Research Article

Transient Stability Improvement for Combined Heat and Power System Using Load Shedding

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The purpose of the paper is to analyze and improve the transient stability of an industrial combined heat and power (CHP) system in a high-tech science park in Taiwan. The CHP system installed two 161 kV/161 kV high-impedance transformers to connect with Taipower System (TPS) for both decreasing the short-circuit fault current and increasing the fault critical clearing time. The transient stabilities of three types of operation modes in CHP units, 3G1S, 2G1S, and 1G1S, are analyzed. Under the 3G1S operation mode, the system frequency is immediately restored to 60 Hz after tie line tripping with the TPS. Under the 1G1S and 2G1S operation modes, the system frequencies will continuously decrease and eventually become unstable. A novel transient stability improvement approach using load shedding technique based on the change in frequency is proposed to improve the transient stability.

1. Introduction

Transient stability improvement plays an important role in the dynamics of mechanical and power systems [1]. This paper presents a novel transient stability improvement approach for the combined heat and power (CHP) system using a load shedding technique. CHP (also called cogeneration) system is an energy production system involving the simultaneous generation of thermal and electric energy by using a single primary heat source. By producing two kinds of useful energies in the same facility, the net energy efficiency yield from the primary fuel increases from 30–35 percent to 80–90 percent [2, 3]. CHP can result in significant cost savings and can reduce any possible environmental effects that conventional energy production may produce. Europe has actively incorporated CHP into its energy policy via the Cogeneration or CHP Directive [4].

The CHP system in a high-tech science park (HSP) in Taiwan is selected for case study in this work. The needs of power service quality and reliability in HSP are much higher than those of general customers. When suffering

from the abnormal power failure and voltage dips, not only did the high-tech manufacturers cause a loss, but even the high-precision processing equipment leads to the serious damages. Therefore, keeping the reliability and stability of power service quality for the HSP becomes a quite important issue. To solve the power quality problems for the HSP, Taipower System (TPS) had additionally set the power substation to the HSP and changed the overhead power wire into underground distribution system with loop scheme. Power system in the HSP keeping a duty of high power quality is the joint duty for the TPS and HSP customers. Especially, many manufacturers in HSP installing the CHP equipment will lead to one of the important factors about the effects of power service quality. Therefore, if we can properly plan CHP units in HSP, it not only effectively copes with insufficient power supply of TPS, but also solves the problems of unstable power quality in power system. The results of this study can make a reference to the CHP facility constructed by high-tech factory and help the high-tech manufacturers to face the dilemma of the current electricity problems.

2. System Structure

The CHP system for this study is built in HSP. The CHP factory has built three 45 MW gas turbine generators and one 36.6 MW steam turbine unit [5, 6]. Single-line diagram of the system is shown in Figure 1. The CHP units are parallel connected with TPS mainly by two three-winding isolation transformers: TRAA and TRBB. The primary and secondary windings of the transformers all adopt 161 kV with Y-connection; their capacities are 90 MVA and 60 MVA, respectively. The third winding adopts 11 kV with Δ -connection; its capacity is 30 MVA. There is a parallel connection between transformers and TPS. In addition to improving the power supply reliability, it also achieves the goal of the fault current restriction.

2.1. Short-Circuit Fault Analysis. The breaker capacity is 40 kA usually used at 161 kV power supply loop. The TPS limits the maximum short-circuit current not exceeding 2 kA for the CHP units because the TPS provides a maximum fault current 38.06 kA. To deal with this problem, the CHP system has set two 161 kV/161 kV high-impedance transformers with tap-changer, which restricts the breaking fault current provided by the CHP units. According to ANSI standard, the breaking speed of the breaker and the parting time of the contact are set as 3 and 2 cycles, respectively. Having been installed two 161 kV/161 kV transformers, the instantaneous fault current provided by the CHP units is 1.54 kA, which will satisfy the demands of TPS. The originally total instantaneous symmetric short-circuit current is 38.06 kA at the TPS Long-Song substation. If the 161 kV/161 kV transformers are not installed, then the instantaneous fault current increases 2.64 kA provided by the CHP units. Unfortunately, the total instantaneous symmetric short-circuit current is increased to 40.7 kA at the Long-Song substation. From the short-circuit fault analysis, if the industrial CHP system is directly connected to the TPS, the short-circuit capacity of the Long-Song substation will be greater than 40 kA when a fault occurs. Therefore, we should adopt the 161 kV/161 kV transformers to connect with TPS and then the short-circuit capacity is less than 40 kA to meet the requirement of the TPS.

2.2. System Modeling. The CHP system consists of generators, exciters, governors, load, and other equipment. In this study we would like to establish the mathematical models of these components first. We will now illustrate the equivalent models of the important components for this system below.

2.2.1. Generator Model. In this paper, the generator sets of the industrial CHP system will take into account the detailed effects of transient and subtransient on the generator. It is assumed that the d -axis and q -axis all have damping coils. We will perform the simulation of the operation of generator under the saturation and unsaturation to obtain the more precise transient stability [7].

