International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 295

MODELLING AND DYNAMIC PERFORMANCE ANALYSIS OF THE POWER SYSTEM UNDER UNIT CONTINGENCY SHUTDOWN ACCIDENTS CONSIDERING DEMAND RESPONSE

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ABSTRACT

The generating unit contingency shutdown accidents in the power systems are increasing around the world, which can bring huge power generation shortage suddenly and result in severe system frequency fluctuations. In this scenario, the secure and stable operation of the power system cannot be guaranteed only by traditional generating units, due to the huge generating unit inertia and insufficient operating reserve capacities. Faced with this challenge, the progressed information and communication technologies make demand response (DR) become feasible to provide contingency reserve for the power system by controlling the power consumption of demand side resources (DSRs). This paper develops the power system model considering DR, where the closed-loop and open-loop transfer functions are obtained to analyze the dynamic performance of the power system under unit contingency shutdown accidents. On this basis, the stability margins of the power system are calculated by Bode plots to illustrate that the power system can become more stable as a result of DR. The proposed models and methods are verified by the numerical studies.

Keywords: power system model, dynamic performance analysis, unit contingency shutdown accident, demand response.

1. INTRODUCTION

The generating unit contingency shutdown accidents and large-scale blackouts in the power systems are increasing in recent years around the world. For example, six gas generating units in Datan power plant shut down and caused the blackout in Taiwan on August 15th, 2017 [1]. Large-scale renewable generating units dropped out from the power system in Australia on September 28th, 2016 and resulted in 50 hours blackout [2]. These generating unit contingency shutdown accidents can bring larger fluctuations to the power system than load power disturbances, because the generating unit capacity is generally larger than loads and the unit shutdown aggravates the shortage of the system reserve capacity. Besides, the practice shows that the generating units have huge inertia and cannot be regulated rapidly, which exacerbates the rapid drop of the power system frequency [3].

Based on the progressed information and communication technologies (e.g., the wireless network and 5G), the demand side resources (DSRs) can be controlled automatically and rapidly [4]. Therefore, the demand response (DR) is more feasible nowadays to provide contingency reserve services for the power system by direct load control (DLC) [5]. Besides, the DSRs have less regulation inertia than traditional generating units, and can be regulated in shorter time [6]. With the phasing out of the traditional generating units, the DSRs provide an alternative method and show huge regulation potential in the near future power systems [7].

Some previous studies have been done on the DR. The deep learning technologies are used to forecast the building-level load for demand response in [8]. The

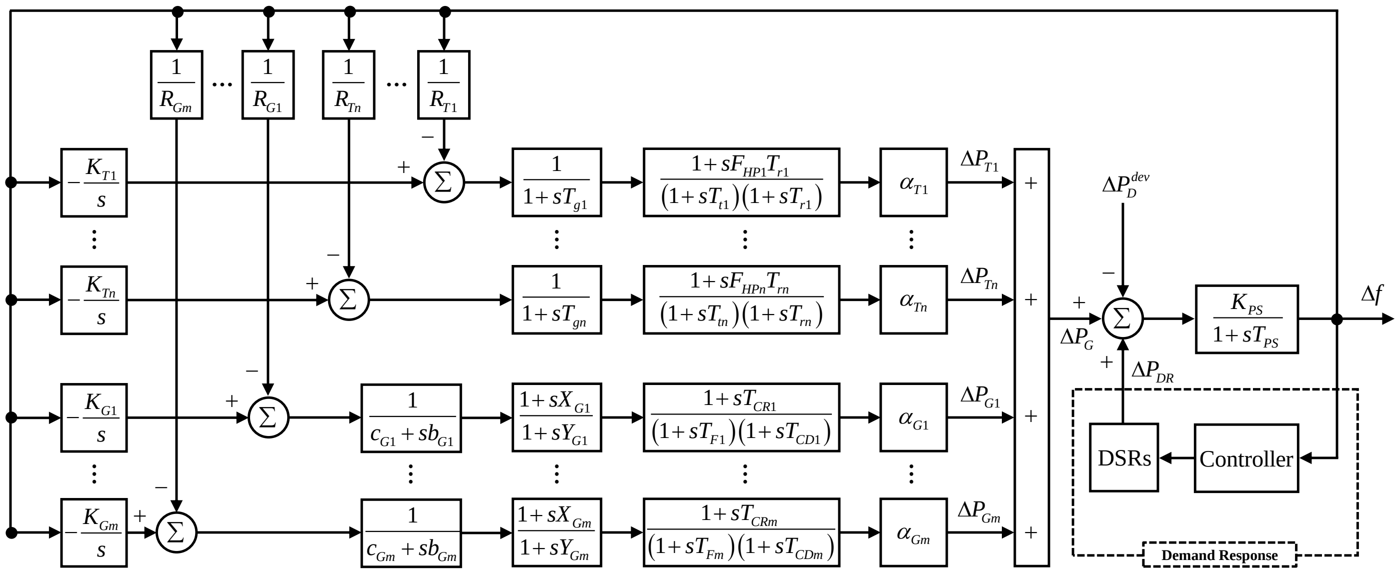

Fig. 1 Modelling of the power system considering demand response [13]-[15].

