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Demand response for frequency control of multi-area power system

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Abstract Over the last few years, lots of attentions have been given to the demand response (DR) for the frequency control. DR can be incorporated with traditional frequency control method and enhance the stability of the system. In this paper, the frequency control strategy of DR for a multi-area power system is specially designed. In order to quickly stabilize the frequency of different areas, the tie-line power is adopted as the additional input signal of DR. To get the optimal parameters of the control system, the frequency control problem is formulated as a multi-objective optimization problem, and the parameters such as the integral gains of secondary frequency control, the frequency bias parameters, and coefficients of DR are optimized. Numerical results verify the effectiveness of the proposed method.

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1 Introduction

Frequency control plays an important role in balancing the electric supply and consumption. If there is an imbalance between electric supply and demand, system frequency will increase or decrease, and the generators will reduce or increase electric power supply accordingly, to make the frequency restore to the nominal value.

Nowadays, increasing attentions are given to the demand response (DR) in the frequency control [1–11]. With the help of the advanced metering technologies, some electrical appliances can increase or decrease their power consumption in response to the frequency deviation, to support the frequency control. The electrical appliances which participate in DR are usually non-essential loads (i.e. refrigerators, freezers, and water heaters). These loads can store thermal energy (heat or cold), just like batteries. Therefore, temporarily increasing or decreasing their power consumption would not cause much inconvenience to residents. Focusing on the frequency control strategies by DR, a variety of control strategies, e.g. hill climbing control method [6], disturbance-magnitude-estimation based method [7], linear quadratic regulator (LQR) based method [8], $H\infty$ control method [9], etc. have been developed. Most of these methods are verified on the models of single-area power system, and show good performance.

As for multi-area power systems, the tasks of frequency control become more complicated. For a multi-area power system, the frequency control should not only maintain area frequency, but also consider the tie-line power between areas. However, very few attentions have been paid to the design of a proper frequency control strategy with DR for a multi-area power system. References [10, 11] applied DR in the multi-area power system. Though the frequency stability is enhanced by DR, the control strategies in [10, 11] are not the best design for the multi-area power system. In [10, 11], only the area frequency is adopted as the input signal of DR. This kind of control method is weak in stabilizing the frequency in different areas.

However, the conventional generation-side tie-line bias control (TBC) method [12–15] provides a good motivation to improve the DR control strategy for the multi-area power system. The TBC activates according to the area control error (ACE) signal, which contains information of both area frequency and tie-line swing. The feedback of the tie-line swing has the following merits:

1) Firstly, it can regulate both area frequency and the tie-line power flow [14].
2) Secondly, it can share generation and frequency support between the interconnected areas [15].

Notwithstanding the advantages of the TBC approach, it is a kind of generation-side frequency control. Little attention has been paid to the load-side control considering the tie-line swing. To fill this gap, this paper makes an improvement on the existing DR control strategy. The main work includes:

1) Propose a DR control method that introduces the tie-line swing as the additional feedback control signal. By this way, the frequency in each area can be well stabilized.
2) Apply the optimization technique to the control system, such that the parameters of the control system are well optimized.

The remainder of this paper is organized as follows. The model development is presented in Section 2. The optimization of the system parameters is presented in Section 3. Numerical case studies are provided in Section 4. Finally, conclusions are summarized in Section 5.

2 Model development

2.1 Frequency response model of a multi-area system

In order to investigate DR's effect on the multi-area power system, here we consider a three-area power system which is supplied by reheated steam generators [16], as is shown in Fig. 1. In Fig. 1, Δf_i is the frequency deviation of area i; s is the laplace operator; H_i is the generator inertia of area i; D_i is the load-damping factor of area i; R_i is the speed droop parameter of area i; B_i is the frequency bias parameter of area i; $\Delta P_{\text{tie},i-j}$ is the tie-line power deviation between area i and j; $\Delta P_{\text{d}i}$ is the disturbance power in area i. $\Delta P_{\text{d}i} < 0$ for a sudden increase in generation, while $\Delta P_{\text{d}i} > 0$ for a sudden increase in load. $P_{\text{DR}i}$ is the DR power (the amount of the power consumption which need to be shed-off or lowered by DR) in area I; T_{i-j} is the tie-line time constant between area i and j; K_i is the integral gain of the automatic generation control (AGC) in area i; a_{ij} is the base change coefficient; T_{gi} is the speed governor time constant of area i; $F_{\text{HP}i}$ is the power fraction of the HP turbine section of area i; T_{ri} is the reheat time constant of area i; T_{ti} is the turbine time constant of area i.

The base power of the three areas are assumed to be 800, 1000, 1200 MW, respectively. Therefore, the base change coefficients a_{12}, a_{23}, a_{13} are $-800/1000$, $-1000/1200$, $-800/1200$, respectively.

