Analysis of “8・15” Blackout in Taiwan and the Improvement Method of Contingency Reserve Capacity Through Direct Load Control

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***Abstract*—Electric power has been one of the most important energy for modern cities. Therefore, blackouts always have great impacts on our modern societies. This paper reviews the process of the large-area blackout in Taiwan on August 15th, 2017. The direct cause of the accident is the incompetence of an employee in the natural gas company, while the fundamental cause is the shortage of the contingency reserve capacity (CRC). Faced with the insufficient installed capacity in Taiwan, this paper proposes an improvement method of CRC through direct load control. A control framework, on account of the system frequency and the gas pipeline pressure, is developed to regulate the power consumption of demand side resources (DSRs). Besides, a droop controller is also proposed to determine the regulation capacity of DSRs. The effectiveness of the proposed control strategy is verified by the numerical studies.**

***Index Terms*—blackout; contingency reserve; direct load control; demand side resource**

I. Introduction

On August 15th, 2017 at 04:51 PM, six gas generating units in Datan power plant were shut down suddenly, which accounted for around 11.94% of the whole power supply in Taiwan [1]. The subsequent result is a large-area blackout, which affects 17 cities and 5.92 million customers. This accident has become the worst blackout accident in the past 20 years of Taiwan. The direct cause of the accident is the incompetence of an employee in the natural gas company, whose incorrect operation leads to the interruption of the gas supply to the Datan power plant. However, the fundamental cause is the shortage of the operating reserve capacity (ORC) [2]. Before the blackout accident, the ORC in Taiwan is only 3.17%, which is far less than the average ORC requirement in the world [1].

The information and communication technologies have made great progress, which makes it easier to control loads remotely [3]. Loads can regulate power consumption to provide ORC for the power system, just as traditional generating units [4]. Moreover, customers can get benefits for the contribution to the system stability [5]. Besides these theoretical research, some field demonstration projects also have been implemented in several countries [6]. For example, the electricity company in New York City installs remote control devices to air conditioners, which assist customers to adjust the operating states of air conditioners to provide ORC [4]. The state grid corporation of China develops a friendly interactive grid demonstration in Jiangsu Province to incent customers to participate in regulation services [7].

However, most of the studies mainly focus on the power balance between supply and demand [8]. The power consumption of demand side resources (DSRs) is determined and controlled based on the system balance state [9]. Besides, some studies also take the system frequency as a trigger signal to implement the regulation of loads [10]. The load power will reduce with the decrease of the system frequency [11]. However, there are few researches on the supply of primary energy. If the supply state of primary energy can be monitored, DSRs can take actions more quickly. Consequently, the faster load shedding can reduce the system frequency deviations, enhance the system stability, and shrink the blackout range.

Based on the analysis of the “8•15” blackout in Taiwan, this paper proposes a novel control framework of DSRs to provide contingency reserve capacity (CRC) for the power system. By monitoring both the system frequency and the pressure of the natural gas pipeline, the abnormal conditions of power generation can be detected earlier. Therefore, the power consumption of DSRs can be regulated in advance. Moreover, a droop controller is developed to determine the regulation capacity. The effectiveness of the proposed model and method are verified in the multi-sources single area system.

The remaining of this paper is organized as follows. Section II analyzes the “8•15” blackout in Taiwan, including the accident process of the natural gas system and the accident process of the power plant. Section III proposes the improvement method of CRC through direct load control (DLC). The test system and the numerical studies are

The research is partially supported by the National Key Research and Development Program of China under Grant 2016YFB0901103 and the China NSFC under Grant 51577167.