thermostatic loads, such as heating, ventilation and air conditioning loads, are studied in [9] for providing primary and secondary frequency regulation for the power system. The self-learning algorithm is proposed in [10] for coordinated control of rooftop units and DR in small- and medium sized commercial buildings. However, the dynamic performances of the power system considering DR are not analyzed in these studies. The dynamic DR in the single-area and two-area power systems are studied in [11] and [12], respectively, while these papers only focus on the load power disturbance scenarios. To the best of our knowledge, the dynamic performance of the power system with DR has not been studied under unit contingency shutdown accidents. Faced with this issue, this paper develops the power system model considering DR and analyzes the corresponding dynamic performance. The contributions of this paper are summarized as follows:

(1) The closed-loop and open-loop transfer functions of the power system are derived under unit contingency shutdown scenarios, which are rarely studied in the previous studies. The system transfer function gets changed when the units drop out from the system, while in the load power disturbance scenarios, the system transfer function remains unchanged.

(2) The DSRs are considered in the power system. On this basis, the dynamic performance of the power system under unit contingency shutdown accidents are analyzed. The stability margins of the power system with and without DR are calculated and compared by Bode plots.

(3) The proposed models and methods are verified by numerical studies. The power system is proved to be more stable as a result of DR, which is significant for the secure operation of power systems, especially in the countries and regions where reserve capacities are insufficient. The uncertainties and sensitivities are also discussed and analyzed.

The remaining of this paper is organized as follows. Section 2 develops the power system model considering DR. The dynamic performances of the power system with and without DR are compared in Section 3. The numerical studies are carried out in Section 4, and Section 5 concludes this paper.

2. MODELLING OF THE POWER SYSTEM CONSIDERING DEMAND RESPONSE

Fig. 1 shows the power system model considering DR [13]-[15]. It is assumed that the power system includes the reheat steam generators and gas turbine generators. In Fig. 1, K_{PS} and T_{PS} are the power system's gain and time constants, respectively. ΔP_D^{dev} and Δf are the disturbance load power and the system frequency deviation, respectively. ΔP_G and ΔP_{DR} are the regulation power provided by the generators and DSRs, respectively. The parameters of the reheat steam generators include: the speed droop gain R_{Ti}, the integral gain K_{Ti}, the speed governor time constant T_{gi}, the steam turbine time constant T_{ti}, the steam turbine reheat time constant T_{ri}, and the high pressure turbine power fraction F_{HPi}. Besides, the parameters of the gas turbine generators include: the proportional and integral gains R_{Gj} and K_{Gj}, the valve positioner constants c_{Gj} and b_{Gj}, the speed governor lead- and lag-time constants X_{Gj} and Y_{Gj}, the fuel time constant T_{Fj}, the combustion reaction time delay T_{CRj}, and the compressor discharge volume-time constant T_{CDj}. The

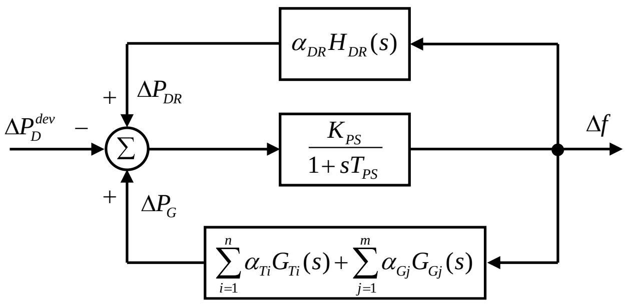

Fig. 2 Simplified power system model with DR.

Table 1 The parameter values of the test power system [13], [14], [16].

Parameters	Values	Parameters	Values
R_{Ti}	0.05	c_{Gj}	1.00
K_{Ti}	0.10 s^{-1}	b_{Gj}	0.05s
T_{gi}	0.20s	X_{Gj}	0.60s
T_{ti}	0.30s	Y_{Gj}	1.00s
T_{ri}	10.00s	T_{Fj}	0.23s
F_{HPi}	0.30	T_{CRj}	0.01s
R_{Gj}	0.05	T_{CDj}	0.20s
K_{Gj}	0.10 s^{-1}	K_{PS}	1.1493
α_{Ti}	0.10	T_{PS}	11.49s
α_{Gj}	0.06	R_{DR}	0.10
P_{Tr}	800MW	K_{DR}	0.50
P_{Gr}	480MW	f_r	60Hz
n	7	m	5

α_{Ti} and α_{Ti} are the ratios of the generating units in the total power system capacity, whose summation is 100%.