2.2.2. Exciter Model. The excitation systems of gas turbine units from GTG1 to GTG3 in the CHP system are all IEEE

FIGURE 1: Single-line diagram of the CHP system.

TYPE3, but the excitation system of steam turbine unit STG is IEEE TYPE2 [8]. Their control block diagrams are shown in Figures 2 and 3, respectively.

2.2.3. Governor Model. The rotor speed of the generator in the governor control system serves as a main feedback signal. The comparison between the signal and reference speed gets the speed error, again by the error; it will serve as the change in the position of the steam valve to regulate the amount of steam entering the turbine. At last, the change in the output of mechanical power for turbine is performed so that the generators after the system disturbance occurred can restore to synchronous operation. The governors of gas turbine from GTG1 to GTG3 in the industrial CHP system are all GAST TYPE, but the governor of steam turbine STG is IEEE TYPE1. Their control block diagrams are shown in Figures 4 and 5, respectively.

3. Relay Setting for Tie Line Tripping

To make sure of the power quality, power supply reliability, and utility safety operation of CHP plant after connecting to the TPS, the CHP plant must install some different types of protection relays at TPS duty point. The CHP generator units or the significant loads inside the plant will be tripped when the fault disturbances are occurred at the TPS. Under the situation, it is necessary to trigger the protection relays to trip the main breaker in TPS tie line. The CHP plant can then be kept at an independent stable operation [9, 10].

FIGURE 2: Block diagram of exciter control system for gas turbines.

FIGURE 3: Block diagram of exciter control system for steam turbine.

FIGURE 4: Block diagram of governor control system for gas turbines.

FIGURE 5: Block diagram of governor control system for steam turbine.

The severest fault in power system is the ground faults. The customer's equipment should ensure keeping continuously stable operation when a ground fault occurred. Therefore, the relay for tie line tripping connected to the TPS must trip within 0.1 sec. Because bus 903 is more close to the fault point than bus 931 and 932, the voltage drop at bus 903 is deeper than others. The voltage drops to 0.2456 pu during the fault period with 161 kV/161 kV transformers and 0.0037 pu without 161 kV/161 kV transformers, respectively. The bus 931 voltage drops to 0.4543 pu and 0.3029 pu, and the bus 932 voltage drops to 0.4223 pu and 0.251 pu. From these results, we observe that the voltage drop at bus 903 is greater than those at bus 931 and 932 [11], as shown in Figures 6 and 7.

In this paper, we will analyze the following three different types of operation modes for the industrial CHP system. The power generation for each gas turbine is 56.25 MW with a power factor of 0.8 and for steam turbine is 36.6 MW with a power factor of 0.8. The total load of the customers in CHP system is 153.97 MW. Table 1 shows all the output power of each CHP unit and total load for three different types of operation modes.

3.1. 3GIS Operation Mode. Under the 3GIS operation mode, we suppose that a fault occurred at bus 901 in TPS at 0.2 sec. The tie line between the CHP plant and the TPS must be tripped after fault occurrence. At the moment, the power

FIGURE 6: Voltage variations at bus 903, 931, and 932 with 161 kv/161 kv transformers.

generation capacity is greater than the load demand, in which the electrical powers of the gas and steam turbines are at their maximum ratings of 45 MW and 36.6 MW, respectively. After the tie line tripping, all the CHP units will settle to a new stable operation point at which the electrical power outputs will achieve the 42.114 MW, 35.839 MW, 39.018 MW, and 39.103 MW, respectively. The CHP system frequency can

TABLE 1: Operation modes of CHP units.

Operation modes	GTG1 (MW)	GTG2 (MW)	GTG3 (MW)	STG (MW)	Total Gen (MW)	Total load (MW)
3GIS* ¹	45	45	45	36.6	171.6	153.97
2GIS* ²	45	45	OFF	36.6	126.6	153.97
1GIS* ³	45	OFF	OFF	36.6	81.6	153.97

*¹Three gas turbine units and one steam turbine unit.

*²Two gas turbine units and one steam turbine unit.

*³One gas turbine unit and one steam turbine unit.

FIGURE 7: Voltage variations at bus 903, 931, and 932 without 161 kv/161 kv transformers.

FIGURE 9: Generator speeds for 3GIS operation mode.

FIGURE 8: Electrical power outputs for 3GIS operation mode.

FIGURE 10: Electrical power outputs for 2GIS operation mode.

fast restore to 60 Hz. Figures 8 and 9 show the curves of the electrical power outputs and speeds.

3.2. 2GIS Operation Mode. Under the 2GIS operation mode, the CHP plant has been isolated from the TPS after the tie line tripping at 23rd cycles (0.384 sec.). The electrical power outputs of the generators have reached their maximum values of 56.25 MW, 39.914 MW, and 56.25 MW. At the moment, the total power generation capacity is less than the load demands. Hence, the generator frequencies will drop slowly so that

these generator units cannot keep operating for a long time, as shown in Figures 10 and 11.

3.3. 1GIS Operation Mode. Under the 1GIS operation mode, after the CHP plant has been isolated from the TPS, the frequency will continuously drop and eventually collapse, as shown in Figures 12 and 13.

