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Multi-objective Optimal Scheduling Method for Power System Based on Wind Power Accommodation

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Abstract

The paper adopts the mobile-peak energy load as an important means to combine the traditional power grid scheduling with the conventional optimal scheduling of power system based on the effect of volatility and anti-peaking characteristics of large-scale wind power integration grid on the traditional power grid scheduling. The multi-objective optimal scheduling model for power system based on wind power accommodation is established on the basis of minimum operation cost of the system and the consumption of electric power network and maximum wind power accommodation. Then, the optimized non-dominated Sorting Genetic Algorithm II， NSGA-II is used to solve the corresponding equation. The calculation results show that the mobile-peak power load if being added to the energy grid system can significantly reduce the start and stop times of the conventional units, make the operation state of the power load more stable and reduce wearing of generators and improve the operation efficiency of the power system based on its good characteristic of peak load shifting. The operating cost of the optimized model is lower than the traditional model, at the same time, it also reduces the great turbulence of integrated power network loss of the system while reducing the cost of power network. The simulation results can provide theoretical guidance for the related engineering projects.

Key words

Wind Power Accommodation, NSGA-II, Mobile-peak power load, Multi-objective optimization model,

1. Introduction

Wind energy is a renewable, non-polluting energy and more and more countries have started to develop wind power technology [1-3], as it of prominent economic and environment effect. Since the scope of the electricity market in a majority of regions and wind power base are “reversely distributed”, the wind power must be connected to the traditional power grid for long-distance transmission, thus it is of great significance to research on the scheduling and optimization of wind power system [4-6]. Furthermore, it has become the problem to be solved urgently for large-scale connection system of the wind power.

Wind power has typical characteristics of intermittence and randomness and the output daily shows regular change between zero and rated output with obvious characteristic of anti-peaking. The the traditional resource regulation of power grid can not meet the demands of wind power accommodation, resulting in operation in wind abandoning for a long time for serious consequences, increasing operating costs and higher waste of resources. As the wind power accommodation is affected by many factors [7-8], it is quite necessary to optimize the wind power accommodation model of the connection grid and carry out research on scheduling of wind power system. For example, in some literature, the influence of the combined model of wind power system[9-11],connection grid of wind power and prediction error of power rate on the stability of power system[12-13]; in other researches, the optimum scheduling model of electric power system is designed according to the reverse deduction, the demand of the main electricity market and the secondary market[14-16].In the above literature, the optimization of power transmission system is analyzed respectively from the perspective of power generation and power demand. In fact, the power generation and the power demand are an organically integrated, moreover, in the background that the current power system adopts the smart grid for scheduling of power, the demand response as an important resource for interaction is an effective means to reduce the volatility of wind power and improve the scheduling ability of power system. The research in recent years are mostly based on hybrid intelligent algorithm and the dual-objective and multi-objective optimization scheduling models are put forward by comprehensive considering wind power accommodation and economic and environmental protection factors of wind power generation [17-19]. But they are lack of thorough research on the mechanism of these modes, so they are not able to show the intrinsic relationship between the unit group and the optimization goal for the decision maker.

The paper adopts the mobile-peak energy load as an important means to combine the traditional power grid scheduling with the conventional optimal scheduling of power system based on the effect of volatility and anti-peaking characteristics of large-scale wind power integration grid on the traditional power grid scheduling. The multi-objective optimal scheduling model for power system based on wind power accommodation is established on the basis of minimum operation cost of the system and the consumption of electric power network and maximum wind power accommodation. Then, the optimized non-dominated Sorting Genetic Algorithm II， NSGA-II is used to solve the corresponding equation. The calculation results show that the operating cost of the optimized model proposed in the paper is lower than the traditional model, at the same time, it also reduces the great turbulence of integrated power network loss of the system while reducing the cost of power network. The simulation results can provide theoretical guidance for the related engineering projects.