In order to clarify the control process, the power system model in Fig. 1 is rearranged and simplified to a standard transfer function model, as shown in Fig. 2, where

$$G_{Ti}(s)=-\left(\frac{1}{R_{Ti}}+\frac{K_{Ti}}{s}\right)\cdot\frac{1}{1+sT_{gi}}\cdot\frac{1+sF_{HPi}T_{ri}}{(1+sT_{ti})(1+sT_{ri})} \tag{1}$$

$$G_{Gj}(s)=-\left(\frac{1}{R_{Gj}}+\frac{K_{Gj}}{s}\right)\cdot\frac{1}{c_{Gj}+sb_{Gj}}\cdot\frac{1+sX_{Gj}}{1+sY_{Gj}}\cdot\frac{1+sT_{CRj}}{(1+sT_{Fj})(1+sT_{CDj})} \tag{2}$$

Moreover, the ratio of DSRs in the power system is expressed as α_{DR}. The DSRs in this paper are also controlled by the proportional-integral controller, just as the speed droop gain and integral gain for traditional generators. Therefore, the transfer function of DR can be described as

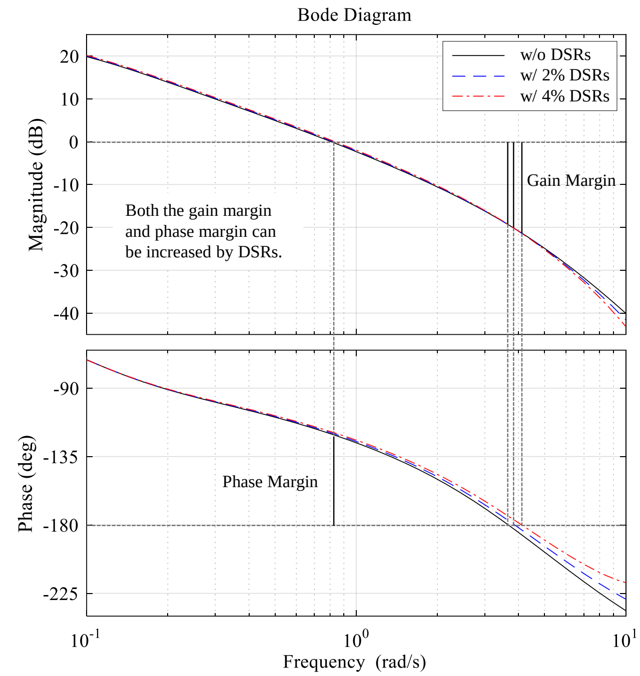

Fig. 3 The Bode plots of the power system under unit contengency shutdown accidents.

Table 2 The gain and phase margins of the Bode plots.

Scenarios	Gain Margin	Phase Margin
w/o DSRs	19.4 dB (at 3.67 rad/s)	59.8 deg (at 0.807 rad/s)
w/ 2% DSRs	20.3 dB (at 3.87 rad/s)	60.2 deg (at 0.821 rad/s)
w/ 4% DSRs	21.4 dB (at 4.11 rad/s)	60.5 deg (at 0.835 rad/s)

$$H_{DR}(s)=-\left(\frac{1}{R_{DR}}+\frac{K_{DR}}{s}\right) \tag{3}$$

where R_{DR} and K_{DR} are the proportional and integral gains, respectively.

3. STABILITY OF THE POWER SYSTEM WITH AND WITHOUT DR

Based on the simplified power system model with DR in Fig. 2, the system frequency deviations can be expressed as

$$\Delta f(s)=\frac{K_{PS}}{1+sT_{PS}}\left(\Delta P_G(s)+\Delta P_{DR}(s)-\Delta P_D^{dev}(s)\right) \tag{4}$$

where

$$\Delta P_G(s)=\left(\sum_{i=1}^{n}\alpha_{Ti}G_{Ti}(s)+\sum_{j=1}^{m}\alpha_{Gj}G_{Gj}(s)\right)\cdot\Delta f(s) \tag{5}$$

$$\Delta P_{DR}(s)=\alpha_{DR}H_{DR}(s)\cdot\Delta f(s) \tag{6}$$

Therefore, the closed-loop transfer function with regard to the disturbance load power can be obtained as