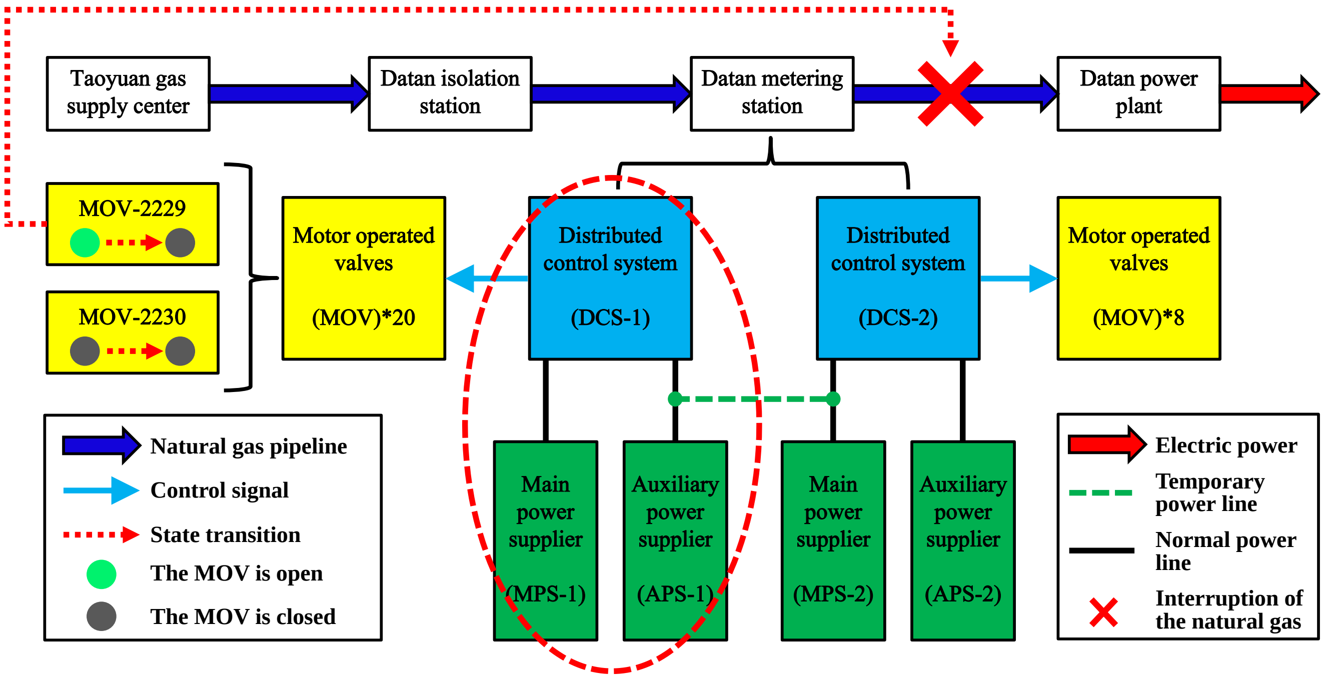

Fig. 1. The interruption process of the natural gas to Datan power plant [1].

presented in Section IV. Finally, Section V concludes this paper.

II. The Analysis of "8•15" Blackout in Taiwan

A. Accident process of the natural gas system [1]

Fig. 1 shows the interruption process of the natural gas to Datan power plant, which comes from the administrative investigation report of Executive Yuan, Taiwan [1]. The gas of Datan power plant is provided by Taoyuan gas supply center, which belongs to the Chinese Petroleum Corporation, Taiwan. On April 1st and 4th, 2016, the power supplier of the distributed control system (DCS) in Datan isolation station had a short circuit accident, which is caused by the radiator fan inhaling dust. In order to prevent these accidents happening again, the corporation decided to replace the power suppliers in Datan isolation station and Datan metering station. All the six power suppliers in the isolation station have been replaced on August 5th, 2017. Four power suppliers in Datan metering station still need to be replaced.

The metering station have two DCSs, which control twenty motor operated valves (MOVs) and eight MOVs, respectively. Among these MOVs, the MOV-2229 and MOV-2230 are the pivotal MOVs, because they control the natural gas pipeline from the metering station to the power plant. The power of the two DCSs are supplied by the main power supplier (MPS) and the auxiliary power supplier (APS). The MPS-2 and APS-2 have been replaced successfully on August 10th, 2017. The accident occurred when replacing the MPS-1 and APS-1 of the DCS-1 on August 15th, 2017.

The employee connected a temporary power line between the MPS-2 and APS-1 to ensure the power supply of the DCS-1. However, the power failure of the DCS-1 occurred suddenly after replacing the MPS-1 and APS-1 at 04:48 PM. The DCS-1 restarted and the MOVs were shut down, including the MOV-2229 and the MOV-2230. The original state of the MOV-2230 was closed, while the original state of the MOV-2229 was open. The subsequent result of the false closure was the decrease of the natural gas pressure in the pipeline. After around 140 seconds, the gas supply to the Datan power plant was interrupted completely.

