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Study on Reactive Power Optimization Including DSSC for New Energy Access to the Power Grid

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Abstract

The vigorous development of new energy has effectively reduced carbon emissions, but it has also brought fluctuating impacts on the carrying capacity of the power grid. In order to improve the voltage stability after integrating new energy sources and promote the scientific consumption of more new energy, this paper proposes the use of Distributed Static Synchronous Compensator (DSSC) devices for flexible and controllable voltage regulation in new energy integration. An improved particle swarm optimization algorithm is then developed to optimize the reactive power considering the regulation of DSSC. The paper conducts power flow calculations based on the DSSC power injection model and establishes a reactive power optimization mathematical model with objectives of minimizing active power loss, minimizing node voltage deviation, and maximizing voltage stability margin in the grid with new energy integration. The improved particle swarm optimization algorithm is utilized to achieve the reactive power optimization. Experimental simulations are conducted using the IEEE 33-node system to analyze the voltage improvement before and after adopting the improved particle swarm optimization algorithm considering the DSSC device in the grid with new energy integration. It is found that the proposed method effectively reduces active power loss and stabilizes voltage fluctuations, demonstrating its practical value.

Keywords: reactive power optimization, new energy, PSO algorithm, distributed static series compensator

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1. Introduction

With the worsening global energy shortage and environmental pollution, renewable energy has been receiving increasing attention. In the 28th International Climate Change Conference, China and the United States jointly issued the "Sunshine Declaration on Strengthening Cooperation in Climate Crisis Response." They plan to triple the global renewable energy installed capacity by 2030 and aim to significantly accelerate the deployment of renewable energy in both countries by 2030 compared to 2020 levels. By the end of 2023, China's total installed capacity of renewable energy reached 1.45 billion kilowatts, accounting for over 50% of the total installed capacity for power generation, marking a historic milestone surpassing that of thermal power[1]. In order to achieve a threefold increase in renewable energy installed capacity by 2030 compared to 2020, the proportion of new energy sources such as wind and solar in China's future power system will continue to rise. With the large-scale and high-proportion integration of renewable energy into the power system, a clean, efficient, and multi-complementary energy structure will gradually take shape. It is crucial to accelerate the planning and construction of a new energy system in order to effectively address the potential challenges to power security and stability brought about by the large-scale integration of renewable energy[2].

After the integration of a large amount of new energy and energy storage devices into the grid, their intermittent fluctuations constantly affect the power quality of the grid, posing significant challenges to its reliable and stable operation. Currently, D-FACTS devices that are widely

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researched and applied include Distributed Static Series Compensator (DSSC), Distributed Series Reactor(DSR), Distributed Series Impedance(DSI) and Distributed Power Flow Controller(DPFC).As an important member of the D-FACTS family, DSSC can adapt to the flexible regulation requirements of the grid. The equipment is easy to be deployed along the grid, enabling real-time on-site power flow adjustment and state perception[3-4].This effectively improves the security, stability, and economic operation level of China's power grid. Compared to other D-FACTS devices, DSSC has lower cost and a wider range of applications, making it a new approach for grid regulation in China. It enables flexible control of the grid system. [5].

Reactive power optimization refers to reasonably optimizing the reactive power output of various regulating device in the system under the premise of satisfying the stability of the grid, so as to control the active and reactive power output of each device under the power flow, improve the power flow distribution and voltage stability of the power system, and reduce the active power loss. Reference [6] explored the feasibility of DSSC in line flow control and conducted preliminary exploration on improving line carrying capacity with DSSC, but did not conduct in-depth research on multi-objective flow optimization. Reference [7] analyzed the voltage quality of a new energy grid with DSSC included, but did not effectively evaluate its economy. Literature [8] puts forward an optimization algorithm that combines Particle Swarm Optimization with Ant Colony Optimization to effectively address the issues of local optimization in Particle Swarm and the time-consuming optimization process of Ant Colony, yet it does not study the effects of new energy integration on system reactive power regulation. Literature [9] takes voltage stability and operation economy as optimization objectives respectively, and uses neural algorithm to optimize reactive power with single objective value respectively, without considering the demand of reactive power regulation in multi-objective situation. Literature [10] puts forward the method of coordinated optimization of series compensation and parallel compensation, and adopts improved ephemera algorithm to solve the model, which effectively reduces the voltage deviation and active power loss, but it is limited by the equipment itself and cannot achieve flexible control. Literature [11] applies the Dragonfly algorithm to solve a multi-objective optimization model aimed at minimizing line loss, voltage deviation, and maximizing voltage stability, which enhances optimization precision. However, it does not account for the integration of new energy sources and the advanced equipment required for the flexible control of grid power flow, which are essential to meet the current demands of large-scale integration of new energy. In order to better integrate new energy into the power grid operation system and establish a stronger and more absorptive new power system, studies the advantages of DSSC in flexible and controllable power flow of the power grid, taking into account the integration of new energy. The objective function of establishing a mathematical model for reactive power optimization is to minimize active power loss, minimize node voltage deviation, and maximize voltage stability margin of the power grid with new energy integration. The improved particle swarm optimization algorithm is used to solve the model, and finally, the reactive power optimization of the power grid with new energy integration taking into account DSSC is achieved.

