ADAPTIVE GOVERNOR CONTROL AND LOAD SHEDDING SCHEME FOR AN INCINERATOR PLANT

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Abstract: This paper presents an adaptive control strategy for the governor system of an incinerator cogenerator to maintain the steam pressure and system power frequency. Due to the unstable steam generation in incinerator plants, the turbine valves have to be controlled adaptively to keep the boiler steam pressure constant for normal operation. After tie-line tripping caused by utility faults, the governor system must be operated with constant frequency control for the islanding system. By this way, the surplus steam supply to turbines will be bypassed effectively. For the islanding operation, the deficiency of steam generation is then supplemented by boilers. To maintain the system stability after transient disturbance for the isolated system, the load shedding scheme is designed by considering the under steam pressure protection. According to the transient stability analysis, the system frequency can be restored successfully after tie-line tripping with the adaptive change of governor control system from the constant steam pressure mode to the constant frequency mode. *Copyright © 2006IFAC*

Keywords: Governor control system; boiler; cogeneration system; load shedding; transient stability

1. SYSTEM DISCRIPTION

To study the effectiveness of governor controller for cogenerators with unstable steam system, an incinerator plant in Taiwan with three sets of boilers and an extraction-condensing type of turbine generator as shown in Fig. 1 was selected for computer simulation using CYMSTAB software package. Different from conventional cogeneration systems of industrial customers, all steam generated from the incinerator boilers is exhausted by the turbine generator, and then condensed as the feed water for boilers. The power output of the incinerator cogenerator varies with the steam generation according to the amount of refuse burned. Due to the variation of heat value in the trash, the steam flow generated by incinerator cogeneration will fluctuate very seriously. Therefore, the governor control system of the turbine has to be operated with constant pressure control to maintain the boiler steam pressure for normal operation.

For the severe fault contingencies of external Taipower system, cogeneration systems are normally isolated by opening the tie-line breakers, and the governor systems of cogenerators are adaptively changed to the constant frequency control to prevent the isolated power system from collapsing. With the unstable steam generation, it becomes very difficult to control the steam pressure and system frequency for the isolated cogeneration. In this paper, an adaptive governor control system for the turbine generator has been presented to maintain the stable operation of the incinerator cogeneration system.

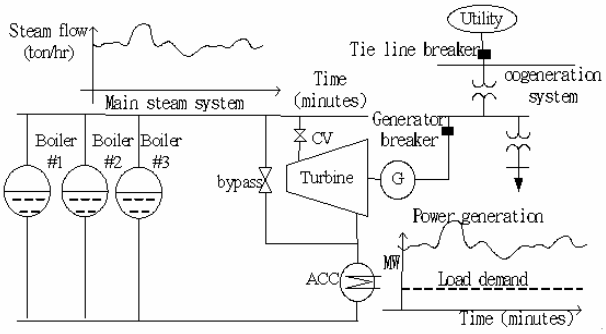

Fig. 1. Incinerator cogeneration system.

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2. GOVERNOR SYSTEM MODEL WITH BOILER DYNAMICS

The governor system model with boiler dynamics for the incinerator cogeneration system is represented as shown in Fig. 2. The dynamic change of steam flows generated by boiler systems affects the power output of the cogenerator, which can be calculated as the product of the valve flow area x_2 and the throttle pressure x_4 of steam inlet. The valve flow area can be controlled by the governor system so that the turbine inlet pressure will be proportional to the integral of the net inflow passing through the tube of distributed superheater. K_{SH} is the friction coefficient of the tubes in the superheater, and K_D is the overall storage volume coefficient of the boilers. Both parameters dominate the time response of incinerator boiler systems. The steam pressure drop from drum to inlet turbine is represented as the square of mechanical input power P_m. The steam generation of boiler Q_B is determined by the heat release in waterwalls depending on the amount of trash burned. Instead of considering the fuel dynamics and the boiler control system, the steam flow Q_B directly controlled by operators can be considered as the input variable of this model. The turbine power output can be derived according to the dynamic steam flows measured by the distributed control system (DCS).

T_1, T_2, T_{CH} are the time constants of the speed relay, servomotor and steam chest of the turbine, respectively. For constant pressure operation of the governor controller WOODWARD505, the PID frequency controller is cascaded by the PID pressure controller. By this way, the speed reference ω_{ref} can be adjusted to maintain the constant steam pressure of header according to the variation of steam flows, and the power output of cogenerator is independent of the system frequency fluctuation. For constant frequency operation, the PID pressure controller and the frequency droop controller R1 are deactivated as shown in Fig. 3. The speed reference is then set equal to the actual speed, and adjusted automatically to reach the synchronized speed with rate change of 2rpm per second.