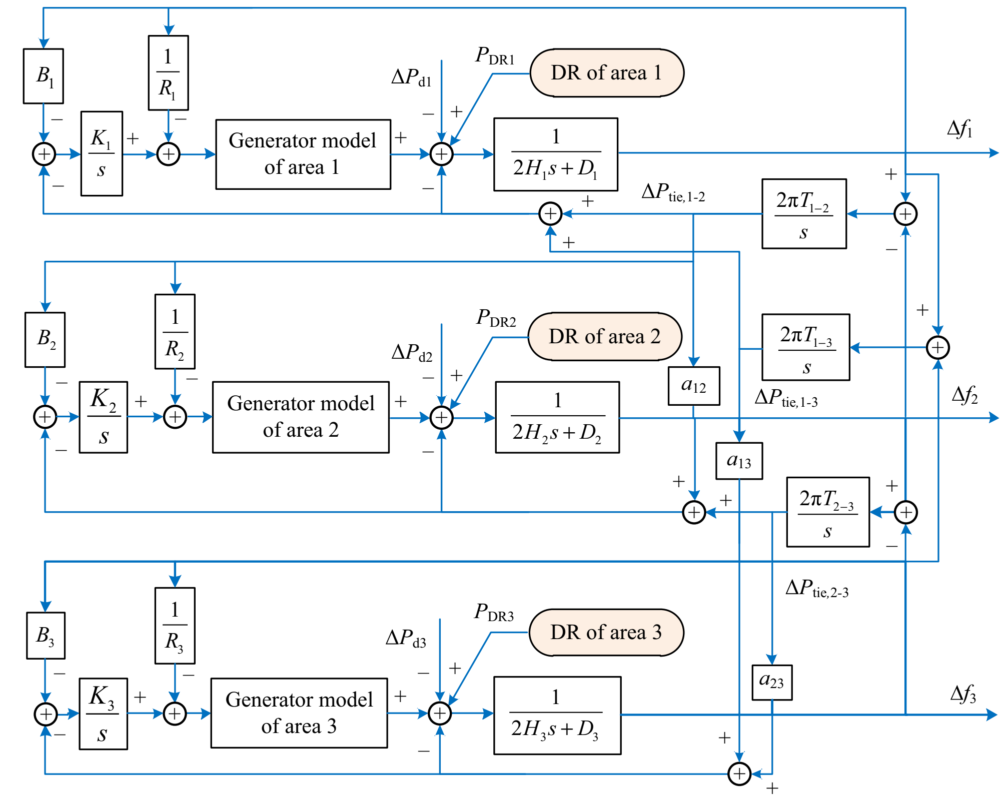
As can be seen from Fig. 1, each area is equipped with primary frequency control and automatic generation control (AGC) system. If there's a sudden disturbance that makes the frequency decline, the primary frequency control takes the first step to intercept the frequency fluctuation. The AGC is performed to adjust the area frequency and the tie-line power to their nominal values. When these frequency control methods are unable to stop the frequency decline, under-frequency load shedding (UFLS) may operate to protect the system from collapsing.

To enhance the stability of the power system, in the considered power system the DR is implemented in each area. When the sudden disturbance occurs, DR will be activated (to shed-off or lower the power consumption of some electrical appliances) to cause a change of $P_{\text{DR}i}$ to the total demand, in order to support the frequency control.

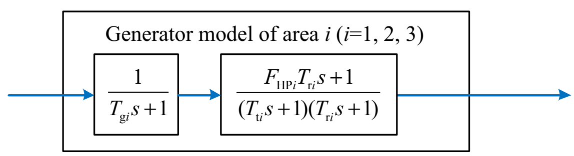
2.2 DR control strategy

Each DR appliance for the frequency control mainly consists of two parts [1]: the electrical appliance and the controller. The electrical appliance may be an electrical water heater, a refrigerator, or an air conditioner, etc. And the controller can automatically change the on/off state or smoothly adjust the power consumption of the appliance (according to some control strategy) to support the frequency control. Though a single DR appliance contributes very little to the system frequency, numerous DR appliances can have a great impact on the system frequency [1–11].

The performance of DR in the frequency control depends on the control strategy of DR. In the past a few years, lots of DR frequency control strategies are proposed. Nearly all the DR control methods are based on the frequency deviation Δf [1–11]. For example, if the frequency deviation Δf is detected below some threshold, some amount of DR appliances will be activated. By properly managing the power consumption of large amount of DR appliances, the DR's



(a) General model of the three-area power system



(b) Generator model of area i

Fig. 1 Frequency response model of three-area power system

aggregate frequency response characteristic can be similar to the conventional thermal generators (shown in Fig. 2) [2, 3]. It should be noted that the response of a single DR appliance is usually discrete, since most of the DR appliances can only be switched on or off. However, if we manage the frequency threshold of each DR appliance properly, the aggregate DR can provide a smooth frequency response characteristic which is shown in Fig. 2.

