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智能电网经济运行的多目标调度优化策略

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A Multiobjective Dispatch Optimization Strategy for Economic Operation of Smart Grids

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ABSTRACT: Monitoring, dispatching and optimal operation of power grids under new circumstances are discussed. Moreover, the security, economy and cleanliness for smart grids are evaluated with quantitative indices such as active power loss, emission pollution and voltage stability. Doubly fed induction generator (DFIG) model is integrated with the traditional optimal power flow (OPF) model in algorithm presented in this paper, and the impact of large-scale wind power integration on power systems is considered. Taking the above-mentioned indices as optimization objectives, the algorithm adopts strength Pareto evolutionary algorithm (SPEA2) to get solution for the optimization model. It is shown that the algorithm enables multi-objective optimization and multiple aspects for monitoring in smart grids. Therefore, it provides new thoughts for monitoring in smart grids.

KEY WORDS: smart grid; monitoring indices; doubly fed induction generator (DFIG); strength Pareto evolutionary algorithm (SPEA2); multi-objective optimization

摘要：探讨了新形势下电网监控调度和优化运行的问题。根据智能电网安全、经济、清洁的特点，以有功网损、污染气体排放量和系统电压稳定程度 3 个指标对电网的安全性、经济性和环保性进行量化评估，并将双馈感应发电机的模型加入到潮流计算的模型中，考虑了大容量风电并网对系统的影响，将上述指标作为优化目标，用强度 Pareto 进化算法对优化模型进行求解，并对上述 3 个优化目标进行寻优，很好地解决了智能电网中多方面的监测和多目标优化运行问题，为智能电网的监控运行提供了思路。

关键词：智能电网；监控指标；双馈感应发电机；强度 Pareto 进化算法；多目标优化

0　Introduction

Nowadays, many developed countries, like U.S., UK, France and Germany, have joined the research of smart grid and have proposed a comprehensive package of measures to boost the networks' security and competitiveness[1]. In China, the smart grid is also a hotspot in the development of electric power system. For example, the East China Grid Company Limited is promoting a smart grid related project, called Constructing Digital Grid and Informatized Enterprise. In a word, smart grid will be playing an essential role within the power industry in the 21st century.

A smart grid integrates electricity and communications in an electric network that supports the new generation of interactive energy and communication services and supplies digital quality electricity for the final customer, thereby having excellent features of being reliable, self-healing, fully controllable and asset efficient[2]. However, how to monitor the operating system and maintain safe operation economically and effectively, is an important subject in the research of smart grid, which is the focus of this paper.

Generally, the objective of optimal operation in power system may be to minimize the line losses of the system[3-4]. However, with the utilization of renewable energy and promotion of competitive electricity market, a considerable large amount of objectives, such as the environmental impact reduction and voltage stability improvement, have to be taken into account to ensure efficient operation of an interconnected power network[5-6]. Therefore, the optimal operation will be an optimization problem with non-convex, non-smooth, and non-differentiable multi-objective functions[7]. With classical optimization

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techniques, a multi-objective problem is converted to a single objective problem by linear combination of different objectives as a weighted sum. However, these techniques usually provide a unique optimal solution and the selection of weighting functions may seem to be arbitrary in most cases[8]. Thus, it is imperative to consider new optimization techniques that are efficient to overcome these drawbacks and have good performance in dealing with the above-mentioned multi-objective problem.

Besides, as a result of the promotion towards utilization of renewable energy resources, wind resource, as a kind of renewable energy, becomes more and more popular in many countries[9]. In practical applications of large-scale wind power, doubly fed induction generator (DFIG) has been the most common type of generator so far. Most of new wind farms in East China will employ DFIG based wind turbines. But the characteristics of the wind power, such as discreteness and randomness, have been proven to be the increasing threats to the stability and reliability of the grid[10]. The integration of big wind farms, equipped with DFIGs, will bring new challenges to optimal operation of electric power systems. Thus, making best use of the wind resource and maintaining the stable operation at the same time will be a great concern in the future. In conclusion, solving the multi-objective optimal power flow (OPF) equation with large wind farms is an important issue in the development of the East China Grid.

In this paper, a multi-objective OPF equation is described in detail, the mathematical model of DFIG and the proposed optimization method are presented, and several simulation cases are tested.