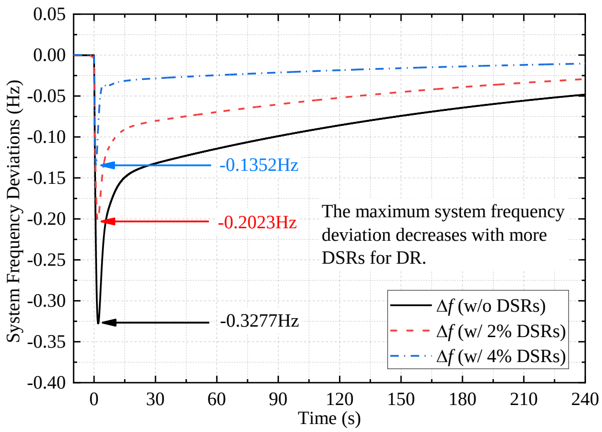

Fig. 4 System frequency deviations in the three cases when

$$\Phi(s) = \frac{\Delta f(s)}{\Delta P_D^{dev}(s)} = \frac{-M(s)}{\underbrace{1 - M(s)\left(\sum_{i=1}^{n}\alpha_{Ti}G_{Ti}(s) + \sum_{j=1}^{m}\alpha_{Gj}G_{Gj}(s) + \alpha_{DR}H_{DR}(s)\right)}_{\Psi(s)}} \quad (7)$$

where $\Psi(s)$ is the corresponding open-loop transfer function, and $M(s)$ is

$$M(s) = \frac{K_{PS}}{1 + sT_{PS}} \quad (8)$$

In the unit contingency shutdown accidents, the power generation losses can be regarded as the disturbance power. Similar with the previous studies [6], [11], [12], the disturbance power is treated as a step function, which is expressed as

$$\Delta P_D^{dev}(s) = \frac{|\alpha_{Tk}G_{Tk}(s)|}{s} + \frac{|\alpha_{Gl}G_{Gl}(s)|}{s} \quad (9)$$

where k and l are the number of shutdown units.

Different from the load power disturbance, the closed- and open-loop transfer functions of the power system will get changed when the unit contingency shutdown accident occurs. The open-loop transfer function in Eq. (7) can be transformed as

$$\tilde{\Psi}(s) = M(s)\left(\sum_{i=1, i\neq k}^{n}\alpha_{Ti}G_{Ti}(s) + \sum_{j=1, j\neq l}^{m}\alpha_{Gj}G_{Gj}(s) + \alpha_{DR}H_{DR}(s)\right) \quad (10)$$

Based on the two open-loop transfer functions $\Psi(s)$ and $\tilde{\Psi}(s)$, the Bode plots can be obtained to show the stability of the power system with and without DR under generating unit shutdown accidents. The parameter values of the test system are shown in Table 1 [13], [14], [16]. It is assumed that the power system without DSRs in Case 1, with 2% DSRs in Case 2 and with 4% DSRs in Case 3. Two reheat steam generating units

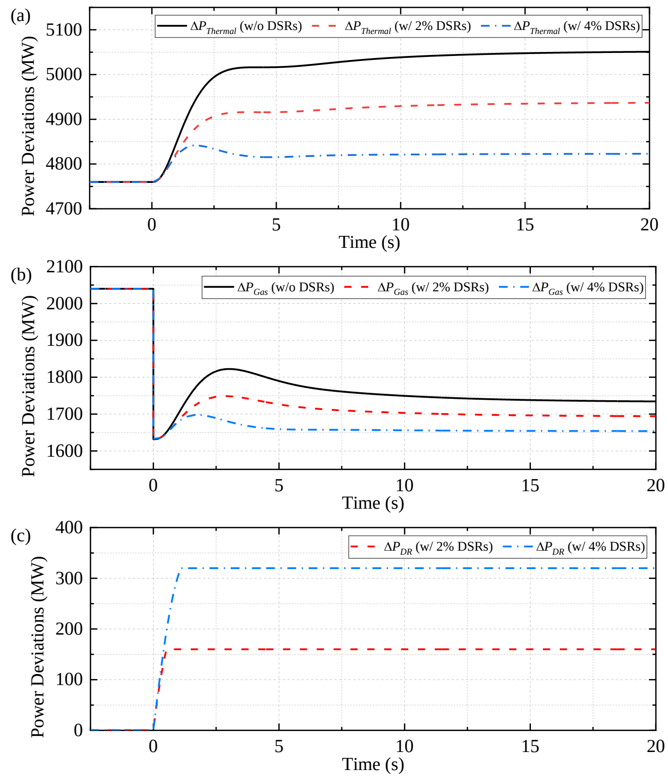

Fig. 5 Power deviations in the three cases: (a) the total power deviations of the reheat steam generators, (b) the total power deviations of the gas turbine generators, (c) the regulation power provided by DSRs.

are assumed to be shut down suddenly.