In Fig. 2, the total amount of the activated DR resource $P_{\mathrm{DR}i}$ -can be formulated as

$$P_{\mathrm{DR}i} = \begin{cases} -P_{\mathrm{DR\ max}i} & \Delta f_i > \Delta f_{\mathrm{max}i} \\ -k_{\mathrm{DR}i}\Delta f_i & -\Delta f_{\mathrm{max}i} \le \Delta f_i \le \Delta f_{\mathrm{max}i} \\ P_{\mathrm{DR\ max}i} & \Delta f_i < -\Delta f_{\mathrm{max}i} \end{cases} \quad (1)$$

where $k_{\mathrm{DR}i}$ is a pre-defined coefficient; $\Delta f_{\mathrm{max}i}$ is the frequency regulation range by DR, and $P_{\mathrm{DRmax}i}$ is the maximum available DR for the frequency control. The value of $k_{\mathrm{DR}i}$ can be determined by:

$$k_{\mathrm{DR}i} = \frac{P_{\mathrm{DRmax}i}}{\Delta f_{\mathrm{max}i}} \quad (2)$$

For these control methods, the only input signal for the DR controller is the frequency deviation, and the tie-line swing between the areas is not considered. Therefore, these DR control strategies aim at only restoring the area frequency. These control strategies are not good for damping inter-area oscillations and stabilizing the frequency in different areas.

Here we propose a frequency control method considering not only area frequency, but also the tie-line swing between the areas. For the area i, the activated DR resource $P_{\mathrm{DR}i}$ -takes the following expression:

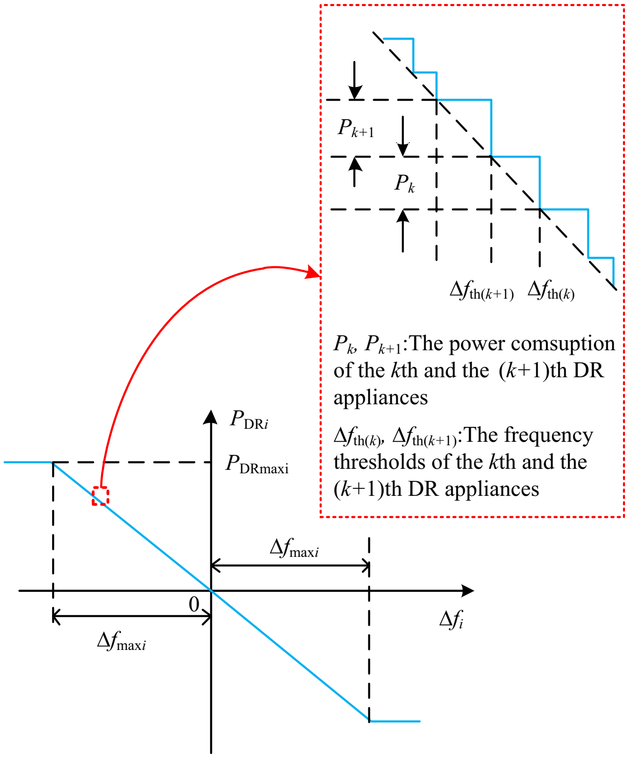


Fig. 2 Frequency response characteristic of aggregate DR

$$P_{\mathrm{DR}i}=\begin{cases}-P_{\mathrm{DRmaxi}} & \Delta f_i>\Delta f_{\mathrm{maxi}}\\ -k_{\mathrm{DR}i}\Delta f_i-l_{\mathrm{DR}i}\sum\limits_{\substack{j\in N_{\mathrm{A}}\\ j\neq i}}\Delta P_{\mathrm{tie},i-j} & -\Delta f_{\mathrm{maxi}}\le\Delta f_i\le\Delta f_{\mathrm{maxi}}\\ P_{\mathrm{DRmaxi}} & \Delta f_i<-\Delta f_{\mathrm{maxi}}\end{cases}\tag{3}$$

where $l_{\mathrm{DR}i}$ is a pre-defined coefficient and N_{A} is the number set of the areas. The first term and the second term in (3) (under conditions $-\Delta f_{\mathrm{max}i}\le\Delta f_i\le\Delta f_{\mathrm{max}i}$) are the feedback of the frequency deviation and the feedback of the tie-line power deviation, respectively. The corresponding block diagram of (3) is shown in Fig. 3.

Since primary frequency control is critical to the power system stability, the activated DR resource $P_{\mathrm{DR}i}$ should be strictly according to the frequency deviation (e.g. Eq. (3) and Fig. 3) without the economic concern. However, the parameter $P_{\mathrm{DRmax}i}$ can be properly scheduled to achieve some economic objectives, e.g. minimizing the operation costs. The $P_{\mathrm{DRmax}i}$ can be considered as the primary reserve that provided by DR. Therefore, the determination of $P_{\mathrm{DRmax}i}$ can be incorporated in the day-ahead or in-day scheduling problems. By solving the scheduling problem, the optimal dispatch of $P_{\mathrm{DRmax}i}$ and other resources (e.g. the primary reserve provided by the traditional thermal generators) can be obtained. Due to the focus of this paper, we do not discuss much about the DR scheduling. But one should note that, in a real power system, $P_{\mathrm{DRmax}i}$ may be

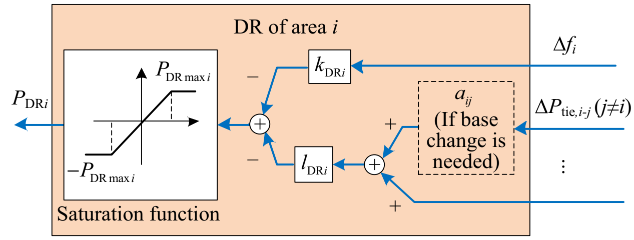


Fig. 3 Block diagram of the proposed DR control method

continuously changing. Therefore, once $P_{\mathrm{DRmax}i}$ is changed, it is necessary to recalculate $k_{\mathrm{DR}i}$ and other parameters. In addition, the system operators should sign contracts with the electric consumers for offering DR. These contracts will allow the system operator (or the aggregators) to manage the electricity consumption of the DR appliances through a technology named Virtual Power Plant (VPP) [2, 17, 18]. And the consumer will get some payment in return. These contracts guarantee the reliability of the DR resources when the grid needs them in the frequency control.