2. Multi-objective optimal scheduling model for power system based on wind power accommodation

2.1 Wind power output

As the wind power generation has the typical characteristics of intermittence and randomness, there are errors existing in the prediction results. The output power of wind power can be regarded as the sum of the short-time prediction of wind power output and prediction error.

$$P_O = P_p + \Delta P_e \tag{1}$$

P_O is the actual output power of wind power; P_p is the predicted power within the time; ΔP_e is the prediction error. Figure 1 is the predicted power of one wind power plant in one day, absolute value of the errors between the actual output power and the corresponding predicted power.

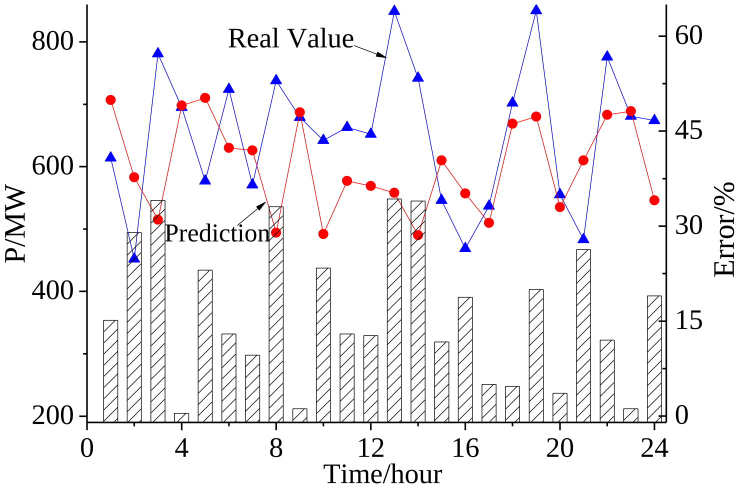

Fig.1 Output power and prediction error of wind power

Wind power is scheduled and transmitted through the traditional power system and the equivalent load of the system is:

$$P_E = P_L - P_O$$

(2)

P_L is the original active load of power system.

2.2 Mobile-peak energy load

In order to reduce the impact of turbulence of wind power on the prediction and regulation of electric power, the traditional approach is to retain a certain amount of positive and negative reserve. But the phenomenon that the output force of wind power being too high has led to wind abandoning of the power grid still exists, so the wind power accommodation is limited. Based on the above situation, this paper puts forward a interactive load model with mobile peak which can effectively improve the obstacle that the reserve capacity for short-term power generation of the power grid is in shortage caused by the transient large-scale connection of wind power. Interactive load refers to the ability to actively provide the willing of power utility and automatically adjust its power utility behavior according to the scheduling plan of the power grid so as to achieve the interactive load for users which operate with power grid.

The mobile-peak load can adjust the operation and scheduling of the power system based on the interaction mode of the source load and according to the willing curve of power consumption and the cost of mobile-peak in the power grid. The comprehensive willing curve of power consumption shows the characteristics of the load cycle, the output force variation, the start and stop time in the loading process and other parameters. The decision variables of high energy load for starting can be expressed as:

$$D_{Sj} = \begin{cases} 0 & t \neq t_{Sj} \\ 1 & t = t_{Sj} \end{cases}$$

(3)

D_{Sj}=0 shows that high energy load stops for operation within time t_{Sj}. D_{Sj}=1 shows that it is in operation in this period. The active load WL_{Sj} of high energy load with mobile-peak j within period t is:

$$WL_{Sj} = \left(1 - \sum_{t_1=1}^{T} D_{Sj}\right) WL_{Sj1} + \sum_{t_2=1}^{T_{Sj}} D_{Sj}^{t-t_2+1} S_j^{t_2}$$

(4)

In the equation, WL_{Sj1} is mobile-peak load value of original willing curve for power consumption within period t; S_j^{t2} is the load value after the mobile peak within time t_2;T_{Sj} and are respectively the peak load cycle and system scheduling cycle. On the basis of the adjusted and interrupted characteristics of high load and when the mobile-peak load is enabled, the limitation conditions based on equation 3 will place the curve sequence of power consumption in the different periods of active load according to the degree of power demand; when the mobile-peak load is stopped, the value of WL_{Sj} is determined according to the first item on the right of equation 4, which makes it the same as the willing curve for power consumption.