1 Multi-objective optimization of smart grid

1.1 Minimization of lineloss

One of the most important issues in economic operation of power system is the minimization of lineloss, which is also an objective commonly implemented in the conventional OPF. The lineloss can be expressed as:

$$F_1 = \sum_{i=1}^{N}\sum_{j=1}^{N} G_{ij}(U_i^2 + U_j^2 - 2U_iU_j\cos\theta_{ij}) \tag{1}$$

where G_{ij} is the real part of the branch admittance; N refers to the number of system buses; U_i and U_j refers to voltage of bus i and bus j; F_1 refers to the total real power losses; θ_{ij} is the phase angle difference between bus i and bus j.

1.2 Environmental impact reduction

As compared to conventional technologies, wind generation produces energy with less greenhouse gas emissions and other pollutants. It is of great benefit to the environmental protection[11]. Optimizing the wind farm integrated system should consider this factor and minimize the pollutants emitting from conventional power plant, which can be expressed as:

$$F_2 = \sum_{i=1}^{N_\mathrm{P}} \rho_{\mathrm{EI}i} G_{\mathrm{EBI}i} \tag{2}$$

with

$$\begin{cases} \sum_{i=1}^{N_\mathrm{P}} \rho_{\mathrm{EI}i} = 1 \\ 0 \le \rho_{\mathrm{EI}i} \le 1 \end{cases} \tag{3}$$

where $\rho_{\mathrm{EI}i}$ is the weighting factor for the ith pollutant; N_P is total number of pollutants of interest; $G_{\mathrm{EBI}i}$ is the amount of emissions of the ith pollutant and can be expressed as:

$$G_{\mathrm{EBI}i} = \sum_{j=1}^{B} P_{\mathrm{EG}j} G_{\mathrm{AE}ij} \tag{4}$$

where $P_{\mathrm{EG}j}$ is the electric energy generated by the jth conventional generator; $G_{\mathrm{AE}ij}$ is the amount of emission of the ith pollutant for the jth conventional generator per MWh of energy generated; B is the total number of conventional generators in the system.

1.3 Voltage stability improvement

Improving voltage stability is one of the most important concerns of operation practices. Although voltage stability is a dynamic problem, there is a scope to study the system using static approaches to estimate the distance of the operating point to the point of voltage collapse. Static approaches can provide a good insight of the system status via calculating stability indices[12]. In reference [13], a stability index, which indicates the severity of the loading stress in the network, is proposed according to Fig. 1. The index will reach a maximum value (close to 1) at a stage when it is very close to the point of collapse. So, voltage stability improvement can be

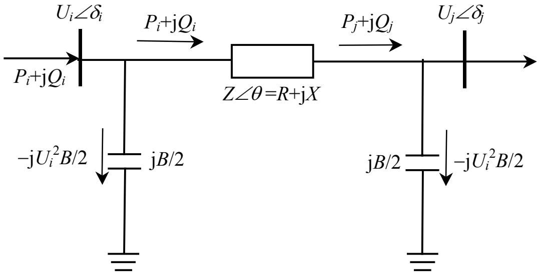

图 1 电力系统传输线模型

Fig. 1 The transmission line model of power system

achieved via minimizing the calculated values of the stability index. Equation of the index is given as:

$$L_{\mathrm{VSI}}=\frac{4P_j Z\cos\theta}{[U_i\cos(\theta-\delta)]^2} \tag{5}$$

where $\delta=\delta_i-\delta_j$; $U_i\angle\delta_i$ and $U_j\angle\delta_j$ are the sending and receiving end voltages; R and X are the line resistance and reactance respectively; $P_j+\mathrm{j}Q_j$ is the power injected into node j; L_{VSI} is designated as the stability index that indicates the status of the transmission line and approximately shows how close the operating point is to the limit of instability. For any value of L_{VSI} greater than 1, the system is considered to be unstable. If the network is loaded beyond this critical limit, U_j becomes imaginary and voltage collapse occurs at that point.

Therefore, the voltage stability index of the whole system can be defined as:

$$F_3=\max_{k\in S}(L_{\mathrm{VSI}k}) \tag{6}$$

where $L_{\mathrm{VSI}k}$ refers to voltage stability index of branch k; S is the branch set of the whole system.