Instead of the proportion-integral (PI) controller [8, 10, 11], our DR control strategy only adopts proportional controller. The reason that we do not adopt the PI controller is because the integral element will permanently change $P_{\mathrm{DR}i}$. In another word, even after the system frequency is restored to the nominal value, the PI controller cannot reduce $P_{\mathrm{DR}i}$ to zero. This will permanently change the electric load and may cause inconvenience to the electric consumers.

3 Optimization of parameters

The purpose of this section is to optimize the parameters of the multi-area frequency control system. The parameter settings of DR integrated power system are very important. On one hand, the settings of the DR parameters are very important for DR's effectiveness. Improper setting of parameters will negatively affect the system's performance. On the other hand, the system characteristics changes when DR participates in the frequency control. The AGC parameters should be reset accordingly to get better response characteristics. Therefore, in this paper, the optimization should consider not only the DR parameters, but also the AGC parameters.

In the control system, the droop parameter R_i and DR coefficient $k_{\mathrm{DR}i}$ are fixed, because these parameters are related to the requirement of primary frequency control, and are dependent on how much primary reserve the generator or the DR can deliver.

Though the frequency bias parameter B_i is usually set equal to the area frequency response characteristic (AFRC)

[19]. It can also be optimized in order to obtain a better frequency control performance [16]. Furthermore, other control parameters, i.e. the integral gain of AGC K_i, and DR coefficient $l_{\mathrm{DR}i}$, need to be properly determined.

To implement the optimization, a proper objective function should be determined firstly. According to [16], the objective function is defined as the integral square error (ISE) of the area frequency deviation and the tie-line power:

$$\min \int_0^T \Delta f_i^2 \mathrm{d}t + \int_0^T \Delta P_{\mathrm{tie},i-j}^2 \mathrm{d}t \quad (4)$$

However, the objective function has the following weaknesses:

1) It only optimizes the frequency and tie-line power of one particular area (area i), but does not take into account the optimization of other areas.
2) The optimization only considers one particular situation (e.g. step disturbance in area i), but does not consider other situations (e.g. step disturbance with different magnitude in different areas)

In view of the above, the objective function can be modified as following:

$$\min \sum_{s\in N_{\mathrm{S}}} \left(\sum_{i\in N_{\mathrm{A}}} W_{i,s} \int_0^T \Delta f_{i,s}^2 \mathrm{d}t + \sum_{\substack{i,j\in N_{\mathrm{A}} \\ i\neq j}} W_{i-j,s} \int_0^T \Delta P_{\mathrm{tie},i-j,s}^2 \mathrm{d}t \right) \quad (5)$$

where $W_{i,s}$, $W_{i-j,s}$ are the weighting factors; $\Delta f_{i,s}$ is the frequency deviation of area i in the s^{th} scenario, and N_{S} is the number of scenarios. Compared with the function in (4), the modified objective function in (5) makes the main improvement that it considers the frequency of different areas under different scenarios (scenarios of disturbances with different magnitude in different areas). For the considered three-area power system, the objective function in (5) considers 6 scenarios:

Scenario 1: 0.5% step disturbance in Area 1;
Scenario 2: 1% step disturbance in Area 1;
Scenario 3: 0.5% step disturbance in Area 2;
Scenario 4: 1% step disturbance in Area 2;
Scenario 5: 0.5% step disturbance in Area 3;
Scenario 6: 1% step disturbance in Area 3.

Note that the Scenarios 1 $\sim$ 6 only give an example of the scenarios in (5). The determination of the scenarios should be based on the actual requirements.

Based on the objective function in (5), the optimization can be implemented. In this paper, the parameters B_i, K_i, and $l_{\mathrm{DR}i}$ are optimized by the genetic algorithm (GA) method. GA is a robust optimization technique based on the principles of evolution [20, 21]. Different with traditional optimization methods, GA searches for a global optimal solution and does not need to calculate the gradient of the objective function. These features make GA suitable to solve a variety of complicated problems.

The steps to implement the GA method are as follows:

Step 1: Generate a random initial population of chromosomes.
Step 2: Evaluate the fitness of each chromosome based on the objective function in (5).
Step 3: Select the fittest members of the population.
Step 4: Reproduce the next generation population.
Step 5: Execute crossover operation on the reproduced chromosomes.
Step 6: Execute mutation operation on the reproduced chromosomes.
Step 7: Repeat Step 2–Step 6 until the end criterion is satisfied.

