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Research for Participation of Electric Vehicles in the Power System Optimal Dispatching

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Abstract. The rapid development of renewable clean energy and low-carbon transportation has brought new opportunities and challenges to the safety and economic operation of power system. This paper studies the economic dispatching operation of the power system that contains clean energy and large-scale electric vehicles, and establishes the objective function of minimizing the amount of discarded wind power and the lowest cost of thermal power generating units. In order to improve the optimization efficiency, the original system is decoupled into the wind-vehicle-hydro subsystem and the thermal power subsystem according to the characteristics of multi-source output. The two subsystems are connected by the load balance and the reserve constraints of the system, and their respective scheduling models are given respectively. In this paper, an improved random black hole particle swarm optimization (IRBHPSO) algorithm with fast convergence and effective avoidance of local optimization is proposed by combining the black hole theory and particle swarm optimization. The effectiveness and superiority of the improved algorithm were verified on a 10-unit test system. Finally, this paper modifies the IEEE-RTS system according to the proportion of installed capacity of the Northeast Power Grid. The simulation results verified the feasibility of the proposed optimal scheduling model and the effectiveness of the algorithm, which provides strategies and feasible suggestions for the large-scale electric vehicles to participate in the economic dispatching operation of the power system.

1. Introduction

In recent years, clean energy represented by wind power and photovoltaics has developed rapidly. However, large-scale clean energy access to the power grid will not only further increase the peak-valley difference in the power load, but even threaten the safe and economic operation of the power system. Existing research shows that the interactive technology between electric vehicle and power grid can provide support for clean energy on-site consumption and stable grid connection [1].

At present, it has become a research hotspot to reveal the influence of electric vehicles on the economic dispatching and safe operation of power system by considering the random and time-varying factors of electric vehicles and clean energy. The reference [2] discusses the V2G electric vehicle scheduling strategy with “power source” and “load” characteristics in the microgrid. The research also considers the uncertainty of wind power and photovoltaic power, and reduces the network operation cost and pollution emission by establishing a two-stage model. The reference [3] proposes the cost between the balanced distribution company and the distributed power source investor, introduces V2G and distributed power supply as the coordination factor for coordinating the power generation environment benefit, and uses the distribution network random power flow



calculation method to solve the problem. The reference [4] researches the hybrid scheduling optimization problem of electric vehicles and renewable clean energy units, and proposes the new stochastic optimization method to solve the hybrid scheduling problem, which reduces the total cost of power grid operation. The reference [5] proposes a two-layer model considering the marginal cost of power generation and the dynamic electricity price to obtain the optimal charging strategy, in order to solve the contradiction between the total power generation cost and the local cost. The reference [6]-[7] propose a multi-objective optimization scheduling scheme for intelligent power distribution systems including large-scale electric vehicles, and establish a conceptual model of the electric vehicle management system, and analyse the impact of electric vehicle operating costs and air pollutant emissions. The simulation results show that the total air pollutant emissions can be reduced by changing the charge and discharge strategy and power grid optimization scheduling.

This paper researches the different types of electric vehicle charge-discharge modes are involved in the economic optimization scheduling of power system that includes large-scale clean energy, and establishes the objective function of minimizing the amount of discarded wind power and the lowest cost of thermal power units. In order to simplify system scheduling, so the large system is decomposed into wind-vehicle-hydro subsystem and thermal power subsystem. The two subsystems are combined by power balance and standby constraints. The IRBPSO algorithm is proposed based on the improvement of black hole particle swarm optimization, and the effectiveness and superiority of the improved algorithm are verified by a test system. Finally, a case study is conducted to verify the effectiveness and feasibility of the proposed algorithm and model in this paper.

2. Scheduling model

2.1. Electric vehicle model

The plug-in electric vehicle charging mode is divided into two types: free charging and orderly charging based on time-of-use electricity price. The objective function and constraints of the orderly charging modes are as in equation (1) and equation (2), respectively.

$$\min \sum_{i=1}^{1440} P(t) \times price(t) \quad (1)$$

$$\begin{aligned} a. \quad & P(t) = \gamma \times \xi_t \times P_c \\ b. \quad & \xi_t = \begin{cases} 1 & t \in (t_{smart}, t_{smart} + t_{charge}) \\ 0 & \text{others} \end{cases} \\ c. \quad & t_c = \frac{ca \times (1 - soc)}{P_c \times \gamma} \\ d. \quad & t_{charge} = \min(t_c, t_{leave} - t_{start}) \end{aligned} \quad (2)$$

Where, $P(t)$ is the expected value of the charging load of the electric car at time t , $price(t)$ represents the charging price of the electric vehicle at each moment t ; γ is charging efficiency, P_c is the charging power; ca is the battery capacity, t_{start} and soc obey different distributions depending on the type of electric vehicle and the charging location, the value of t_{smart} is determined by the above intelligent charging criteria.