2. Basic structure and calculation model of DSSC

2.1. The basic structure of DSSC

The basic structure of DSSC is shown in Figure 1, which mainly consists of single-phase coupling transformer, filtering circuit, single-phase full bridge inverter, equipment controller, communication module and other electrical components. By configuring sensors and communication modules that can collect voltage and current on the ij line, real-time online voltage and current parameters of the line can be obtained. The controller controls the switch of the occasional transformer in parallel, and adjusts the single-phase full bridge converter setting to ultimately achieve adjustment of the voltage amplitude and phase angle of the line[12]. When the power flow is stably controlled, the controller can realize the flexible exit of control by turning off the switch, which effectively reduces the equipment loss. The configuration of DSSC on the line needs to be simultaneously configured in ABC three phases, thus forming a set of stable and reliable regulation controllers.

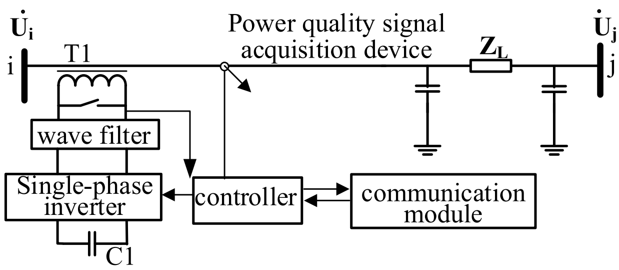

Figure 1. The Basic structure of DSSC

2.2. DSSC equivalent circuit and calculation model

When the DSSC device is configured in the power network, it can be equivalent to a series voltage source U_T and an equivalent reactance. When the distance of the transmission line is less than 240km, the influence of the capacitance and conductance of the line is ignored, as shown in Figure 2[13-15]. U_i indicates the terminal voltage of the line, and its phase angle is φ_i . U_j indicates the terminal voltage of the line, X_{ij} represents the equivalent reactance between node I and node J, I represents the current of the line i-j, U_S

represents the output voltage of a DSSC module, whose phase angle of the output voltage is δ_S. The phase angle difference between the current of the whole line and the output voltage of the DSSC is 90°. According to the equivalent circuit diagram, when the included angle between the voltage output by the DSSC device and the current flowing through the line ij is +90°, the DSSC works in an inductive state. When the included angle between the voltage output by the DSSC device and the current flowing through the line ij is -90°, the DSSC works in a capacitive state. Based on the phasor of line terminal voltage, the phasor diagram between transmission line current and voltage of a single DSSC module in different states is shown in Figure 3[16].

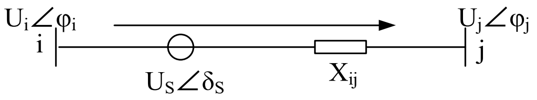

Figure 2. DSSC equivalent circuit diagram

When multiple DSSC devices are configured in the power network, the effect of each DSSC series converter can be equivalent to a controllable voltage phasor, which is equivalent to multiple voltage phasors acting together on the controlled transmission line. The amplitude and phase angle of each series voltage phasor can be set according to the actual demand of the transmission line. This dual-objective working mode not only sets the control objectives of each group of converters according to the requirements of converter access points, but also sets the control objectives of the whole device according to the control requirements of the whole system[17-19].