Here we utilize optimization toolbox of MATLAB to implement GA. GA parameter settings are: population size is 20; crossover rate is 0.8; mutation rate is 0.1; the number of generations is 50 [3]. Numerical results are presented in the next section.

4 Numerical results

In this section, numerical case studies are performed to verify the proposed method. The system model adopts the three-area power system in Fig. 1, with the parameters listed in the appendix. In the optimization, the weights $W_{i,s}$, $W_{i-j,s}$ are equally set to 1 without special statement.

4.1 Comparison of the DR control methods

Here we examine the performance of proposed DR controller (in (3)). For the contrast study, the following 3 cases are investigated:

Case 1: No DR participates in the frequency control (indicating that $P_{\mathrm{DR1}} = P_{\mathrm{DR2}} = P_{\mathrm{DR3}} = 0$).
Case 2: DR participates in the frequency control. The activated DR resource $P_{\mathrm{DR}i}$ is only based on the frequency deviation (in (1)). This idea is in accordance with many existing DR control methods [2–6].
Case 3: DR participates in the frequency control. The activated DR resource $P_{\mathrm{DR}i}$ is based on the proposed method (in (3)).

The parameters B_i, K_i, and $l_{\mathrm{DR}i}$ of the Cases 1 $\sim$ 3 are based on the GA optimization results. In the optimizations, the objective function in (5) is adopted, and the system model depends on the each case.

The parameters B_i, K_i, and $l_{\mathrm{DR}i}$ for Cases 1 $\sim$ 3 are listed in Table 1.

Table 1 Optimized parameters B_i, K_i, and l_{DRi}

Optimized parameter	Case 1	Case 2	Case 3
B_1	23.90	49.69	48.71
B_2	16.61	49.78	15.40
B_3	19.95	47.01	15.62
K_1	0.09	1.11	1.85
K_2	0.27	0.52	0.55
K_3	0.18	0.39	0.53
l_{DR1}	–	–	18.22
l_{DR2}	–	–	35.67
l_{DR3}	–	–	46.22

Considering 1% step disturbance in Area 1 ($\Delta P_{d1} = 0.01$ p.u.), the simulation results are shown in Fig. 4. From the simulation results we have the following observations:

1) Compared with the case without DR (Case 1), the cases with DR (Case 2 and Case 3) tend to have a smaller frequency deviation and shorter settling time, indicating the DR can support the frequency control.
2) In contrast with Case 2, the case with the proposed method (Case 3) is faster in settling the oscillations of the tie-line power, and results in smaller frequency deviation in Area 1. Case 2 results in larger than 0.022 Hz maximum frequency deviation in Area 1. However, as for Case 3, the frequency drop in Area 1 is limited to 0.012 Hz, and the maximum frequency deviation of all the three areas does not exceed 0.016 Hz. It indicates that the proposed method (Case 3) has better comprehensive performance than the methods [2–6] in stabilizing the system frequency in all the areas. When there's disturbance in Area 1, the DR resources in Area 2 and Area 3 can also provide strong support for frequency control in Area 1 (Fig. 4h, i), so that the maximum frequency deviation can be reduced.

Table 2 summarizes the maximum frequency deviation of the 3 areas in each case. It can be seen that Case 3 (with the proposed method) results in smallest value of maximum frequency deviation, indicating the proposed method is superior to the other cases.

4.2 Comparison of the optimization cases

This subsection is to examine the effectiveness of the proposed optimization method. In the following, the DR controller adopts (3). The optimization of the parameters B_i, K_i, and l_{DRi} is what we are interested with. For the contrast study, here we also consider 3 cases:

Case 1: The parameters B_i, K_i, and l_{DRi} are determined without optimization.