In the battery-change mode, the vehicle and battery are no longer considered as a whole. After the electric vehicle electric energy residual value of the electric switching mode in use is low to a certain extent, the charge-discharge power station is driven to remove the low-power battery and replace the charged battery. However, the paper considers that the charging load of the electric vehicle is to be satisfied by the upper and lower limits of charge-discharge, the actual charge-discharge power value is

significantly different from the charge target value. The specific calculation method of the charge-discharge value of the electric vehicle at time t is as in equation (3).

$$P_{EV}(t) = \begin{cases} P_{EVcmax}(t) & P_{EV}^P(t) > P_{EVcmax}(t) \\ P_{AR}^P - P_{Load}(t) & -P_{EVdmax}(t) \leq P_{EV}^P(t) \leq P_{EVcmax}(t) \\ -P_{EVdmax}(t) & P_{EV}^P(t) < -P_{EVdmax}(t) \end{cases} \quad (3)$$

Where, $P_{EV}(t)$ is the actual charge-discharge power of the electric vehicle at time t ; $P_{EVcmax}(t)$ and $P_{EVdmax}(t)$ are the maximum values of the EVs charge-discharge power at time t , which is not a simple fixed value determined by the technical constraints of charge-discharge power, but a variable that is affected by the remaining power and last minute energy requirements at the previous moment in the optimization process. Specific and detailed constraints for four modes of electric vehicles can be found in the reference [6]- [7]

2.2. Objective function

The dispatching process should ensure that the wind power is preferentially connected to the power grid, and the discard wind power is minimized. Equation (4) shows the relationship of minimizing the amount of the discarded wind power.

$$\min \Delta W = \sum_{t=1}^T (P_{W,t}^0 - P_{W,t}) \quad (4)$$

Where, $P_{W,t}^0$ is the wind power output, $P_{W,t}$ is the wind power consumed by the power grid, T represents the scheduling period. The operating cost of the thermal power units is as in equation (5).

$$\min F_{total} = \left(\sum_{t=1}^T \sum_{i=1}^{N_t} u_{i,t} F_{i,t}(P_{Gi,t}) + S_c \right) \quad (5)$$

$$F_{i,t}(P_{Gi,t}) = a_i P_{Gi,t}^2 + b_i P_{Gi,t} + c_i$$

Where, F_{total} is the total operating cost of the thermal power; F_c is the total fuel cost of the thermal power units; S_c is the total start-stop cost of the thermal power units; $F_{i,t}$ and $P_{Gi,t}$ are the coal consumption cost and the output power of the i -th thermal unit at the moment t , respectively; $u_{i,t}$ is the start -stop state of the i -th thermal unit at the moment t ; a_i, b_i, c_i is the characteristic parameter that characterizes the relationship between the i -th thermal unit output and the coal cost.

2.3. Wind-vehicle- hydro subsystem scheduling model

The optimal scheduling of power systems including electric vehicles and wind power is a complex, multi-variable, highly nonlinear, complex hybrid constrained programming problem. Due to the complicated situation, it is difficult for the algorithm to obtain accurate results. So this paper decouples the large system and decomposes it into wind-vehicle-water subsystem and thermal power subsystem to optimize separately. The objective functions of the wind-vehicle-water subsystem are as in equation (6).

$$\min F_1(P_{Hi}) = \sum_{t=1}^T \left| \Delta \left(P_{L,t} + P_{EV1,t} + P_{EV2,t} - \left(\sum_{i=1}^{N_h} P_{Hi,t} + \sum_{i=1}^{N_w} P_{Wi,t} \right) \right) \right| \quad (6)$$

$$\max F_2(P_{Hi}) = \sum_{t=1}^T \sum_{i=1}^{N_h} P_{Hi,t}$$

Where, $P_{G,t}$, $P_{L,t}$ are the thermal power output and load at that time t , respectively; $P_{EV1,t}$, $P_{EV2,t}$ are the plug-in EVs and V2G mode at that time t , respectively; $P_{Hi,t}$ and $P_{Wi,t}$ are the output power of the i -th hydro and wind units at the moment t , respectively; Nh and Nw are the number of hydro and wind units in the power system.