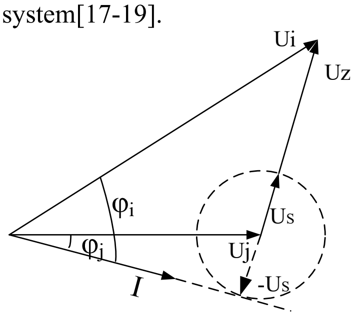

Figure 3. Vector diagram of line with DSSC

DSSC device can optimize system voltage, realize grid voltage control, and indirectly change line power flow. In Figure 2, excluding DSSC access, the active power flowing through the traditional high-speed line is:

$$P = \frac{U_i U_j}{X} \sin \delta_{ij} \tag{1}$$

Where: δ_{ij} is the phase angle difference of the line ij containing DSSC. When DSSC is configured in the system, it can be equivalent to a controlled voltage source for the entire system, and the active power P flowing through its line can be expressed:

$$P^{'} = \frac{U_1 U_2}{X} \sin \delta - \frac{U_1 U_S}{X} \cos \frac{\delta}{2} \left[\frac{\sin \frac{\delta}{2}}{\sqrt{\left(\frac{U_1 + U_2}{2U_2}\right)^2 - \frac{U_1}{U_2} \cos^2 \frac{\delta}{2}}} \right] \tag{2}$$

In order to facilitate the calculation and analysis of power flow considering DSSC, considering the small voltage phase angle difference between the two ends of the line, it can be considered as a simplified equation $\sin \delta \approx \delta, \cos \frac{\delta}{2} \approx 1$ in Equation 2, and the new energy power flow model of DSSC can be further simplified as follows:

$$P^{''} = \frac{U_1}{X}(U_2 \delta - U_S) \tag{3}$$

2.3. Power flow calculation method with DSSC

When the DSSC is deployed on the node I side of line ij, and the power flow equations at both ends of the line where the DSSC is deployed are modified, the power flow equations of other nodes remain unchanged [20]. According to the voltage vector diagram constructed in Figure 3, which takes into account dssc, the model parameters can be adjusted according to the actual situation. In order to facilitate the optimal power flow optimization, it can be obtained by extrapolation:

$$\begin{cases} P_{i(\text{in})} = \mathrm{U}_j \mathrm{U}_S [b_{ij} \sin(\varphi_j + \delta_S) - g_{ij} \cos(\varphi_j - \delta_S)] + U_S^2 g_{ij} \\ Q_{i(\text{in})} = U_i U_S [g_{ij} \sin(\varphi_i - \delta_S) - (\mathrm{b}_{ij} + \mathrm{B}_c / 2) \cos(\varphi_i - \delta_S)] \\ P_{j(\text{in})} = -U_j U_T [g_{ij} \cos(\varphi_j - \delta_S) + \mathrm{b}_{ij} \sin(\varphi_j - \delta_S)] \\ Q_{j(\text{in})} = -U_j U_S [g_{ij} \sin(\varphi_j - \delta_S) + \mathrm{b}_{ij} \cos(\varphi_j - \delta_S)] \end{cases} \tag{4}$$

Where: $P_{i(\text{in})}$, $P_{j(\text{in})}$, $Q_{i(\text{in})}$, $Q_{j(\text{in})}$ represents the active and reactive power injected into node i and node j after the line is connected to the DSSC device using an equivalent power injection model simplification.

3. Reactive power optimization model considering new energy access

3.1. Objective function

The green demonstration projects with new energy as the main body provide ideas for the development of new energy. Taking into account the economic and stability of the power grid operation after the integration of volatile new energy, in the case of multi-point decentralized new energy not being worth it, in order to ensure more reasonable consumption of new energy and green and low-carbon transformation of energy structure, a reactive power optimization mathematical model is established with the goals of minimizing active power loss, minimizing node voltage deviation, and maximizing voltage stability margin of the power grid with new energy integration. Its objective function is:

$$\min f = \lambda_P \Delta P + \lambda_U \sum_{i \in N_{PQ}} \left(\frac{U_i - U_{i,\lim}}{U_{i,\max} - U_{i,\min}} \right)^2 + \lambda_C S \tag{5}$$

$$S = \min \frac{1}{s} = \max_{i,j \in N} \frac{4\left[\left(P_j X_{i,j} - Q_j R_{i,j} \right)^2 + U_i^2 \left(P_j R_{i,j} - Q_j X_{i,j} \right) \right]}{U_i^4} \tag{6}$$

Where: ΔP is the active loss of power grid; λ is the weighting factor of voltage and voltage stability coefficient; N_{PQ} is the total number of PQ nodes, and S is the static voltage stability margin.