B. Accident process of the power plant [1]

Fig. 2 shows the power supply curve of the system on August 15th, 2017, which comes from the administrative investigation report of Executive Yuan, Taiwan [1]. The loads reached the peak value 36,450MW at 01:58 PM, when the maximum generating capacity was 37,600MW. The operating reserve capacity was only 1,150MW, which accounted for around 3.17% of the loads. Because of the decrease of solar power generation and the shutdown of a power generator at 03:32 PM, the generating capacity of the system reduced to 36,840MW at 04:50 PM (before the accident).

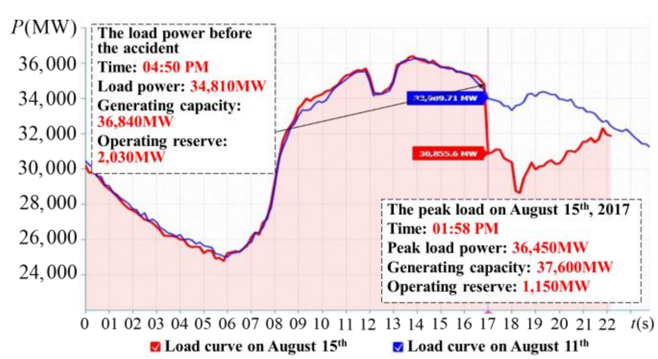

Fig. 2. The load curve on August 15th, 2017 [1].

Due to the supply interruption of the natural gas, all the six gas turbine generators were shut down at 04:51:02, which leads to a decrease of 4,156MW generation power. That is to say, 11.28% power generation of the system lost suddenly, which is far more than the operating reserve capacity 5.51%. Therefore, the system frequency dropped quickly and the relay protection devices started under-frequency load shedding (UFLS) automatically. Around 3,360MW loads (1.54 million customers) were cut down. The system frequency returned to the rated value (60Hz) at 04:58 PM. In order to ensure the system stability during the recovery process of Datan power plant, four rolling blackouts were carried out from 06:00 PM to 09:40 PM. Finally, around 5.92 million customers were affected in the blackout accident.

III. IMPROVEMENT METHOD OF CONTINGENCY RESERVE CAPACITY THROUGH DIRECT LOAD CONTROL

A. *The framwork of direct load control*

Base on the analysis of "8•15" blackout in Taiwan, the fundamental cause is the shortage of the ORC, especially for contingency reserve capacity (CRC). This paper proposes the improvement method of CRC through direct load control (DLC), as shown in Fig. 3. Both the system frequency and the pressure of the gas pipeline are monitored by the controller, which can send signals to the demand side resources (DSRs). When the system frequency drops or the gas pipeline pressure decreases abnormally, the controller will reduce the power consumption of DSRs to provide CRC for the system.

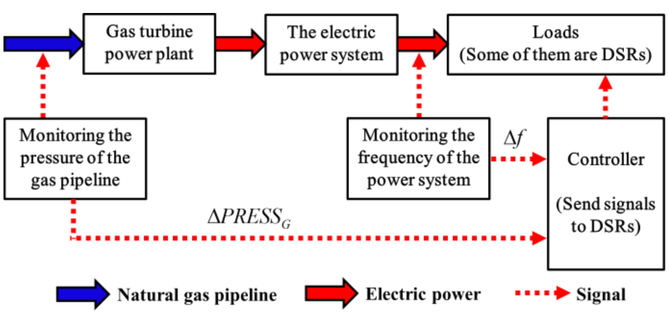

Fig. 3. The framework of DLC considering the gas pipeline pressure.

B. *Control strategy*

The controller is designed as the droop control theory, which is an important theory of generating units to provide primary frequency regulation service. The controller can be described as

$$\Delta P_{DLC} = \gamma_0 \Delta f + \int \beta_0 \Delta f dt + \sum_{j=1}^{m} \int \beta_j \Delta PRESS_{Gj} dt \tag{1}$$

where ΔP_{DLC} is the regulation capacity of the DLC. Δf is the frequency deviation of the power system. $\Delta PRESS_{Gj}$ is the pressure deviation of the gas pipeline, respectively. γ_0 and β_0 are the proportional coefficient and the integral coefficient of the frequency deviation, respectively. β_j is the integral coefficient of the *j*-th gas pressure deviation.

As shown in Fig. 4, the regulation capacity rises with the increase of the frequency deviation (or the gas pressure deviation). The maximum value is ΔP_{DLC}^{max}.