1.4 Multi-objective optimization equation

In this paper, lineloss, emission of pollutant and voltage stability are all considered to realize multi-objective dispatch optimization. The optimization equation can be expressed as:

$$\min(F)=\min(F_1,F_2,F_3) \tag{7}$$

1.5 Problem constraints

Various technical, economic, and institutional aspects relating to the wind penetration problem had been addressed early in reference [14]. In order to retain acceptable service reliability, the operation of the wind-diesel system is constrained by the requirement that the wind generation must not exceed a certain percentage of the system load. This requirement introduces the interdependence between the wind generation and the system load, which should be taken into account in the operation. The wind generation is not allowed to exceed a certain part of the system load so that the wind generator cluster does not severely degrade the quality of the power line voltage waveform. Thus, the penetration level is given as:

$$\sum P_{\mathrm{WTG}i}\le\delta\sum P_{\mathrm{LD}} \tag{8}$$

where $P_{\mathrm{WTG}i}$ is the unit capacity of wind turbine; P_{LD} is the total system load; δ refers to wind penetration factor.

Consequently, a multi-objective OPF equation with large wind farms should consider various equality and inequality constraints. These constraints can be summarized as follows:

$$\begin{cases}P_{\mathrm{G}i}^{(k)}-U_i^{(k)}\sum\limits_{j=1}^{N}U_j^{(k)}(G_{ij}\cos\delta_{ij}+B_{ij}\sin\delta_{ij})=0\\ Q_{\mathrm{G}i}^{(k)}+C_i^{(k)}-U_i^{(k)}\sum\limits_{j=1}^{N}U_j^{(k)}(G_{ij}\sin\delta_{ij}-B_{ij}\cos\delta_{ij})=0\\ \sum\limits_{i=1}^{N_{\mathrm{G}}}P_{\mathrm{G}i}^{(k)}+\sum P_{\mathrm{WTG}i}=P_{\mathrm{D}}^{(k)}\\ \underline{P}_{\mathrm{G}i}\le P_{\mathrm{G}i}^{(k)}\le\overline{P}_{\mathrm{G}i},\quad(i=0\cdots N_{\mathrm{G}})\\ \underline{Q}_{\mathrm{G}i}\le Q_{\mathrm{G}i}^{(k)}\le\overline{Q}_{\mathrm{G}i},\quad(i=0\cdots N_{\mathrm{G}})\\ \underline{U}_i\le U_i^{(k)}\le\overline{U}_i,\quad(i=0\cdots N_{\mathrm{L}})\\ \underline{P}_{ij}\le P_{ij}^{(k)}\le\overline{P}_{ij},\quad(i=0\cdots N_{\mathrm{b}})\\ \underline{C}_i\le C_i^{(k)}\le\overline{C}_i,\quad(i=0\cdots N_{\mathrm{C}})\\ \sum P_{\mathrm{WTG}i}\le\delta\sum P_{\mathrm{LD}}\end{cases} \tag{9}$$

where $P_{\mathrm{G}i}^{(k)}$ and $Q_{\mathrm{G}i}^{(k)}$ stand for output of generator i in kth period; $C_i^{(k)}$ is the reactive power compensation capacities of generator i in kth period; $P_{\mathrm{WTG}i}$ refers to output of wind turbine; N_{G}, N_{L}, N_{b}, and N_{C} are the number of the generators, load buses, branches, and compensating capacitors respectively; $P_{\mathrm{D}}^{(k)}$ is the load in kth period; $P_{ij}^{(k)}$ is active power flow of line; $U_i^{(k)}$ is voltage amplitude of generator i; $\overline{P}_{\mathrm{G}i}$ and $\underline{P}_{\mathrm{G}i}$ are upper limit and lower limit of $P_{\mathrm{G}i}$ respectively; $\overline{Q}_{\mathrm{G}i}$ and $\underline{Q}_{\mathrm{G}i}$ are upper limit and lower limit of $Q_{\mathrm{G}i}$ respectively; $\overline{U}_i$ and $\underline{U}_i$ are upper limit and lower limit of U_i respectively; $\overline{P}_{ij}$ and $\underline{P}_{ij}$ are upper limit and lower limit of P_{ij} respectively; $\overline{C}_i$ and $\underline{C}_i$ are upper limit and lower limit of C_i respectively.