Fig. 3 shows the Bode plots of the three cases. The corresponding gain margins and phase margins are shown in Table 2. It can be seen that the gain margin increases from 19.4 dB in Case 1 to 21.4 dB in Case 3. The phase margin increases from 59.8 deg in Case 1 to 60.5 deg in Case 3. That is to say, the stability of the power system is enhanced with the increasing number of DSRs under the generating unit shutdown accidents.

4. CASE STUDIES

The power system frequency deviations and power generation deviations are simulated in the case studies. The test system adopts the power system in Fig. 1 [13]-[15], and the parameter values are set as Table 1 [13], [14], [16]. It is assumed that one gas turbine generator is shut down suddenly, which is similar with the actual gas generating plant accident in Taiwan [1].

The simulation results are shown in Fig. 4 and Fig. 5. It can be seen from Fig. 4 that the maximum system frequency deviation decreases with the increase of DSRs for providing DR. It is -0.3277Hz in Case 1 when there is no DR, and decreases to -0.2023Hz and -0.1352Hz in Case 2 and Case 3, respectively.

The power deviations are shown in Fig. 5. The

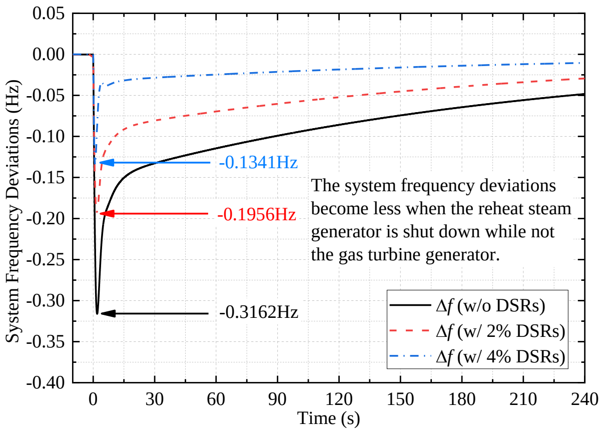

Fig. 6 System frequency deviations in the three cases when

accident is the shutdown of one gas turbine generator, which can be seen from Fig. 5(b). The total power of the gas turbine generators decrease from 2039MW to 1631MW suddenly and cause the gap between the power generation and consumption. Faced with the accident, the reheat steam generators and the remaining gas turbine generators in normal operation state begin to increase the power generation, as shown in Fig. 5(a) and Fig. 5(b), respectively. Moreover, the DSRs in Case 2 and Case 3 also starts to provide regulation power by cutting down their power consumption, as shown in Fig. 5(c). The DSRs can be regulated quickly to decrease the gap between power generation and consumption, which contributes to the decrease of the system frequency deviations, as the comparisons in Fig. 4.

Moreover, in order to analyze the uncertainties, i.e., the reheat steam generators are shut down while not the gas turbine generator, another three cases are analyzed. It is assumed that the same generation power by the reheat steam generator gets lost suddenly (Scenario 2). Other parameters are the same with the scenario where one gas turbine is shut down (Scenario 1). The system frequency deviations are shown in Fig. 6. Compared with the cases in Fig. 4, the maximum system deviations are less. Because the regulation power are provided by the rest generators in good condition, where more gas turbines in Scenario 2 than Scenario 1. The gas turbines can get regulated more rapidly than reheat steam generators. Therefore, the system frequency deviations are less in Scenario 2 than Scenario 1, which reminds that the gas turbine generator should be paid more attention considering the frequency regulation services in practical power systems.

5. CONCLUSIONS

Faced with the increasing generating unit contingency shutdown accidents, this paper proposes an alternative method of traditional generators to provide regulation power by DSRs. Firstly, the power system model considering DR is developed. On this basis, the transformed closed- and open-loop transfer functions are derived. Then, the Bode plots are obtained to analyze the dynamic performances of the power system under unit contingency shutdown accidents, which illustrates that the stability of the power system can be enhanced by DR. The numerical studies show that the maximum system frequency deviation can be decreased from -0.3277Hz to -0.1352Hz when the DR is considered. The proposed models and methods in this paper contribute to guiding the DR in the power systems, especially in the countries and regions where reserve capacities are insufficient.

ACKNOWLEDGEMENT

The research is partially supported by the National Key Research and Development Program of China under Grant 2016YFB0901100 and the China NSFC under Grant 51577167.

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