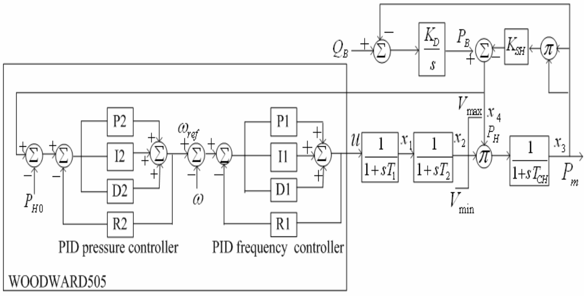

Fig. 2. Pressure control of governor system model.

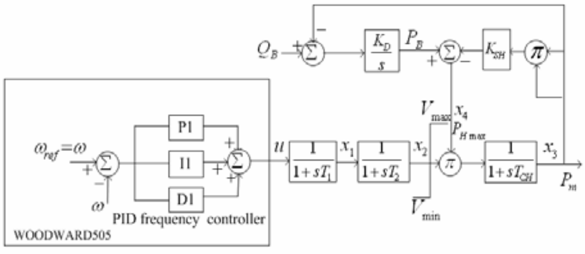

Fig. 3. Frequency control of governor system model.

3. THE MATHEMATICAL MODEL OF THE INCINERATOR COGENERATION SYSTEM

Table 1 lists the parameters of the incinerator cogeneration unit, which were provided by the manufacturer, or obtained from performing the field test. The typical values were used for the time constants of the servomotor of governor system and the steam chest of turbine. The coefficient of steam pressure drop K_{SH} was estimated based on the calculation of fluid dynamics for the incinerator boiler systems. The parameter K_D was derived from the dynamic relationship between steam pressure of header and total steam generation. The parameters of PID frequency controller of the governor system were tuned for the possible maximum load rejection to maintain the stable operation of the incinerator cogenerator.

To develop the better system analysis with the above parameters of the cogeneration unit, the governor system model with constant pressure control in Fig. 2 is linearlized as shown in Fig. 4. The output *u* of the controller is calculated in Eq. (1). The transfer function is expressed as Eq. (2), and the corresponding parameters H are solved by Eq. (3), (4), (5) and (6), respectively with constants A, B, C, D calculated as follows. By the same way, the mathematical model of the isolated-incinerator cogeneration system with constant frequency operation is linearlized as shown in Fig. 5. The corresponding state equation of the system can be represented as Eq. (7).

Table 1 Parameters of the cogeneration unit

Gen.	kV	MW	H	X_d	X_q	X'_d	X'_q	X''_d
	11.9	54	8	1.964	1.08	0.257	0.6	0.169
	X''_q	τ'_{d0}	τ'_{q0}	τ''_{d0}	τ''_{q0}	$S_{G1.0}$	$S_{G1.2}$	D
	0.2	6.54	1.5	0.031	0.08	0.12	0.6	1
Gov. and Boiler	T_1	T_2	T_{CH}	V_{max}	V_{min}	R_1	P_1	I_1
	0.05	0.05	0.2	1.0	0	0.05	4	1
	D_1	R_2	P_2	I_2	D_2	K_D	K_{SH}	
	0.4	0	4	0.1	0	0.01	0.25	

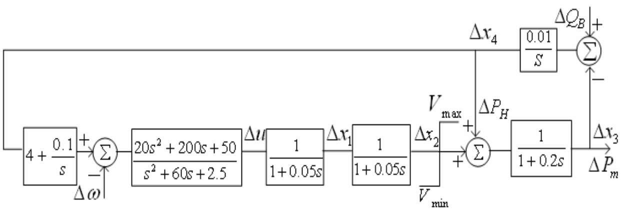

Fig. 4. Linearlized governor system model for constant pressure operation.