From the preceding results, if the system frequency wants to restore the 60 Hz and keep stable operation for both 1GIS and 2GIS operation modes, then it must perform the

FIGURE 11: Generator speeds for 2GIS operation mode.

FIGURE 13: Generator speeds for 1GIS operation mode.

FIGURE 12: Electrical power outputs for 1GIS operation mode.

load shedding. The foregoing cases can be simulated using electrical transient analysis program (ETAP) software [12].

4. Load Shedding Strategy

The CHP plant performs the parallel operation with the TPS in order to supply power with reliability and safety. When the system operates at a stable equilibrium status, the CHP plant is not necessary to carry out any load shedding. However, when the fault occurred and the tie line is tripped to isolate from the TPS, the electric power generation may be insufficient to supply to the demand inside the CHP system. The system frequency will continuously drop. Consequently, it causes the industrial CHP units to trip and factory to power off. Therefore, after the CHP system has isolated from the TPS, performing the load shedding based on the change in frequency becomes an extremely important thing. Through shedding some unimportant load, generator units can maintain and restore the stable operation.

After performing the tie line tripping, we can compute the initial frequency decay rate of the industrial CHP system. From (1), the amount of load to be unloaded can be determined [13] to avoid the occurrence of a misjudged thing due to the rapid load changes. The incorrect unloading in the CHP units results in the collapse of the power system. From (1), the initial frequency decay rate can be solved to determine the amount of unloading which can reduce the drawbacks of both excess in unloading and insufficient unloading. Moreover, the computation of (1) spends less time:

$$P_{\text{step}} = \frac{2H_{\text{sys}}}{w_0} \frac{d\Delta w}{dt} = \frac{2H_{\text{sys}}}{60} m_0, \quad (1)$$

where P_{step} is the total amount of load to be shed. m_0 is the initial frequency decay rate at the moment of tie line tripping:

$$H_{\text{sys}} = \frac{H_1 \text{MVA}_1 + H_2 \text{MVA}_2 + \dots + H_n \text{MVA}_n}{\text{MVA}_{\text{sys}}}, \quad (2)$$

where H_{sys} is the equivalent system inertia constant of the CHP system and n is the number of the CHP units.

This study finds that the CHP system encountered the short-circuit fault in the 1GIS and 2G2S operation modes and performed the tie line tripping from the TPS, it was necessary to execute load shedding to prevent frequency continuously drop and had an opportunity of recovering to 60 Hz. We adopted the load shedding of a detective frequency drop manner to perform the unloading. For 1GIS operation mode, we obtained the inertia constant H and m_0 as 2.065 and 11.84 based on (1) and (2). For 2GIS operation mode, the H and m_0 can be computed as 3.101 and 2.69. Again, substituting the foregoing values into (1), we can obtain the P_{step} as 81.5 MW and 27.8 MW, respectively.

Under the 2GIS operation mode, the electrical power outputs after the tie line tripping from the TPS and load shedding are shown in Figure 14. At this moment, the amount of power generation and the amount of load demand inside the CHP plant have reached the balanced condition. Namely, the output power of the gas and steam turbines are 48.004 MW,

FIGURE 14: Electrical power outputs for 2GIS operation mode with load shedding.

FIGURE 15: Generator speeds for 2GIS operation mode with load shedding.

36.578 MW, and 44.988 MW, respectively. Figure 15 shows the generator speeds after the tie line tripping from the TPS for the 2GIS operation mode. This figure shows that the system performs the load shedding after 3.86 sec.; the frequency of the CHP plant has been restored to the stable state of 60 Hz.

Under the 1GIS operation mode and after the tie line tripping from the TPS, the amount of power generation and the amount of load demand inside the CHP plant have reached the balanced condition. The power outputs of the gas and steam turbines are 48.247 MW and 36.62 MW, as shown in Figure 16. The generator speeds before and after load shedding are given in Figure 17. This figure shows that the frequency of the CHP system has restored to the stable state of 60 Hz after performing the load shedding and through 6.645 sec.

FIGURE 16: Electrical power outputs for 1GIS operation mode with load shedding.

FIGURE 17: Generator speeds for 1GIS operation mode with load shedding.

5. Conclusions

This paper mainly investigates the power system transient stability for the high-tech science park with CHP facility. The load shedding has been applied to the industrial CHP system under the different tie line tripping opportunities and operation modes. If the system adopts 161 kV/161 kV transformers to connect to the TPS in parallel, this study finds that the industrial customer's system voltage sags can be improved during fault contingency. The manufacturers can avoid a serious loss caused by the power failure, which contributes the coordination between the protective relays [14]. In addition, the mechanism of tie line tripping is very important between CHP plant and the TPS. We can not only select the frequency relays to activity but also utilize the undervoltage relays to perform a proper load shedding. In this way, the improper tie line tripping can be avoided due to the internal fault of CHP system, and both power systems of the TPS and CHP plant can keep a normal independent operation after the tie line tripping.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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