3.2. Constraint condition

Equality constraints

The equation constraint mainly considers that all points of the system should also maintain power conservation after DSSC, which is mainly manifested in the injection of active and reactive power after accessing DSSC [21]. In the case of new energy access, due to the requirements of wind, scenery and climate conditions and grid demand response, the actual grid-connected quantity varies aperiodically, so the influence of node PQ and compensation device of new energy generator set should be specially considered. Taking node I as an example, the equation constraint equation is as follows:

$$\begin{cases} P_i + P_{Di} = U_i \sum_{N}^{j=1} U_j \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij} \right) + P_{i(\text{in})} \\ Q_i + Q_{Di} + Q_{Ci} = U_i \sum_{N}^{j=1} U_j \left(G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij} \right) + Q_{i(\text{in})} \end{cases} \tag{7}$$

Where, P_i , Q_i are the active power and reactive power injected into the node respectively; P_{Di} , Q_{Di} are the active power and reactive power of the grid-connected new energy load node respectively. Q_{Ci} is the reactive power of the reactive power compensation device at node I.

According to Formula 7, the newly injected active and reactive power should be considered after the DSSC device is installed, and the reactive power generated by the supporting compensation device should be considered after the integration of new energy.

Inequality constraints

Inequality constraints are the boundary conditions of optimal power flow and the premise of maintaining system stability [22]. In conventional power grid, each equipment in the system should meet its reactive and active power limits, and the voltage should be maintained within a controllable range to ensure system stability., namely:

$$\begin{cases} Q_{Gmin} \le Q_G \le Q_{Gmax} \\ U_{Gmin} \le U_G \le U_{Gmax} \\ Q_{Ci\,min} \le Q_{Ci} \le Q_{Ci\,max} \\ T_{min} \le T \le T_{max} \end{cases} \tag{8}$$

Among them, it is the upper and lower limits of the corresponding parameters such as reactive power, voltage and OLTC gear. After installing DSSC, DSSC injects a series voltage with adjustable amplitude and 90 phase angle with current into the line, with the following constraints:

$$U_{Smin} \le U_S \le U_{Smax} \tag{9}$$

$$0 \le \delta \le \pi \tag{10}$$

Where U_S , δ_S are the voltage amplitude and phase angle connected to the DSSC device respectively, as shown in Figure 2.

4. The model to improve the particle swarm optimization

4.1. Improved Particle Swarm Optimization

PSO is one of the excellent bionic algorithms for solving the multi-objective optimal solution of power system. It is initialized as a group of random particles, and then the optimal solution is found through iteration[23]. In each iteration, the particles track the local optimal extreme value and the global optimal extreme value, and their ultimate goal is to solve the optimal position vector to achieve the optimal value of the target effect. When DSSC equipment is introduced into the line, the parameters such as voltage control, current control and reactive power capacity are added to the reactive power optimization model in addition to the traditional adjustment variables, that is, the vector composed of generator terminal voltage, the number of DSSC coupling transformers, the switching capacity of reactive power compensation devices and the control variables set by DSSC. This method mainly adopts a group of three single-phase DSSC which are respectively configured in different positions of the system, and its iterative formula is:

$$v_{ij}(t+1) = w v_{ij}(t) + c_1 r_1 \left(p_{ij}(t) - x_{ij}(t) \right) + c_2 r_2 \left(p_{gj}(t) - x_{ij}(t) \right) \tag{11}$$

The iterative updating formula of position is:

$$x_{ij}(t+1) = x_{ij}(t) + v_{ij}(t+1) \tag{12}$$

Particle swarm should usually meet the requirements of global search in the early stage before iteration and local optimization in the middle and late stage until it converges to the global optimal solution. When the inertia weight coefficient w is larger, the particle velocity is larger, which is more conducive to global optimization; When the inertia weight coefficient w is small, the particle velocity is small, which is more conducive to local optimization. Therefore, the inertia weight coefficient w is designed to keep a large value in the early stage so that the particles can traverse the whole world, and to stabilize at a small value in the later stage, so that it can converge quickly and accurately. According to a large number of experimental conclusions, the optimization effect of the algorithm is the best when w varies from 0. 5 to 0. 85. In addition, considering the problem that the algorithm may fall into local optimum in the later stage, we can add a control adjustment function not less than 1 to the formula, and at the same time limit the random number value by using the numerical characteristics of trigonometric function to prevent the algorithm from diverging. To sum up, the inertia weight coefficient w is improved as follows:

$$w=\frac{1}{1+e^{-\frac{20}{n}}}+r\times\cos\left(\frac{\pi}{2}\times\frac{n}{n_{\max}}\right)-0.1 \qquad (13)$$

Where n is the number of iterations, $n_{\max}$ is the maximum number of iterations, and r is the random number in the interval [0,1].