$$\Delta u = \frac{20s^2+200s+50}{s^2+60s+2.5}\left((2+\frac{1}{s})\Delta x_4 - \Delta\omega\right) \quad (1)$$

$$\begin{bmatrix}\Delta x_3\\ \Delta x_4\end{bmatrix} = \begin{bmatrix}H_{11} & H_{12}\\ H_{21} & H_{22}\end{bmatrix}\begin{bmatrix}\Delta\omega\\ \Delta Q_B\end{bmatrix} \quad (2)$$

$$H_{11} = \left.\frac{\Delta x_3}{\Delta\omega}\right|_{\Delta Q_B=0} = \frac{-AB}{1+BD+ABCD} \quad (3)$$

$$H_{12} = \left.\frac{\Delta x_3}{\Delta Q_B}\right|_{\Delta\omega=0} = \frac{BD+ABCD}{1+BD+ABCD} \quad (4)$$

$$H_{21} = \left.\frac{\Delta x_4}{\Delta\omega}\right|_{\Delta Q_B=0} = \frac{ABD}{1+BD+ABCD} \quad (5)$$

$$H_{22} = \left.\frac{\Delta x_4}{\Delta Q_B}\right|_{\Delta\omega=0} = \frac{D}{1+BD+ABCD} \qquad (6)$$

$$A = \frac{20s^2+200s+50}{(s^2+60s+2.5)(1+0.05s)^2} \quad B = \frac{1}{1+0.2s}$$

$$C = 4+\frac{0.1}{s} \qquad D = \frac{0.01}{s}$$

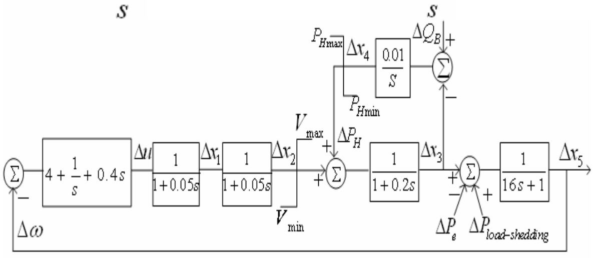

Fig. 5. Linearlized governor system model for constant frequency operation.

$$\begin{bmatrix} \Delta\dot{x}_1 \\ \Delta\dot{x}_2 \\ \Delta\dot{x}_3 \\ \Delta\dot{x}_4 \\ \Delta\dot{x}_5 \end{bmatrix} = \begin{bmatrix} -\frac{1}{T_1} & 0 & 0 & 0 & 0 \\ 0 & -\frac{1}{T_2} & 0 & 0 & 0 \\ 0 & \frac{1}{T_{CH}} & -\frac{1}{T_{CH}} & \frac{1}{T_{CH}} & 0 \\ 0 & 0 & -K_D & 0 & 0 \\ 0 & 0 & \frac{1}{2H} & 0 & -\frac{D}{2H} \end{bmatrix} \begin{bmatrix} \Delta x_1 \\ \Delta x_2 \\ \Delta x_3 \\ \Delta x_4 \\ \Delta x_5 \end{bmatrix} + \begin{bmatrix} \frac{1}{T_1} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & K_D & 0 \\ 0 & 0 & -\frac{1}{2H} \end{bmatrix} \begin{bmatrix} \Delta u \\ \Delta Q_B \\ \Delta P_e \end{bmatrix} \qquad (7)$$

For an actual remote fault of external Taipower system without causing the tripping of tie-line, the dynamic response of system frequency has been monitored as shown by line 1 in Fig. 6. To maintain a constant steam pressure, the speed reference of governor controller has been adjusted accordingly with the change of system frequency as shown by line 2. Figure 7 shows the steam flow of the header and power generation of the cogenerator. It is found that the power generation of the incinerator cogeneration system can be adaptively controlled by constant pressure operation of the governor system with the variation of system frequency and steam flow.

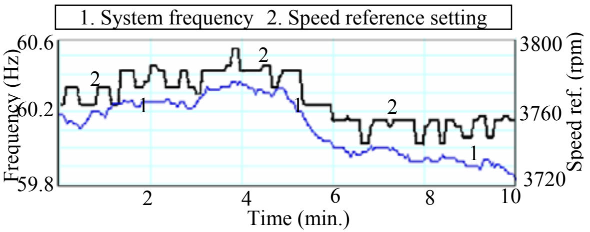

Fig. 6. Actual system frequency and speed reference setting.

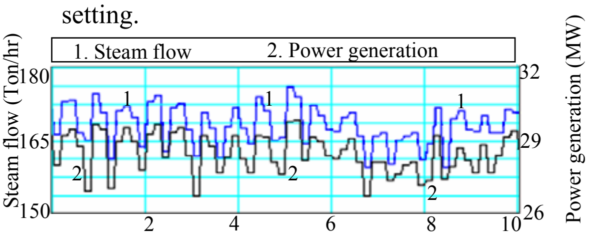

Fig. 7. Steam flows of the header and power generation.