2.4. Thermal power subsystem scheduling model

The objective function of thermal power subsystem is consistent as in equation (5). The constraints of the thermal power subsystem need to meet the correction of the system spare capacity constraints that are modified by the wind-vehicle-hydro subsystem optimization results, which is as in equation (7).

$$\sum_{i=1}^{Ng} P_{Gi,max} - \sum_{i=1}^{Ng} P_{Gi,t} \geq \max(0, PR_t) \quad (7)$$

Where, Ng is the number of thermal power plants in the system; $P_{Gi,max}$ is the maximum output of the i -th thermal power unit; PR_t is the system standby correction value.

The two subsystems pass the system power balance constraint as in equation (8) and the system backup constraint as in equation (9) combined into a complete system. Because the limited space of the paper, the actual constraints of thermal power, hydropower and wind power plants not considered in this paper can be found in reference [8].

$$\sum_{i=1}^{Ng} P_{Gi,t} + \sum_{i=1}^{Nh} P_{Hi,t} + \sum_{i=1}^{Nw} P_{Wi,t} = P_{L,t} + P_{EV1,t} + P_{EV2,t} \quad (8)$$

$$PR_t \leq \left(\sum_{i=1}^{Ng} P_{Gi,max} - \sum_{i=1}^{Ng} P_{Gi,t} \right) + \left(\sum_{i=1}^{Nh} P_{Hi,max} - \sum_{i=1}^{Nh} P_{Hi,t} \right) + (P_{EV2d,max,t} - P_{EV2,t}) \quad (9)$$

3. Optimized scheduling algorithm

The implementation method of the RBHPSO algorithm is as in equation (10). RBHPSO algorithm is improved according to the reference [9]. The radius is related to the current position of the particle and the global optimal position, and is updated in each iterative calculation. On the one hand, a lot of calculation work is avoided, on the other hand, the particle can be made to move at a faster speed. The improved algorithm is calculated as in equation (11).

$$\begin{cases} v_{id}^{k+1} = wv_{id}^k + c_1 r_1^k (pbest_{id}^k - x_{id}^k) + c_2 r_2^k (gbest_d^k - x_{id}^k) \\ x_{id}^{k+1} = x_{id}^k + v_{id}^{k+1} \\ l_{id}^k \geq p \end{cases} \quad (10)$$

$$\begin{cases} x_{id}^{k+1} = gbest_d^k + D_{id}^k \\ D_{id}^k = 2R(r_3^k - 0.5) \\ R = \rho |gbest_d^k - x_{id}^k| \end{cases} \quad l_{id}^k < p \quad (11)$$

Where, l_{id}^k is the probability value of the d -th dimension variable of the i -th particle in the k -th iteration; P represents the probability threshold representing the particle being sucked into the black hole, and is a constant in the $[0, 1]$; R is the radius of the black hole, which is a constant; r_3^k is a uniformly distributed random number in the $[0, 1]$, ρ is a uniformly distributed random number in

the $[0, 1]$; $|gbest_d^k - x_{id}^k|$ represents the distance of the current position of the i -th particle from the global optimal particle.

This paper uses the 10-unit system in [10] as an example to verify the effectiveness and superiority of the improved algorithm. The results are shown in table 1.

Table 1. Comparison of statistical results of improved algorithms.

Algorithm	Maximum cost(\$)	Minimum cost(\$)	Average cost (\$)
PSO	39124.43	38782.26	38952.47
RBHPSO	38874.14	38564.67	38692.20
IRBPSO	38647.77	38144.48	38414.35

The comparison results show that the optimization effect of the black hole particle swarm optimization algorithm is better than that of the ordinary particle swarm optimization algorithm, which proves the correctness of the black hole theory and particle swarm optimization in Table 1. It can be found that the IRBPSO algorithm has optimization results of lower maximum, minimum and average cost than that of the traditional PSO and the RBHPSO algorithm, which proves that the proposed algorithm has the superiority of the global search capability. The scheduling flow chart is shown in figure 1.