2.3 Objective function

The wind power accommodation can be enhanced effectively by adopting the mobile-peak high energy load, but at the same time, it increases the operation costs of high load energy in power grid system and the pollution degree to the environment. Therefore, the multi-objective optimization and scheduling model is established by considering the two parameters of accommodation ability of wind power and operation cost of the system, at the same time, the relevant security constraints of the power grid should also be taken into consideration.

a. The lowest operation cost for the system.

The operation cost of the system includes power generation cost and switching, startup and shutdown costs of the mobile-peak high energy load.

$$\min C_{oc} = C_{gen} + C_{rp}$$

(5)

C_{gen} is the cost of power generation and it is consisted by the operation cost and switching cost of the mobile-peak high energy load.

$$C_{gen}=\sum_{t=1}^{T}\sum_{j=1}^{N}\left\{U_{Gj}^{t}\left(\left[\alpha_j+\beta_j P_{Gj}+\gamma_j\left(P_{Gj}\right)^2\right]\right)+\left(1-U_{Gj}^{t-1}\right)\left[\eta_{0j}+\eta_{1j}\left(1-e^{\tau/\tau_j}\right)\right]\right\}$$

(6)

N is the number of generators; T is the operation cycle; $U^{t}{}_{Gj}$ is the decision variable of conventional units. When the value is zero, it is stopped; when the value is 1, it is started. P_{Gj} is the conventional output power; α、β、γ、η *and* τ are the cost parameters; C_{rp} is the startup and shutdown costs of mobile peak and its expression equation is:

$$C_{rp}=\sum_{t=1}^{T}\sum_{k=1}^{N}\lambda_k D_k P_k \Delta T$$

(7)

D_k is similar to equation 3; P_k is the capacity of mobile-peak high energy load; λ is the parameter of unit regulation cost.

b. The wind power is the minimum if the wind-power connection grid is not accommodated.

$$\min F=\sum_{i=1}^{N_w}\Delta P_{wi}$$

(8)

N_w is the number of wind power plants; ΔP_{wi} is wind power amount which is not accommodated for *i* wind power plant

c. It is the minimum cost of power grid.

In order to eliminate the extra wind power in the wind power system, the mobile-peak high energy load must be scheduled for utilization. In the process of scheduling for utilization, it will cause the change of flow distribution of the power grid system and lead to the network costs of power system, so B coefficient method is used to calculate the network costs of the system

$$\min L=\sum_{t=1}^{T}\left(\sum_{i=1}^{K}\sum_{j=1}^{K}P_i B_{ij} P_j+\sum_{i=1}^{K}B_{i,o}P_i+B_{o,o}\right)$$

(9)

K is the number of nodes of the system; B_{ij}、B_{io} and B_{oo} are parameters of B coefficient; P_i and P_j are the active power of any node.

2.4 Constraint conditions

For the wind power long-distance transmission of wind power accommodating, as the turbulence of wind power makes mobile-peak high energy load start and stop frequently, the security restraints must be made for the proposed model by corresponding conditions so as to ensure the stable operation of the power system.

a. Constraint for the power balance of system.