2 Mathematical model of wind power DFIG

The promotion towards utilization of renewable energy resources makes wind generation become more and more popular in many countries. The integration of large wind farms will bring new challenges to optimal operation of power systems, which will be an essential and urgent subject in future smart grid.

Many early wind farms are equipped with fixed-speed wind turbines induction generators. However, power efficiency of such wind generators is fairly low for most wind speed. In order to improve the efficiency and overcome other shortcomings of fixed-speed wind turbines, most modern wind generators adopt DFIG equipped wind turbines. DFIG has been the common type of generator in large wind farms. The equivalent circuit of DFIG is shown in Fig. 2, where $\dot{I}_{\mathrm{s}}$, $\dot{I}_{\mathrm{r}}$ and $\dot{I}_{\mathrm{m}}$ refer to the current

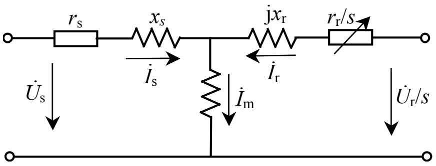

图 2　双馈感应发电机的等效电路

Fig. 2　Equivalent circuit of DFIG

that flows through stator, rotor and excitation winding respectively; r_r refers to rotor resistance; r_s is the stator resistance; x_s refers to stator reactance; s is the slip frequency, and can be obtained by the speed characteristic curve of wind turbines; $\dot{U}_s$ refers to the stator terminal voltage vector; $\dot{U}_r$ refers to the rotor terminal voltage vector; x_r refers to rotor reactance.

From this equivalent circuit, the following performance characteristics of DFIG[15] can be obtained. Rotor active power is:

$$P_r = \frac{r_r x_{ss}^2 (P_s^2 + Q_s^2)}{x_m^2 |U_s|^2} + \frac{2 r_r x_{ss}}{x_m^2} Q_s - sP_s + \frac{r_r |U_s|^2}{x_m^2} \quad (10)$$

where P_s and Q_s refer to stator active and reactive power; x_m refers to exciting reactance; $x_{ss}=x_s+x_m$.

So the total output of active power from DFIG equipped wind turbines is:

$$P_e = P_s + P_r = \frac{r_r x_{ss}^2 (P_s^2 + Q_s^2)}{x_m^2 |U_s|^2} + \frac{2 r_r x_{ss}}{x_m^2} Q_s + (1-s)P_s + \frac{r_r |U_s|^2}{x_m^2} \quad (11)$$

The output of reactive power from DFIG wind turbines is made up of two components, one is generated by the converter, and the other is from stator. Reactive power from converter is so small that this part of power can be neglected, and then the total output of reactive power from DFIG is approximately equal to stator reactive power Q_s. Ordinarily, DFIG wind turbines operate in two modes, namely Constant Power Factor Control and Constant Voltage Control. The former is to maintain the power factor of stator constant，and the latter is to provide the system with certain amount of reactive power to regulate voltage stability when system voltages are low. Generally, the former control mode is more widely used in wind farms. Therefore, in this paper, Constant Power Factor Control is considered as the operational mode of wind farms when calculating the power flow, and then the output of reactive power from DFIG is:

$$Q = P_s \tan\phi \quad (12)$$

where P_s is stator active power; ϕ refers to power factor angle, which is calculated by the given power factor.

3　Multi-objective optimization method

3.1　Pareto-optimal solutions

There are many multi-objective optimization problems in the real world, which involve simultaneous optimization of incommensurable and often competing objectives. Generally, single optimal solution may seem arbitrary, and a set of alternative solutions seems more natural for these problems. These solutions are optimal in the wider sense that no other solutions in the search space are superior to them when all objectives are considered. They are known as Pareto-optimal solutions. All Pareto-optimal solutions constitute the Pareto-optimal front or Pareto-optimal set. The core of multi-objective optimization method is to coordinate the relationship between various objective functions and to find the optimal solution set which makes solutions of all objective function be as maximal/minimal as possible.

3.2　Strength Pareto evolutionary algorithm 2 (SPEA2)

SPEA, an acronym for strength Pareto evolutionary algorithm, is a relatively recent technique for finding the Pareto-optimal set for multi-objective optimization problems. However, SPEA does not guarantee the extreme solutions to be kept in the archive, and appears to stagnate without having reached a well spread distribution of solutions. Hence, further progress has been made to overcome these shortcomings and improved SPEA (SPEA2) has been proposed in reference [16]. In contrast with SPEA, SPEA2 provides a better distribution of points, especially when the number of objectives increases. It has been widely used in different applications and has shown very good performance in comparison to other multi-objective evolutionary algorithms[17]. In this paper, the SPEA2 is applied to solve the proposed multi-objective OPF.