4.2. Algorithm implementation steps

The improved particle swarm optimization algorithm is used to solve the optimization model, and the reactive power compensation nodes are determined by configuring lines and common and new energy load data, and then the position and speed of particles are continuously updated, and the fitness value of each particle is obtained according to the objective function, and the local optimal solution and global optimal solution of the algorithm are continuously updated, and the global optimal solution is finally obtained according to the convergence conditions. The flow chart is shown in Figure 4.

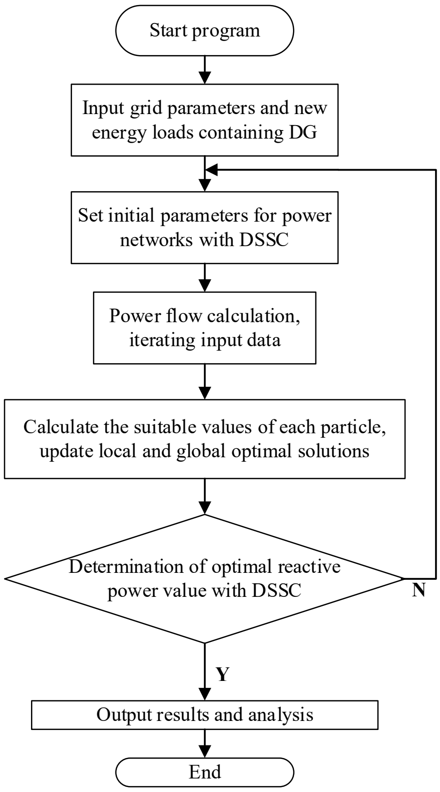

Figure 4. Flow chart of reactive power optimization based on improved particle swarm optimization

5. Example analysis

In order to verify the applicability of the proposed improved particle swarm optimization in reactive power optimization of DG-containing power grid, this paper simulates and verifies the proposed reactive power flow optimization considering new energy access by using the improved particle swarm optimization through an IEEE9-bus system (Figure 5), with a reference voltage of 12. 66kV and a power reference value of 300kW. Node 28 is connected to a photovoltaic power supply, node 12 is connected to a wind turbine, and nodes 6 and 31 are respectively connected to a set of DSSC devices. Its main parameters are set in reference [24].

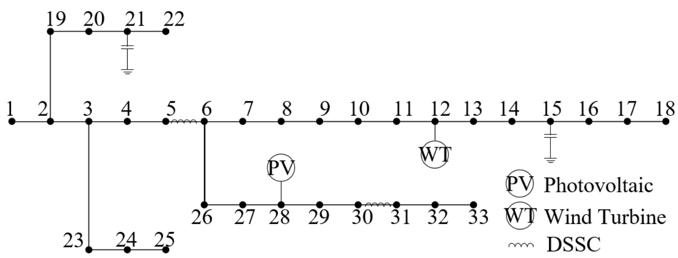

Figure 5. IEEE9-node system model considering DSSC and new energy access

The improved particle swarm optimization algorithm is used to solve the reactive power optimization model of this example, and the optimization results are compared with those of the traditional PSO algorithm. Figure 6 shows the convergence curves of the two algorithms when optimizing the objective function. It is obvious that the improved PSO algorithm has fewer iterations and smaller optimal fitness value.