Power balance in the system is realized if the total output power of conventional power generation and wind power is equal to that of total load.

$$\sum_{i=1}^{N_O} P_{Oi} + \sum_{j=1}^{N} U_{Gj}^{t} P_{Gj} = P_L + \sum_{k=1}^{N_k} D_k P_k$$

(10)

P_L is the total output power bear by the system.

b. The accommodation constraint of wind power.

$$0 \le \Delta P_{wi} \le P_{wi}$$

(11)

c. Power constraints of conventional power output.

$$U_{Gj} P_{j\min} \le P_{Gj} \le U_{Gj} P_{j\max}$$

(12)

P_{jmin} and P_{jmax} are respectively the minimum and maximum output power of the conventional units.

d. Capacity constraint of high energy load.

$$P_{k\min} \le \sum_{k=1}^{N} D_k P_k \le P_{k\max}$$

(13)

P_{kmin} and P_{kmax} are respectively the minimum and maximum capacity of the high energy load

f. Time constraint of startup and shutdown of mobile-peak high energy load.

$$\begin{cases} \left(D_k^{t-1} - D_k^{t}\right)\left(T_{k,on}^{t} - T_{k,on}^{\min}\right) \ge 0 \\ \left(D_k^{t} - D_k^{t-1}\right)\left(T_{k,off}^{t} - T_{k,off}^{\min}\right) \ge 0 \end{cases}$$

(14)

$T^t_{k,on}$ and $T^t_{k,off}$ refer to the time duration of mobile-peak load within time t; the *min* on the right top side refers to the minimum cost of the load and the time of shutdown.

g. Integrity constraints of mobile-peak high energy load.

$$\sum_t I_{Sj}^t \quad t \notin [t_{Sj}, t_{Sj} + T_{Sj}]$$

(15)

The scheduling integrity of willing curve of power utilization in the demanding side can be guaranteed from 14.

3. Solution of multi-objective model

In terms of the multi-objective optimization scheduling problem in the power system, because of the multiple restraints of accommodation ability of wind power, operation cost of the system and the setup of upper section are in conflict and it is impossible to make multiple targets simultaneously realize the optimal solution. On the basis of the fact that the goal in this paper is to reduce the operation cost of the system as much as possible on the premise to satisfy all constraint conditions and maximize the wind power accommodation, therefore, in the set of many optimization results, it is necessary to find out the best compromise solution, that is to say, it is necessary to balance the scheduling schemes of the above objectives. The satisfaction degree of each objective function is defined by the fuzzy membership function.

$$m_i = \begin{cases} 0 & \varphi_{i\max} < \varphi_i \\ \dfrac{\varphi_{i\max} - \varphi_i}{\varphi_{i\max} - \varphi_{i\min}} & \varphi_{i\min} < \varphi_i < \varphi_{i\max} \\ 1 & \varphi_i < \varphi_{i\min} \end{cases}$$

(16)

Φ_i is the ith objective function; φ_{imin} and φ_{imax} are respectively the upper and lower limits of the objective function. According to equation 15, when m_i=0, the objective function is not in line with the optimization condition; when m_i=1, it means that scheduling staff are totally satisfied with the value of the objective function. The standardized satisfaction value of the objective function is:

$$M = \frac{1}{\mu} \sum_{i=1}^{\mu} m_i$$

(17)

μ is the number of quasi objective functions' is standardized satisfaction value; Therefore, the optimal compromise solution can be defined as a set of solutions that can not be further optimized without the value of any one of the objective functions. Therefore, the multi-objective optimization model of power system can be expressed as:

$$\begin{cases} \min \varphi_i(x) & i=1,2,\ldots,n \\ h_j\left(x\right) & j=1,2,\ldots,p \\ g_k\left(x\right) & k=1,2,\ldots,q \end{cases}$$

(18)

x is the decision vector; $h_j(x)$ is the equality constraint function; $g(x)$ is the inequality constraint function.

In this paper, the NSGA-II algorithm is used to resolve the multi-objective optimization problems, on such basis, the elitist reserve strategy is introduced and the fast non-dominated sorting method is used to improved the NSGA-II algorithm, so the detailed ideas are shown int the following content:

(1) Initial population. The active power of the conventional unit and the wind turbine can be regarded as continuous variable and the mobile-peak energy load can be regarded as a discrete variable based on the starting and stopping of the unit.

2) Carry out calculation of the the non-dominated sorting and crowding distance of the initial population to get the next generation population through genetic algorithm.