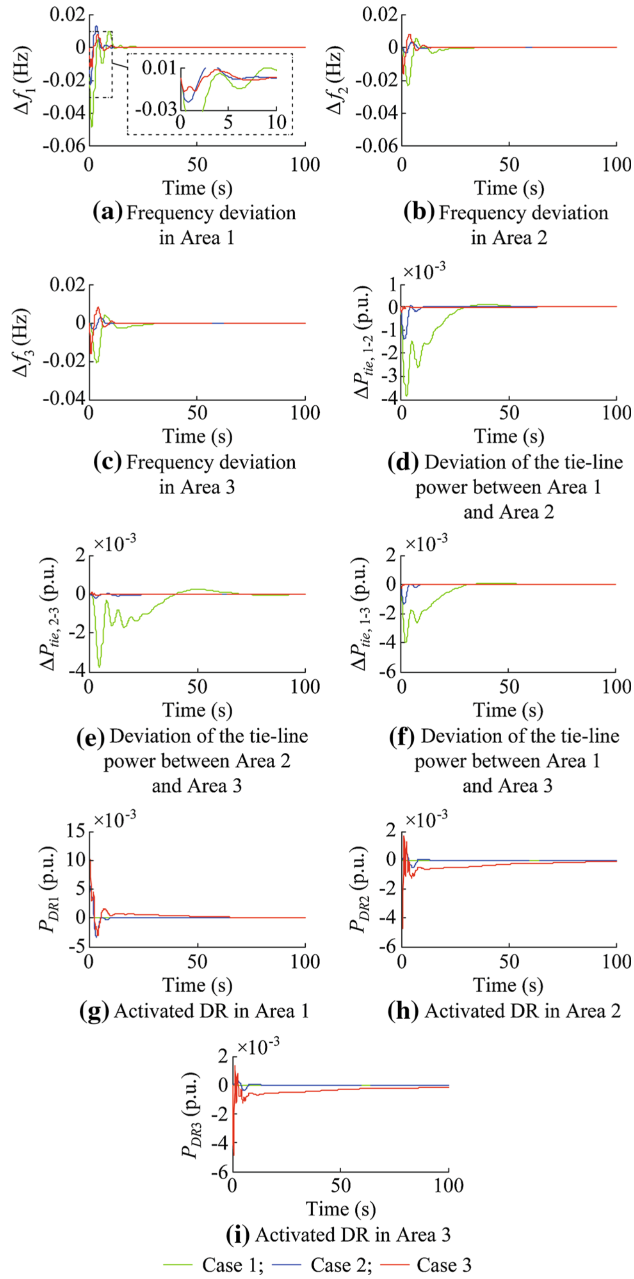


Fig. 4 Simulation results of different DR control methods

Table 2 The maximum frequency deviation in each case

Case	Maximum frequency deviation of the 3 areas (Hz)	In which area?
Case 1	0.048	Area 1
Case 2	0.022	Area 1
Case 3	**0.016**	Area 2

Case 2: The parameters B_i, K_i, and l_{DRi} are determined by the GA-based optimization. The objective function follows the idea of [16], that is:

Table 3 Parameters B_i, K_i, and l_{DRi} for the optimization cases

Parameters	Case 1	Case 2	Case 3
B_1	20	33.18	48.71
B_2	20	46.92	15.40
B_3	20	29.57	15.62
K_1	0.5	1.19	1.85
K_2	0.5	1.94	0.55
K_3	0.5	0.14	0.53
l_{DR1}	1	49.59	18.22
l_{DR2}	1	3.87	35.67
l_{DR3}	1	1.22	46.22

$$\min \int_0^T \Delta f_1^2 \mathrm{d}t + \int_0^T \Delta P_{\mathrm{tie},1-2}^2 \mathrm{d}t$$

Only one scenario (1% step disturbance in Area 1) is considered.

Case 3: The parameters B_i, K_i, and l_{DRi} are determined by the GA-based optimization. The objective function adopts the proposed method (adopts (5) with $W_{i,s}$, $W_{i-j,s}$ equally to be 1). All the 6 scenarios are considered.

By executing the GA-based optimization, the optimal parameters B_i, K_i, and l_{DRi} of the three cases are obtained in Table 3.

The simulation results with 1% step disturbances in Area 1 ~ 3 are shown in Figs. 5, 6, and 7, respectively. The following observations can be made:

1) Though the un-optimized parameters B_i, K_i, and l_{DRi} (Case 1) can stabilize system frequency eventually, the frequency deviation in Area 1 is much larger than that of Area 2 and Area 3. The maximum frequency deviation is as large as 0.022 Hz.
2) Though Case 2 is good at coping with the disturbances in Area 1 (Fig. 5), it is inferior in coping with disturbances in Area 2 and Area 3 (Figs. 6 and 7). By contrast, the proposed method (Case 3) has much better performance in coping with disturbances in all the three areas (Figs. 5, 6, and 7), and the maximum frequency deviation of all the 3 areas is limited within 0.016 Hz.

In the proposed optimization method, the weights $W_{i,s}$, $W_{i-j,s}$ also directly affect the optimization results. In a multi-objective optimization problem, the weights reflect the importance of different objectives [3]. Setting $W_{i,s}$, $W_{i-j,s}$ equally to be 1 indicates stabilizing $\Delta f_{i,s}$ and $\Delta P_{\mathrm{tie},i-j}$ are of the equal importance. However, if some specific objectives are more preferred (e.g. stabilizing the disturbances in Area 1

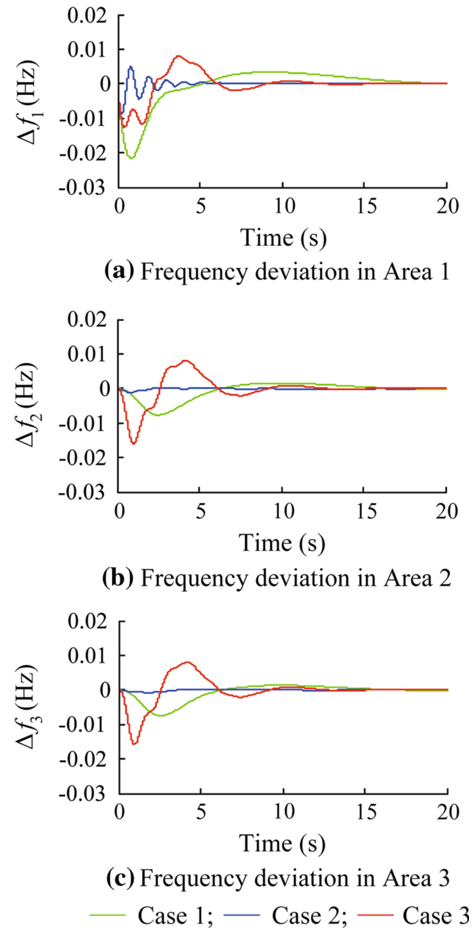


Fig. 5 Simulation results of 1% step disturbances in Area 1

is considered to be more important than other areas), the $W_{i,s}$, $W_{i-j,s}$ should be adjusted accordingly.