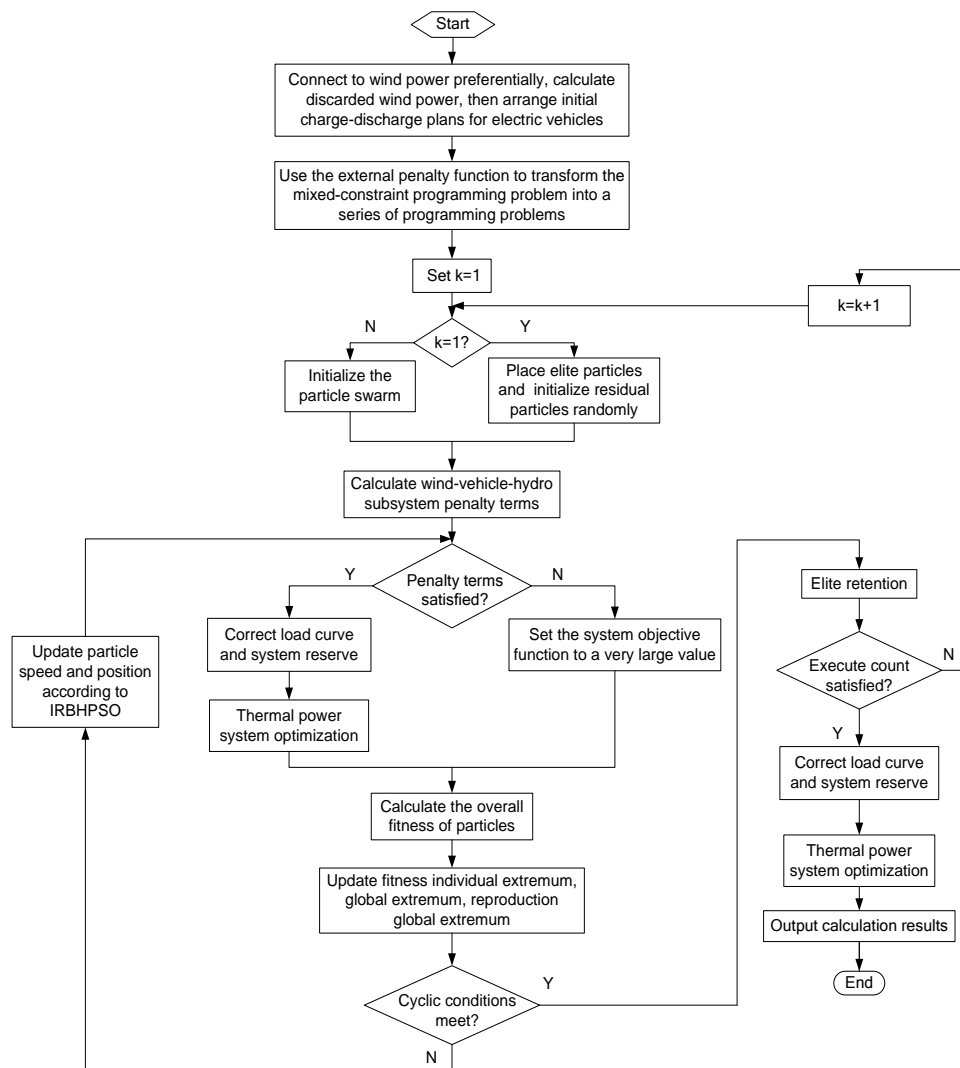


Figure 1. Power system optimization scheduling flowchart.

4. Simulation studies

4.1. Simulation example

This paper takes the modified IEEE-RTS standard test system as an example [11]. The test system has a total installed capacity of 2920MW, and the total installed capacity of the system is 4130MW. The maximum load of the system is 2475.0MW and the minimum load is 1542.6MW. The original system output is shown in figure 2.