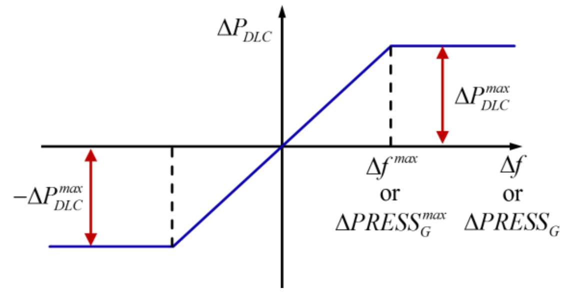

Fig. 4. The control strategy considering the gas pipeline pressure.

IV. CASE STUDIES

A. *Test system*

The test system is set to simulate an electric power system, which has a low level of operating reserve capacity, just as the power system in Taiwan. In this paper, the test model adopts the multi-sources single area system, as shown in Fig. 5 [12], [13]. It is assumed that the number of reheat steam generators and gas turbine generators are $N = \{ i \in N \mid 1, 2, \cdots, n \}$ and $M = \{ j \in M \mid 1, 2, \cdots, m \}$, respectively. s is the Laplace operator. Δf is the frequency deviation of the power system. R_{Ti} and K_{Ti} are the speed droop parameter and the integral gain of the *i*-th reheat steam generator, respectively. R_{Gj} and K_{Gj} are the speed droop parameter and the integral gain of the *j*-th gas turbine generator, respectively. T_{gi}, T_{ti} and T_{ri} are the speed governor time constant, the steam turbine time constant and the steam turbine reheat time constant, respectively. F_{HPi} the power fraction of the high pressure turbine section. c_{Gj} and b_{Gj} are the gas turbine valve positioner and the gas turbine constant of the valve positioner, respectively. X_{Gj} and Y_{Gj} are the lead time constant and the lag time constant of the gas turbine speed governor, respectively. T_{Fj} is the gas turbine fuel time constant. T_{CRj} is the gas turbine combustion reaction time delay. T_{CDj} is the gas turbine compressor discharge volume-time constant. ΔP_D^{dev} is the power deviation of loads. K_{PS} and T_{PS} are the gain and time constant of the power system, respectively. α_{Ti} and α_{Gj} are the participation factors of the generators, whose summation is 100%:

$$\sum_{i=1}^{n} \alpha_{Ti} + \sum_{j=1}^{m} \alpha_{Gj} = 100\% \tag{2}$$

In the case studies, it is assumed that there are 7 same reheat steam generators and 5 same gas turbine generators. The installed capacity of the two kinds of generators are 800MW and 480MW, respectively. The rated system frequency is 60Hz. The rated gas pressure is 55kg/cm^3. Other parameters are set as [12], [14]: $R_{Ti} = 0.05$; $K_{Ti} = 0.10$; $T_{gi} = 0.20$s ; $T_{ti} = 0.30$s ; $T_{ri} = 10.00$s ; $F_{HPi} = 0.30$; $R_{Gj} = 0.05$; $K_{Gj} = 0.10$; $c_{Gj} = 1.00$; $b_{Gj} = 0.05$s ;