4　Simulation results

4.1　Parameters in calculation examples

The proposed multi-objective OPF equation with large wind farms is tested on a modified IEEE 30-bus test system. As shown in Fig. 3, the traditional generator of the 13th node is removed and replaced

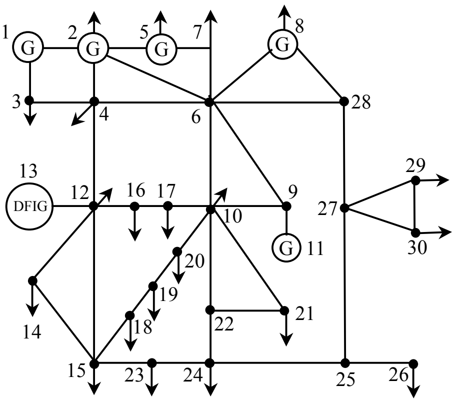

图 3 IEEE 30 节点系统的结构

Fig. 3 Structure of IEEE 30-bus system

with a wind farm that has 14 wind turbine units, each of which operates in parallel, and the rated power is 1.5 MW. Besides, this test system has 5 traditional generators, 4 transformers, and 4 reactive power compensators, with a total active and reactive power demand of 272.8 MW and 124.3 Mvar respectively. The characteristics of wind turbines equipped with DFIG are listed in Tab. 1 and Tab. 2. Pollutant emission of each generator in IEEE 30-bus system is shown in Tab. 3. The wind generators adopt constant power factor control strategy, and power factor is 0.95. Single wind generator parameters are as follows: r_s=0.001 692 Ω, x_s=0.036 92 Ω, r_r=0.002 423 Ω, x_r=0.037 59 Ω, x_m=1.456 8 Ω, and synchronous speed is 1 000 r/min, speed range is 700 r/min to 1 220 r/min.

表 1 双馈感应发电机的功率特性

Tab. 1 Power characteristics of DFIG

Wind speed/(m/s)	3	4	5	6	7	8
Output/kW	0	33.4	97.7	199.9	332.2	502.1
Wind speed/(m/s)	9	10	11	12~25	>25	
Output/kW	716.4	978.3	1 294.6	1 500	0	

表 2 双馈感应发电机的转速–风速特性

Tab. 2 Rotational speed-wind speed characteristics of DFIG

Wind speed/(m/s)	1	2	3	4
Rotational speed/(r/min)	154.13	308.26	462.38	683.30
Wind speed/(m/s)	5	6	7	8
Rotational speed/(r/min)	683.30	683.30	793.12	915.14
Wind speed/(m/s)	9	10	11~25	
Rotational speed/(r/min)	1 024.95	1 134.77	1 220.18	

表 3 IEEE 30 节点系统发电机的污染气体排放量

Tab. 3 Pollutant emission of generators in IEEE 30-bus system

Generator Number	Node Number	CO_2/(kg/MW·h)	SO_2/(kg/MW·h)	NO_x/(kg/MW·h)
1	1	850	1.0	1.2
2	2	750	0.8	1.0
3	5	900	1.1	1.3
4	8	800	1.2	1.2
5	11	820	1.1	1.0

4.2 Optimization results and discussions

The proposed OPF equation is handled as a multi-objective problem where voltage stability, network losses and pollutant emission were optimized simultaneously by using SPEA2. The calculated Pareto-optimal front is shown in Fig. 4. It is clear that the proposed method provides a better distribution of points, having good characteristics of diversity. And the obtained Pareto-optimal solutions are well distributed.