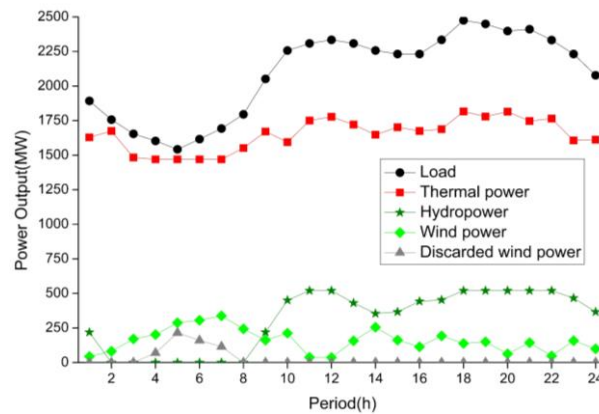


Figure 2. Power system output distribution under original load.

4.2. Influence of Plug-in Electric Vehicle Access on Power System Economic Dispatch

The results in figure 3 show that when the plug-in electric vehicle is connected to the grid in disorderly charging mode, the peak load is increased from 2475 MW to 2608 MW, and the peak period is moved from 18:00 to 21:00. At 5:00, the load valley is only increased from 1543 MW to 1555 MW, the load peak-valley difference is obviously increased, and the thermal power output volatility significantly increases. Because the charging load accesses the power system when the load is low valley, the amount of discarded wind power is slightly reduced. As can be seen from figure 4, when the plug-in electric vehicle is connected to the grid in the orderly charging mode based on time-of-use electricity price, the peak load remains at 2475 MW, and the time period is maintained at 18:00. The load valley rises to 1661 MW, and the load peak-valley difference drops significantly at 5:00.

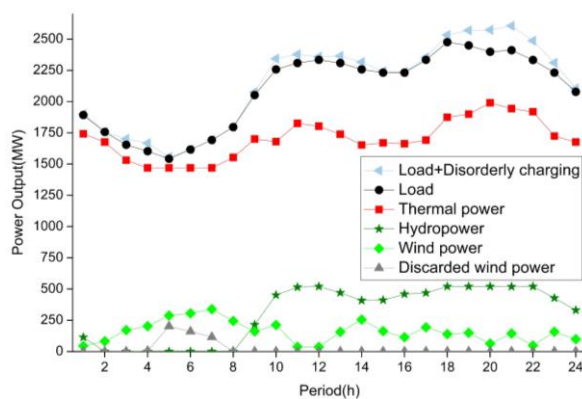


Figure 3. System output distribution in disorderly charging mode.

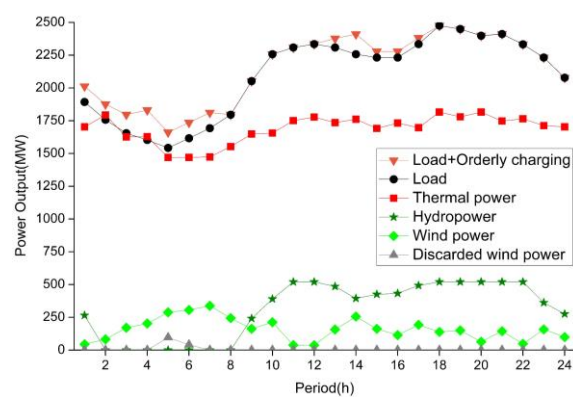


Figure 4. System output distribution in orderly charging mode.

The results can be seen from table 2 that the total coal cost in the free charging mode is 502226 dollars during the scheduling period, but the cost is only 493065 dollars in the orderly charging mode. This is because the orderly charging mode reduces the volatility of the thermal power output, and the thermal power output tends to be a stable value in each period. The thermal power units operate in the

economic zone and thus the coal burning cost is less. The thermal power unit operates in a steady output state, which reduces the pressure of adjusting the load peak, and the start-stop cost is also reduced accordingly. After adding the orderly charging load, the start-stop cost of thermal power units in the scheduling period decreased from 20402.9\$ to 18629.9\$. It can be concluded that the orderly charging mode based on time-of-use electricity price greatly reduces the impact on the power system compared with the disorderly charging mode, which reduces the coal burning costs and start-stop costs of power system and also decreases the discarded wind power.

