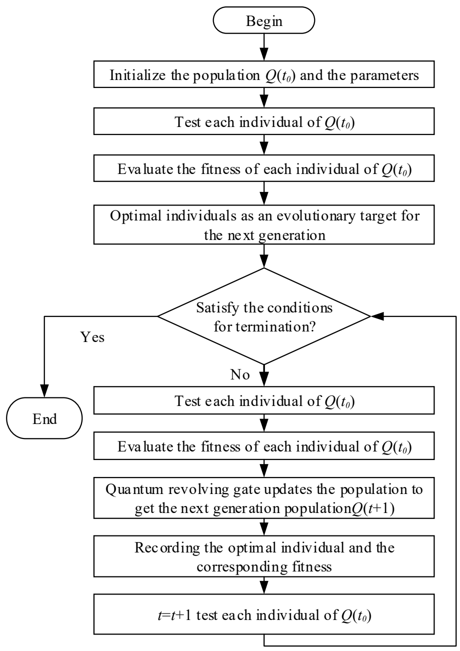

Figure 2. Quantum genetic algorithm solving process

During the initialization of population $Q(t_0)$, all genes $\left(\alpha_i^t, \beta_i^t\right)$ of chromosomes within the population are set to $\left(\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}\right)$. In this context, a particular chromosome represents the superposition of all possible states with equal probability：

$$\left|\psi_{q_j^t}\right\rangle \sum_{k=1}^{2^m} \frac{1}{\sqrt{2^m}} \left|S_k\right\rangle \tag{10}$$

In the formula, S_k represents the chromosome in the kth state, and the binary string $\left(x_1, x_2, \ldots, x_m\right)$ represents its representation. The value of x_i can be either 0 or 1.

To obtain a set of definite solutions, the individuals in the initial population are measured as follows:

$$P(t) = \left\{p_1^t, p_2^t, \ldots p_n^t\right\} \tag{11}$$

Where p_j^t represents the measurement value of an individual, t represents the algebraic ordering of the population, and j represents the ordering of the individual.

After performing the aforementioned operations, the fitness of each individual is evaluated. The individual with the best fitness is selected as the target value for further evolution. These steps are repeated in a loop iteration until the optimal solution is found.

3. Example analysis

The power supply in the active distribution network optimization model established in this paper mainly includes wind turbine, photovoltaic turbine, thermal turbine and energy storage equipment. The typical daily parameters of summer in a certain area were divided into 24 hours, and the optimization period was set to 1 hour. The constraint conditions and quantum genetic algorithm are used to solve the objective function, so as to obtain the optimal operation index of the active distribution network system.

Considering that the power load, photovoltaic and wind power output of system are impacted by factors such as load fluctuations, it is difficult to obtain more stable operation data. Therefore, short-term load forecasting is usually used to obtain sample data, and other parameters are shown in Tian's research. [10]The predicted output values of wind turbines, photovoltaic and base load output prediction within 24 h of active distribution network system are shown in Figure 3.

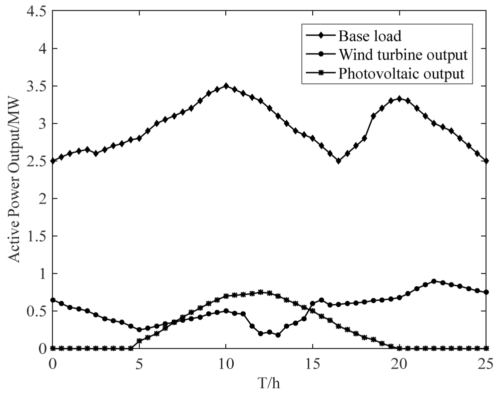

Figure 3. Predicted output values of wind turbines, photovoltaic and base load

As can be seen from Figure 3, the randomness and volatility of photovoltaic output are weak. Compared with photovoltaic, wind power has larger access quantity, stronger volatility, greater randomness, and stronger disturbance to the distribution network. Base load output is relatively stable with little fluctuation.

"Source-network-charge-storage" collaborative interaction was set, including distributed power supply, network, controllable load and energy storage system, and the validity and economicality before and after optimization was comprehensively considered.

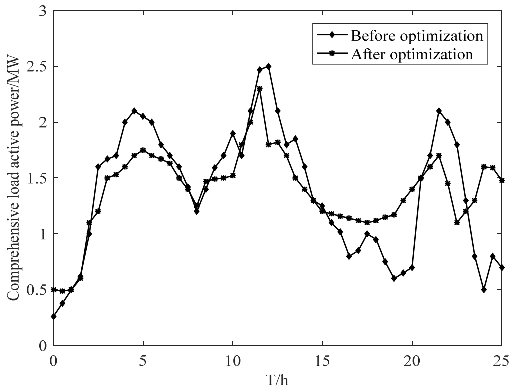

Figure 4. Collaborative optimization results of "source-network-charge-storage"

As can be seen from Figure 4, after optimization, the fluctuation of comprehensive load active power becomes significantly smaller and its stability is enhanced.

Table 1. Comparison of "source - network - load - storage" collaborative optimization

	Maximum load /MW	Minimum load /MW	Peak-valley difference /MW	Load standard deviation	Comprehen sive cost /Yuan
Before optimization	107.9	36.2	71.7	17.162	723059
After optimization	98.2	46.8	51.4	12.103	702537

By comparing the results before and after implementing the collaborative optimization of "source, network, load, and storage", it can be seen that after the optimization, the peak-valley difference decreases from 71.7MW to 51.4MW, and the standard deviation of load decreases from 17.162 to 12.103, the purpose peak of shaving is realized. Meanwhile, the integrated cost also decreases by 20,522 yuan. The operation efficiency and benefit of power grid have been improved.

4. Conclusion

Based on the existing distribution network system optimization model, this paper constructs a two-layer optimization model of "source-netter-load-storage" coordination under the new power system, and uses quantum genetic algorithm for optimization training to solve the output level of each unit, which promotes the overall low level of comprehensive operation cost of active distribution network. The simulation results show the rationality of the optimization scheme proposed in this paper, which can provide positive auxiliary decision for the economic dispatching and power trading of the distribution network system.

Acknowledgments: This paper is supported by Power grid investment planning technology and value derivative evaluation based on multi-objective dynamic balance（1400-202157215A-0-0-00）.

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