To show the effects of $W_{i,s}$, $W_{i-j,s}$ to the optimization results, the following case study will investigate the optimization results when $W_{i,1}$ and $W_{i-j,2}$ (i, $j \in N_A$, and $i \neq j$) select different values, while other weights remain to be 1. The $W_{i,1}$ and $W_{i-j,2}$ are weights corresponding to Scenario 1 and Scenario 2, in which the disturbances take place in Area 1. Therefore, the value of $W_{i,1}$ and $W_{i-j,2}$ reflect the importance of coping with disturbances in Area 1. The optimization results are listed in Table 4. Considering 1% step disturbance in Area 1 and Area 2, respectively, the simulation results are shown in Fig. 8. From Table 4 and Fig. 8 we have the following observations:

1) It can be seen from Table 4 that different values of $W_{i,1}$ and $W_{i-j,2}$ result in different optimization results. As mentioned above, the $W_{i,1}$ and $W_{i-j,2}$ reflect the importance of stabilizing the disturbances in Area 1. Therefore, Smaller $W_{i,1}$ and $W_{i-j,2}$ (all to be 0.1) indicates that stabilizing disturbances in Area 1 is considered to be less important, and therefore lead to

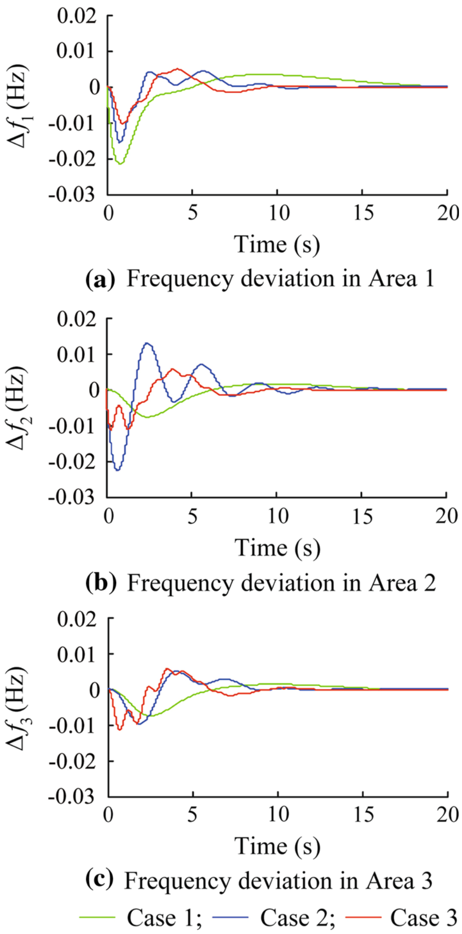


Fig. 6 Simulation results of 1% step disturbances in Area 2

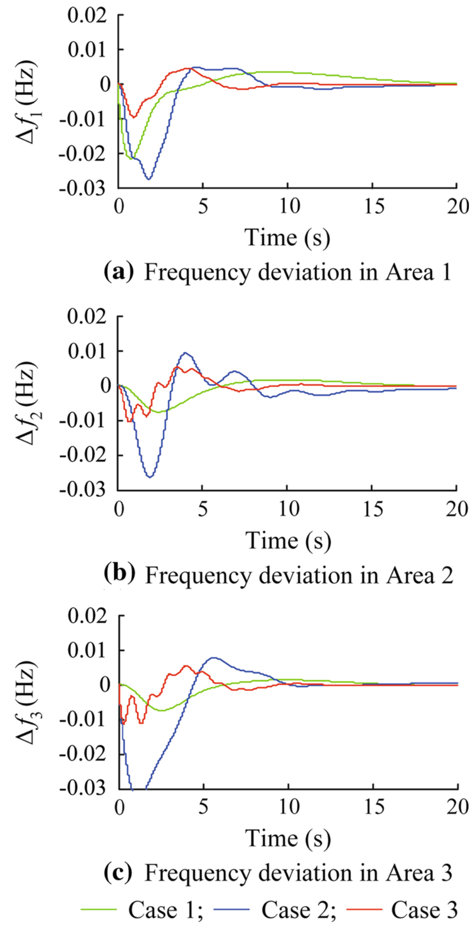


Fig. 7 The simulation results of 1% step disturbances in Area 3

smaller value of K_1 (1.36) and $l_{\mathrm{DR}1}$ (3.08), and vice versa.

2) It can be seen from Fig. 8 that smaller $W_{i,1}$ and $W_{i-j,2}$ (all to be 0.1) lead to larger frequency drop when the 1% disturbance is in Area 1, but smaller frequency drop when the disturbance is in Area 2, indicating the frequency support to disturbances in Area 1 is weakened with smaller $W_{i,1}$ and $W_{i-j,2}$, and vice versa. The results of Fig. 8 are in accordance with Table 4.