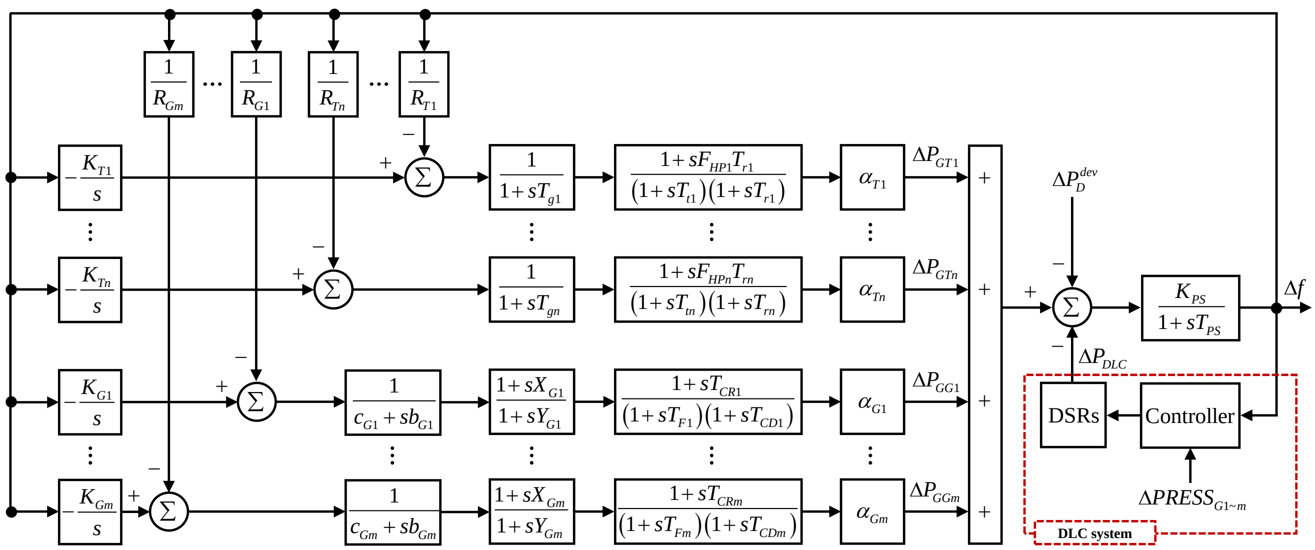

Fig. 5. Transfer function model of multi-sources single area system [12].

$X_{Gj} = 0.60\text{s}$; $Y_{Gj} = 1.00\text{s}$; $T_{Fj} = 0.23\text{s}$; $T_{CRj} = 0.01\text{s}$; $T_{CDj} = 0.20\text{s}$; $\Delta P_D^{dev} = 0.00$; $K_{PS} = 1.1493$; $T_{PS} = 11.49\text{s}$; $\alpha_{Ti} = 0.10$; $\alpha_{Gj} = 0.06$; $\gamma_0 = 10$; $\beta_0 = 0.5$; $\beta_j = 0.1$.

It is assumed that two gas turbine generators are shut down suddenly. Three cases are studies in this paper: (1) No loads provide CRC in Case 1. (2) 10% loads ($\Delta P_{DLC}^{max} = 0.1$) can be controlled to provide CRC by only monitoring the system frequency. (3) 10% loads ($\Delta P_{DLC}^{max} = 0.1$) can be controlled to provide CRC by monitoring both the system frequency and the pressure of the natural gas pipeline.

B. *Simulation results*

Fig. 6 shows the simulation results in Case 1. The generating power of reheat steam generators will increase to the maximum value after the two gas turbines shutting down. The other three gas turbines will also increase the generating power to the maximum value. However, the total generating capacity is still less than the demand of total loads. Therefore, the system frequency will drops, until the relay protection devices in the system start under-frequency load shedding (UFLS) automatically at the -1 Hz .

If 10% loads participate in providing CRC by monitoring the system frequency, the frequency deviation will reduce, as shown in Fig. 7. The load power will decrease and the reheat steam generating power will increase along with the drop of the system frequency. The total load power curve almost always overlaps with the total generating power curve, where the main differences mainly appear at the beginning of the accident. Therefore, the maximum deviation of the system frequency is only -0.301 Hz , which is within the allowed ranges and will not trigger the UFLS.

Fig. 8 shows the simulation results in Case 3, where 10% loads are controlled by monitoring both the system frequency and the pressure of the natural gas pipeline. If the accident is caused by the supply of primary energies, the abnormal gas

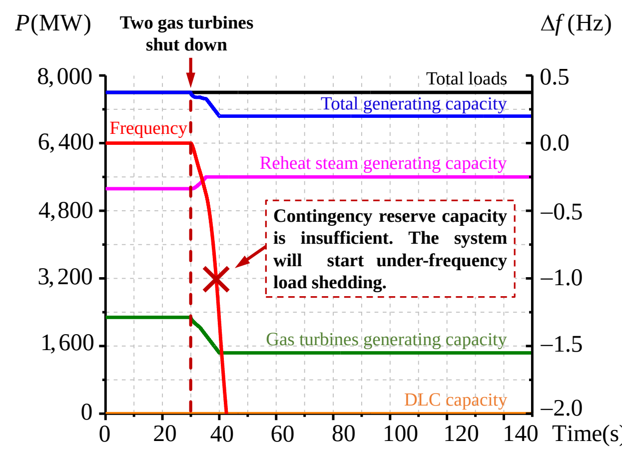

Fig. 6. Simulation results in Case 1: total loads, total generating capacity, reheat steam generating capacity, gas turbine generating capacity, direct load control capacity and the system frequency.