3) Merge the two-generation populations and find out the crowding distance between individuals. Moreover, new generation of parent population is formed through a series of rules, such as reorganization and non-dominance relation. At the same time, to ensure the diversity of the newly-merged population, in the calculation process, test individual u_{ij} based on the poor algorithm is obtained.

$$u_{ij}^{g+1} = \begin{cases} v_{ij} & rand(\cdot) \le C_r \\ u_{ij}^{g} & others \end{cases}$$

(19)

C_r is poor probability; *rand*() is the random number in [0,1].

(4) Solve the multi-objective optimization problem with constraint conditions based on evolutionary algorithm. Suppose the number of individuals u_{ij} and the competition of the parent population obtained through the third step, if the u_{ij} is in dominant position, it will selected in the final set; on the contrary, select the target function within the parent population. If the two are in a mutual non-dominant position, then they will enter the final set of choices at the same time.

4. Calculation cases analysis

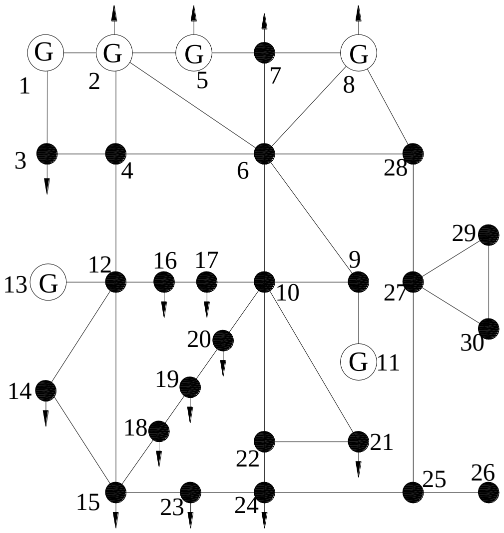

Fig.2 IEEE-RTS30 simulation system

The multi-objective optimization model proposed in this paper is simulated by the IEEE-RTS30 node system. The wiring diagram of the system simulation is shown in figure 2. The The system contains 1 wind plant, a total of 120 sets of wind motors with total capacity of 220MW and the node 27 is the connected nodes of wind power grid. The standby demand for the positive and negative rotation of the conventional unit in power system is 20% of the maximum capacity of the unit.

Three positions in 6, 12 and 30 consist the mobile-peak energy load and the power consumption curve of mobile-peak and mobile-peak cost are shown in Figure 3 with the time period being 24h.

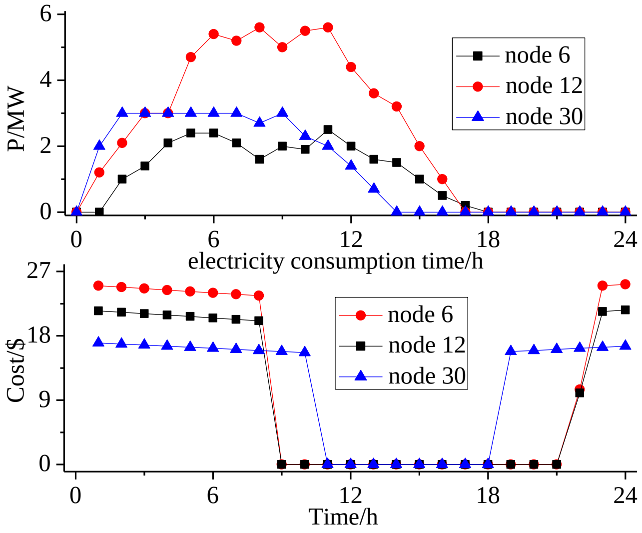

Fig.3 electricity consumption willingness and cost of shift able load

According to the survey of user's willingness of power shows that the peak hours of electricity users in the peak period is from 6-12 hours. After 12 hours, the power consumption is significantly reduced. In the aspect of mobile-peak costs, due to anti-peaking characteristics of wind power, the overall cost is higher in the midnight peak stage and it is lower in the day time.