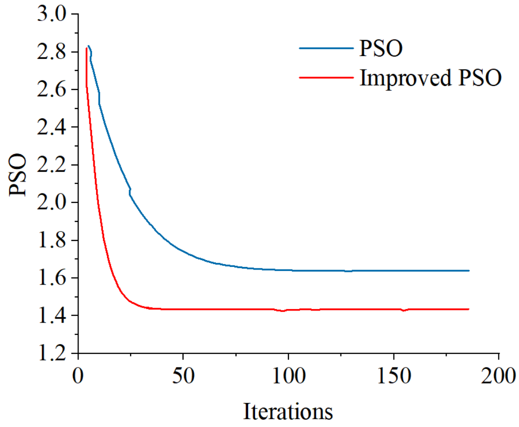

Figure 6. Comparison diagram of node voltage before and after optimization

The calculation of non-DG before optimization, DG-connected before optimization, and DG-connected after reactive power optimization are carried out respectively. The comparison results are shown in Table 1.

Table 1. Comparison Table of Active Power Loss under Different Conditions

Program	Initial state	PSO	PSO Including DG	PSO-DSSC Including DG
Active power loss	242.15	165.07	125.43	110.21
Reduce percentage	0	29.12%;	44.26%	54.55%

From the results in Table 1, it can be seen that the network loss is 242.15kW before DG access optimization; After the optimization of reactive power compensation, the network loss is reduced to 165.07kW, and the network loss is reduced by 29.12%. When the power grid is connected to DG, the reactive power compensation is optimized, and the power grid loss decreases to 125.43kW, and the reduction rate of power grid loss increases to 44.26%. When the power grid is connected to DG, through introducing DSSC device to control and adjust, and then optimizing reactive power compensation, the reduction rate of network loss is further improved. The comparison of node voltage before and after optimization is shown in Figure 7, and the node voltage of power grid is significantly improved after reactive power compensation. After optimization of reactive power compensation, the minimum voltage amplitude is raised from 0.9192pu to 0.9268pu. When DG is added and reactive power optimization is carried out, the node voltage is raised again, and the minimum voltage amplitude is raised to 0. 9783pu. When DSSC is connected, the node voltage is further raised, and the minimum voltage amplitude is raised to 0. 9912pu. To sum up, reactive power optimization can effectively reduce the loss of distribution network and improve the voltage level. When DG is contained in the power grid, the effect of reactive power optimization is obviously improved, and the effect of reactive power optimization regulation is even more obvious after DSSC device is connected.

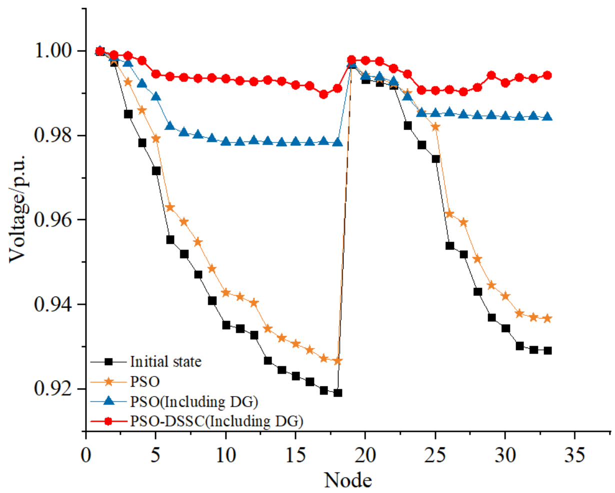

Figure 7. Comparison diagram of node voltage before and after optimization

6. Conclusion

In this paper, a reactive power optimization scheme considering the reactive power support capacity of DSSC is proposed. On the basis of solving the traditional reactive power optimization of power grid, the power flow with DSSC is calculated based on the power injection model, and the objective function and constraint conditions of the power grid with new energy are analyzed. The control output of DSSC, DG reactive power output capacity and shunt reactive capacitor configuration are optimized as control variables at the same time. The objective function determined by the mathematical model of reactive power optimization is established with the minimum active power loss, the minimum node voltage deviation and the maximum voltage stability margin as the objectives. Finally, the improved particle swarm optimization is applied to the model, and the improved IEEE 33-node distribution network is used as the test system. The results of system parameters before and after the particle swarm optimization are analyzed. The method in this paper has good effect in the traditional distribution network without new energy access. After the new energy and DSSC are connected, the reactive power optimization effect is further improved, which can effectively reduce the system loss and improve the voltage quality, which proves that the method is reliable and practical. In terms of algorithm, this paper is based on particle swarm optimization, but there are still many iterations and slow model solving time when large-scale new energy and DSSC devices are connected at the same time. Power flow optimization can be further studied by introducing other intelligent algorithms and mathematical models, and the results are worth comparing with this method.

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