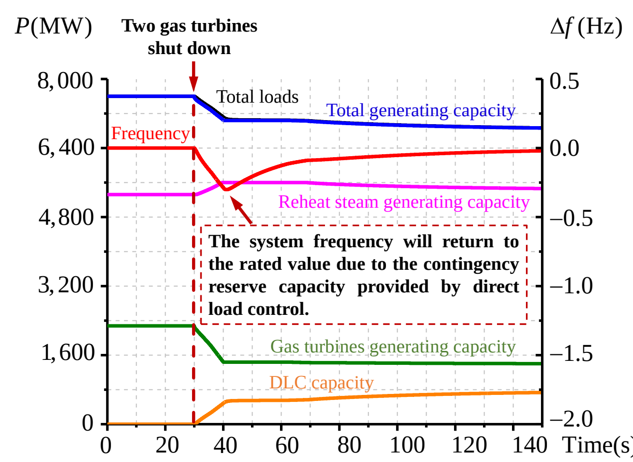

Fig. 7. Simulation results in Case 2: total loads, total generating capacity, reheat steam generating capacity, gas turbine generating capacity, direct load control capacity and the system frequency.

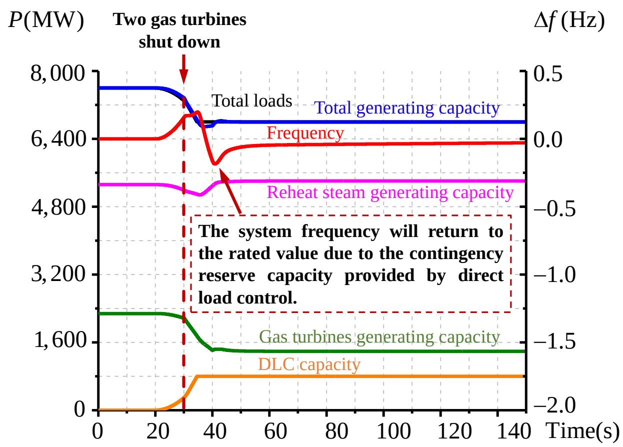

Fig. 8. Simulation results in Case 3: total loads, total generating capacity, reheat steam generating capacity, gas turbine generating capacity, direct load control capacity and the system frequency.

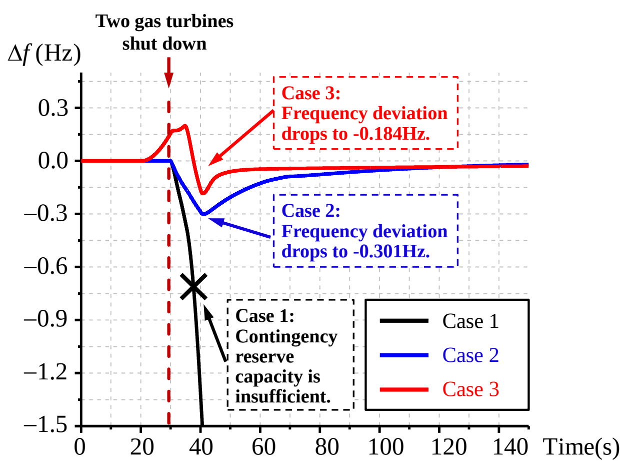

Fig. 9. Simulation results of the system frequency in the three cases.

pressure can be detected earlier than the abnormal system frequency. Therefore, the loads will be controlled in advance to decrease power after detecting the abnormal gas pressure. Compared with the simulation results in Case 3 and Case 2, the DLC capacity in Case 3 is regulated earlier and faster. Besides, the system frequency has a slight increase before the gas turbine generators shutting down, which contributes to dealing with the coming accident. The maximum drop value of the system frequency is -0.184 Hz , which declines 38.87% than that in Case 2.

V. Conclusions

This paper reviews the process of the large-area blackout in Taiwan on August 15th, 2017, including the accident process of the natural gas system and the accident process of the gas power plant. The fundamental cause of the accident is the shortage of the contingency reserve capacity (CRC). Therefore, this paper proposes an improvement method of CRC through direct load control (DLC). The simulation results of the multi-sources single area system shows that the frequency deviation will decrease by controlling demand side resources. Moreover, the loads can be controlled earlier by monitoring both the system frequency and the gas pipeline pressure. The abnormal gas pressure can be detected earlier than the abnormal system frequency, when the accident is caused by the supply of primary energies. Simulation results show that the frequency deviation can decline 38.87% than another case, which only monitors the system frequency.

Our future work will focus on DLC to provide CRC in a multi-sources multi-areas system. Operating state detection of primary energy and corresponding electricity market are also our research directions.

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