Based on the willing of power consumption and mobile-peak cost shown in figure 3, the result of the multi-objective optimization of the system with minimum power network cost and operation cost of the system are shown in table 1.

Tab.1 Optimization results of network loss and operation cost

m	$C_{oc}/\$$	L/MW
0.403	585932	150.4
0.496	609387	145.3
0.537	628904	141.4
0.655	636261	127.9
0.782	636848	126.7
0.846	636939	124.6

From the calculation results in the table, it is seen that the overall degree of satisfaction is m=0.846 obtained by fuzzy membership function, at this time, the system operation cost Coc=$636939, the power network cost is: L=124.6MW. The regulation capacity of mobile-peak high energy load is larger and it can accommodate more wind power. After the power grid cost is reduced significantly after the regulation of high energy load. But the cost of the increased mobile-peak and the interruption compensation result in rising of the overall operating costs, which is unfavorable to the economic operation of the power grid. In general, the scheduling of more interactive load in wind power power grid accommodation can effectively reduce the overall operating cost of the system, and provide more spare power for the grid so that it is endowed with enough adjustment ability to deal with random turbulence of the wind power.

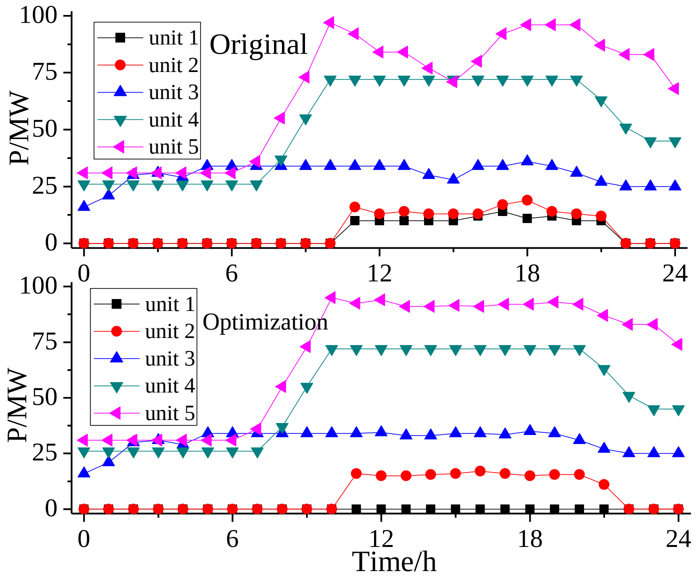

Fig.4 Output curve of conventional units by original model and optimization model

Figure 4 is the output change curve of 4 system nodes of traditional optimization model and the multi-objective optimization scheduling model of power system proposed in the paper. It is seen from the figure that the curve turbulence of the traditional optimization model is larger, this is because when the wind power output is bigger, the system reduces the power grid output while output is increased when the wind power is smaller. At the same time, because the ant regulation peak features of wind power output increases the peak valley difference of the system, the power grid peak can only be met by starting and stopping the node 3 of the .unit. In the multi-objective optimization model proposed in this paper, as the system has increased the mobile-peak high energy load, the peak and valley difference of the system can be significantly reduced by using the energy load when the wind power is fluctuated. The force output curve of the conventional units is obviously more stable than that of the traditional one in figure 4.

In order to further verify the superiority of multi-objective optimization model proposed in this paper, the traditional power system optimization model is compared with the model proposed in this paper. The wind power accommodation for the two situations is shown in Figure 5; the sampling interval is 15min; the sampling time is 24h. The sampling points are 98.