4.3. Influence of battery-change electric vehicle access on power system economic dispatch

In figure 5 and figure 6, the effects of the V2G mode and the low valley charging mode on the power system output are discussed. The comparison between the power system operation cost and the discarded wind power are shown in table 2. According to Fig. 5, Fig. 6 and Table II, when EVs adopt the V2G mode, it can be seen that the load valley is charged, and the load peak time is discharged. Firstly, the amount of discarded wind power is effectively reduced from 559.9 MW to 295.1 MW. Secondly, in the comparison of the figures, the hydropower output is roughly the same, and the hydropower adjusts the load peak as much as possible under the premise of meeting the daily flow integral constraint. Thirdly, the thermal power output in the V2G mode is obviously stable than that in the low valley charging mode.

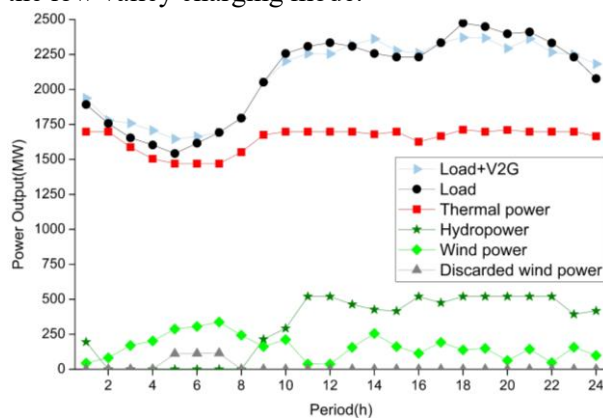


Figure 5. System output distribution in V2G mode.

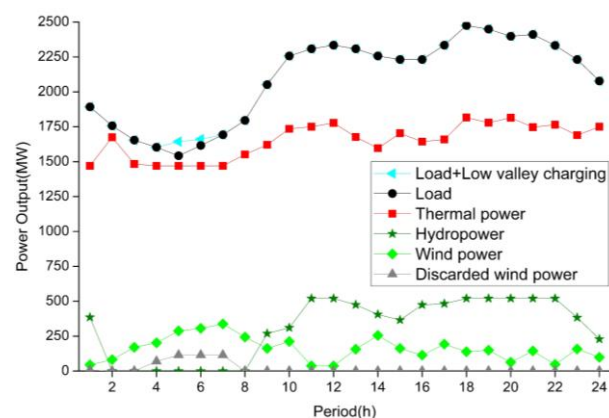


Figure 6. System output distribution in low valley charging mode.

The V2G mode has obvious advantages over low valley charging mode. The V2G mode makes the fluctuations of the hydropower and thermal power output smaller, and the system coal burning cost and start-stop cost are lower, and the amount of discarded wind power is less. It is because the electric vehicles in the V2G mode participating in the coordinated power grid dispatching can “shifting the load peak and filling the load valley”, which is meaning that EVs will store power system’s electricity in the battery during the period of discarded wind power or the load valley, and use the surplus value in the battery storage to discharge power grid during the load peak period, which reduces the power system backup capacity and the pressure of adjusting the system load peak.

Table 2. The power system operating cost and discarded wind power of different types of electric vehicles participating in power system scheduling.

Mode	Fuel cost(\$)	Start-stop cost(\$)	Discarded wind power(MW)
No EV	482418.5	20402.9	559.9
Disorderly charging	502225.9	20336.6	482.4
Orderly charging	493065.5	18629.9	136.9
V2G	472566.1	6614.2	295.1
Low valley charging	481535.1	20402.9	413.2

5. Conclusion

(1) The whole power system is decoupled into wind-vehicle-hydro subsystem and thermal power subsystem to facilitate optimization in this paper, which is proved to be correct by calculation and analysis of the simulation example. Therefore, the decoupling method can provide reference for multi-energy hybrid power system scheduling optimization.

(2) The IRBHPSO algorithm proposed in this paper enters the black hole with a certain probability and leaves the black hole with a certain probability. It not only retains the advantages of the RBHPSO and ordinary PSO algorithm, but also avoids the algorithm falling into the local optimal solution. So the improved algorithm converges faster and is more conducive to finding the global optimal solution.

(3) The simulation results show the scheduling scheme of this paper is reasonable and practical, which verifies the feasibility of the proposed scheduling model and the validity of the algorithm. If different system data is taken as an example, a practical scheduling plan for different situations can be obtained. Therefore, the model and algorithm can provide suggestions for the scheduling of large-scale electric vehicles accessing on the power grid. significant optimization effect on the economic dispatch of the power system.

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