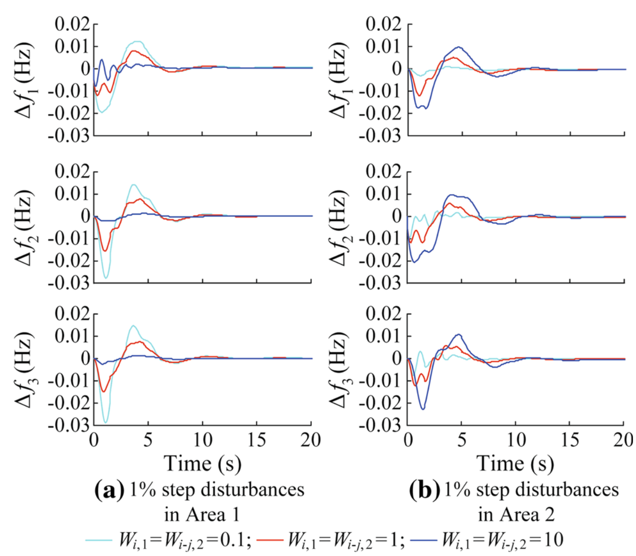


Fig. 8 Frequency of three areas under different values of $W_{i,1}$ and $W_{i-j,2}$

5 Conclusion

This paper proposes a DR control method for the frequency control of the multi-area power system. Compared with the existing studies, the main contribution of this paper can be summarized as follow:

1) A novel DR control method special for the frequency control of the multi-area power system is proposed. Compared with the existing methods, the main difference lies in that the tie-line power between areas is adopted as the additional feedback control signal of

Table 4 Optimization results of B_i, K_i, and l_{DRi} when $W_{i,1}$ and $W_{i-j,2}$ select different values

Values of $W_{i,1}$ and $W_{i-j,2}$	All to be 0.1	All to be 1	All to be 10
B_1	38.27	48.71	49.41
B_2	23.75	15.40	11.67
B_3	31.20	15.62	39.21
K_1	**1.36**	1.85	1.95
K_2	1.49	0.55	0.24
K_3	1.29	0.53	1.98
l_{DR1}	**3.08**	18.22	48.83
l_{DR2}	49.10	35.67	6.75
l_{DR3}	49.93	46.22	11.02

DR. This design can help improving the effectiveness in the frequency control.

2) The control system is formulated as a multi-objective optimization problem. Not only the DR control parameters, but also the AGC parameters are optimized. The optimization improves the performance of the control system.

The proposed method is applied to the frequency response model of a three-area power system and shows better performance in contrast with the existing techniques. Notwithstanding the contributions of this paper, there remain some places need to be improved in our future work:

3) The proposed method should be based on the high-quality two-way communications between the electrical appliances and the control center. However, this paper does not discuss much about the influences caused by communication delay. The communication delay may cause undesirable effect to the overall control performance [6].
4) In this paper, the importance of the objective function in the GA-based optimization is discussed. However, this paper does not discuss about other optimization methods. Several other optimization methods, e.g. particle swarm, artificial neural network, etc. may achieve competitive or ever better performance than the GA-based method.

Therefore, the future work may be developing a more realistic model that considers the two-way communication delay, finding a way to cope with the communication delay, and comparing the GA-based method with other optimization methods.

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Appendix

The parameters of the three-area power system are as follows:

Area 1 (on 800 MW base):

$$H_1 = 10,\ D_1 = 1,\ R_1 = 0.05,$$
$$T_{g1} = 0.2\ \text{s}, F_{HP1} = 0.3,\ T_{r1} = 7\ \text{s},\ T_{t1} = 0.3\ \text{s}$$
$$P_{DRmax1} = 0.15,\ \Delta f_{max1} = 0.6\ \text{Hz},\ k_{DR1} = 0.25\ \text{p.u./Hz}$$

Area 2 (on 1000 MW base):

$$H_2 = 10,\ D_2 = 1,\ R_2 = 0.05,$$
$$T_{g2} = 0.25\ \text{s}, F_{HP2} = 0.2,\ T_{r2} = 11\ \text{s},\ T_{t2} = 0.35\ \text{s}$$
$$P_{DRmax2} = 0.1,\ \Delta f_{max2} = 0.6\ \text{Hz},\ k_{DR2} = 0.17\ \text{p.u./Hz}$$

Area 3 (on 1200 MW base):

$$H_3 = 10,\ D_3 = 1,\ R_3 = 0.05,$$
$$T_{g3} = 0.3s,\ F_{HP3} = 0.25,\ T_{r3} = 9\ \text{s},\ T_{t3} = 0.3\ \text{s}$$
$$P_{DRmax3} = 0.075,\ \Delta f_{max3} = 0.6\ \text{Hz},\ k_{DR3} = 0.125\ \text{p.u./Hz}$$

Tie-line

$$T_{1-2} = 0.625,\ T_{2-3} = 0.5,\ T_{1-3} = 0.625$$
$$a_{12} = -800/1000,\ a_{23} = -1000/1200,\ a_{13} = -800/1200$$

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