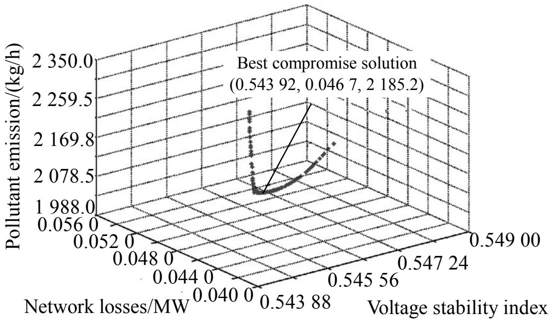

图 4 最优解集的分布情况

Fig. 4 Distribution of optimal solutions

It can be seen from Fig. 4 that there are conflicts among the considered three objectives. It is very unlikely that all the considered objectives are best optimized at the same time. Therefore, a whole set of optimal alternatives, offering a wide variety of options for the decision maker to choose before deciding which solution is the best compromise of different features, is of great importance. But in real application, only one optimal solution is needed, and selecting the required solution from the obtained non-dominant solutions is essential in the decision making.

In practical decision making, the decision makers can select the optimal solution according to their special requirements. For example, the optimal alternative with small value of voltage stability index can be selected as the optimal solution when stable operation is a top priority, the optimal alternative with small value of network loss can be selected as the optimal solution when economic operation is a top priority, and the optimal alternative with small value of pollutant emission can be selected as the optimal solution when environmental protection is a top priority. However, when there is no oriented target, the unbiased solution (best compromise solution shown in Fig. 4) can be chosen as the best solution, where the three objectives are optimized and compromised as much as possible at the same time.

4.3 Results of various methods

Because of the randomness of wind power, the output of wind turbines is changing dynamically. So the OPF equation with wind farms is a dynamic process. Result comparison of various methods, considering different penetration levels of wind generation, is shown in Fig. 5. The outputs of wind turbines at different penetration levels are shown in Tab. 4. The results, corresponding to the proposed method in Fig. 5, are the unbiased solution. It is apparent that the optimal results obtained by the proposed method are better than others, thereby further demonstrating their great superiorities over others. From the foregoing discussion, we can see that the proposed OPF equation will be an efficient method for multi-objective optimal operation of future power systems integrated with large wind farms.

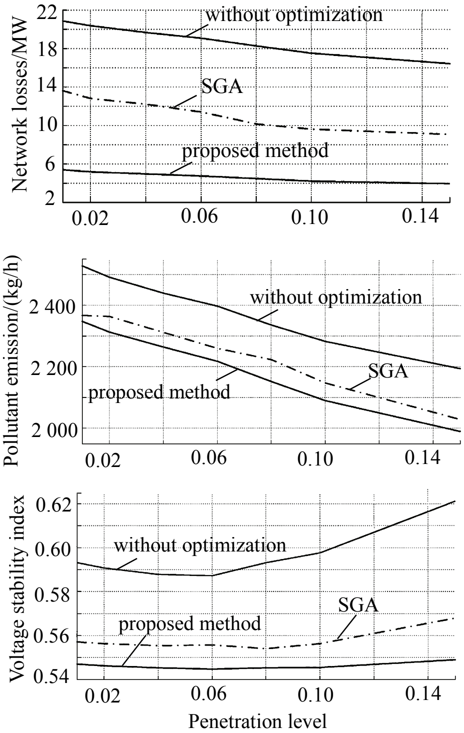

图 5 各种算法在不同穿透功率下所得结果的比较

Fig. 5 Result comparison of various algorithms at different penetration levels

表 4 不同穿透功率下的风机出力

Tab. 4 Outputs of wind turbines at different penetration levels

Penetration level	0.02	0.04	0.06	0.08	0.10	0.12	0.14
$P_{\mathrm{WTG}i}$/MW	5.456	10.912	16.368	21.824	27.28	32.736	38.192

5 Conclusion

In this paper, a new way of ensuring multi-objective optimal operation of future smart grids has been proposed. The obtained results have led to the following conclusions:

1) Three aspects of power grids, security, economy and cleanliness, are evaluated quantitatively with three indices in this paper, all of which, however, may seem insufficient for monitoring, dispatching and optimal operation in future grids, thereby calling for more work on this subject.

2) This article provides new thoughts for monitoring and dispatching in smart grids. But the application and realization of these thoughts remain to be discussed and determined.

3) The economy of network operation, taken as one of the optimization objectives in the proposed algorithm, is considered in this paper. Nevertheless, the economy of power generation is not taken into account, which is also deemed as an important factor in the optimal operation. The coordination of economy of both generation side and network side under new circumstances in smart grids needs further research and study.

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