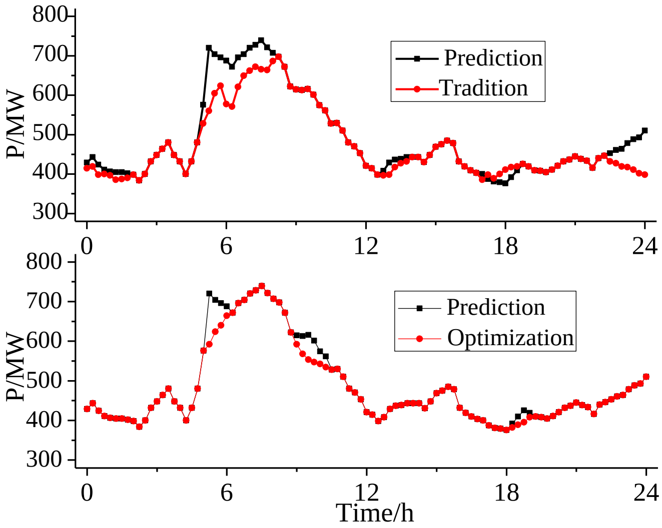

Fig.5 Wind dispatching by original model and optimization model

It is seen from Figure 5, when the traditional optimization scheme of power system is adopted, wind power accommodation of 40 time interval in the 98 sampling time intervals is restricted and the maximum limitation power is up to 160MW; the overall limitation power is up to 1766.4MW·h;when the multi-objective optimization model of wind power system proposed in the paper, only wind power scheduling of 14 time intervals is restricted and the maximum limitation power is only 95MW; the total limitation power is 603.2MW·h;when the conventional power is operating in the power system, as there is no mobile-peak high energy load within the grid and the wind power output is large, the conventional power must be close to the minimum output position in order to ensure the wind power accommodation, which not only increases the overall cost of operation, but also leads to a serious shortage of regulation ability of conventional power. Finally, it must be forced to abandon the wind source. The optimization model proposed in this paper can use less adjustment cost of high energy load to obtain less conventional power generation costs and higher wind power consumption level, which can improve the system economy and wind power accommodation level significantly.

In table 2,the the traditional model is compared with the multi-objective optimization model of power system with wind power accommodating from the three aspects of overall system cost, wind power amount of connection grid of wind power accommodation and wind power consumption. It is seen from the results that if the mobile-peak high energy load is added into the power grid system, the conventional unit start and stop times can be significantly reduced based on its perfect peak load shifting property so as to make the running state of power load more stable; reduce the wearing of generators and improve the running efficiency of the power system. The calculation results show that the operating cost of the optimized model proposed in the paper is lower than that of the traditional model, while reducing the large fluctuation of the wind power grid, the power network loss of the system is also reduced. It also reduces the great turbulence of integrated power network loss of the system while reducing the cost of power network. The limitation of random fluctuation and anti-peaking on the accommodation ability of the system can be reduced by exerting the interactive load on the wind power accommodation so as to improve capacity of accommodation of the wind power and effectively reduce the risk of wind abandoning.

Tab.2 The objective function results of different model

Method	Cost ($)	Network Loss (MW)	Wind Power Consumption (MW·h)
Tradition	661005	141.7	1766.4
Optimization	636939	124.6	603.2

5. Conclusion

(1) The multi-objective optimization model of power system based on wind power accommodation is established and optimized non-dominated sorting genetic algorithm of the second generation is adopted to solve the problem. The model has comprehensively considers the

cost of system operation, power network costs, wind accommodation of wind power connection grid and other factors.

(2) If the mobile-peak high energy load can be added to the power grid system, it can significantly reduce the start and stop times of the conventional unit based on its good peak load shifting characteristics. In this way, the power load will run more stably is more, reduce the wearing of the generator and improve the operation efficiency of the power system. The calculation results show that the operating cost of the optimized model is lower than that of the traditional model. It also reduces the great turbulence of integrated power network loss of the system while reducing the cost of power network.

(3) The limitation of random fluctuation and anti-peaking on the accommodation ability of the system can be reduced by exerting the interactive load on the wind power accommodation so as to improve capacity of accommodation of the wind power and effectively reduce the risk of wind “abandoning”.

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