4. GOVERNOR CONTROL STRATEGY WITH LOAD SHEDDING DESIGN

When the cogeneration system is connected to Taipower with system frequency fluctuation between 58.6Hz and 61.5Hz, the governor system is operated with constant pressure control to maintain the steam pressure for the unstable cogeneration system. The rotor speed of cogenerator is varied with the system frequency because of rather large inertia of the external Taipower system. To prevent the cogenerator from operating with undesired speed to cause the damage of the turbine, an over frequency relay 81H with setting at 62.5Hz and an under frequency relay 81L with setting at 58.6Hz are installed at the tie-line. The electrical signal for turbine tripping is also used with frequency setting at 63Hz to coordinate with the over frequency protection for tie-line tripping. Additionally, the governor control strategy is designed to adaptively change to the frequency control when the incinerator plant exports the surplus power to Taipower with system frequency operation over 61.5Hz.

After tie-line tripping, the power output of cogenerator has to be adjusted rapidly to accommodate the in-plant local load by frequency control of the governor system. At the same time, the fluctuated steam pressure of boiler header is controlled by bypassing the excessive steam, or activating the load-shedding scheme proposed in Table 2. The turbine bypass valve is controlled with setting at 1.08 times of the normal operating steam pressure for the boilers. On the other hand, the load-shedding scheme is designed to maintain the boiler steam pressure to be higher than 0.92p.u for the normal operation of the turbine. The total amount of load to be disconnected is determined by the minimum generated steam flows and the maximum electrical load served by the incinerator plant.

Table 2 Load shedding scheme

Steam pressure (p.u)	Time delay (sec)	Load shedding
0.98	0.1	3MW
0.96	0.1	2MW
0.95	0.1	2MW
0.94	For every 10 second	1MW

5. EFFECTIVENESS OF THE GOVERNOR CONTROL SYSTEM

To demonstrate the effectiveness of the proposed governor control strategy and load-shedding scheme, the tie- line was disconnected intentionally to test the islanding operation of the incinerator plant with different operation scenarios. Before tie-line tripping, three sets of incinerators are operated with in-plant load of 8MW. The power output of cogenerator fluctuated between 25MW and 32MW due to the unstable steam generation. By adding an extra heavy load of 27MW in the plant, the maximum power flow over the tie-line will be changed from exporting by 24MW to importing by 10MW. With the deficiency of power generation in the plant, the load shedding has to be executed to maintain the steam pressure of cogeneration system with constant frequency operation after tie-line tripping. Three different operation scenarios have been selected for computer simulation to solve the system response of the islanding incinerator cogeneration system.

Case A. Small amount of power flows over the tie-line

In this case, the power output of incinerator cogenerator is varied with the reduction of steam generation as shown in Fig. 8. The tie-line power flow is assumed to be changed by ±3MW. Figure 9 shows the system frequency response of the incinerator cogeneration system with constant steam pressure operation after intentionally tie-line tripping. For the cogeneration system with exporting 3 MW to Taipower system before tie-line tripping, the isolated system frequency will be increased to 61Hz, and then gradually decreased to 60.6Hz due to the governor control action. On the other hand, the frequency will be decayed to be less than 58Hz within a very short time for the operation condition of importing 3 MW from Taipower before tie-line tripping. It is found that the fluctuation of system frequency could result in the unnecessary load shedding or generator tripping if the constant pressure operation is implemented for the isolated incinerator cogeneration system. If the constant frequency control mode of the governor system is adaptively applied after tie-line tripping, the system frequency can be restored to 60Hz effectively as shown in Fig.10 despite of the dynamic fluctuations of power generation of cogenerator and steam pressure of boiler.

Case B. Steam generation surplus of the cogeneration system

In this case, the power output of incinerator cogenerator is 32MW, and the total load demand for the auxiliary boiler systems is 8MW, which implies that the imbalance of power generation and load demand will be 24MW. Figure 12 and 13 show the responses of system frequency and power output of cogenerator by applying the constant frequency control after tie-line tripping for the islanding operation of incinerator plant. With such a large power generation surplus for the isolated system, the system frequency is increased to 62.8Hz during the reduction of power generation from 32MW to 8MW. The surplus steam is bypassed effectively to limit the steam pressure of boilers at 1.08p.u, and the system frequency was restored to 60Hz in 30 seconds.

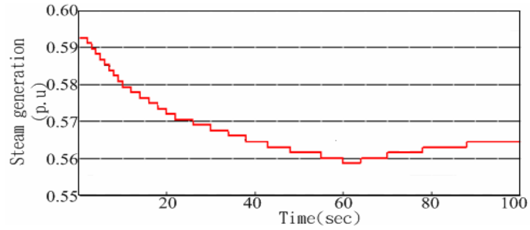

Fig. 8. Dynamic change of steam generation.

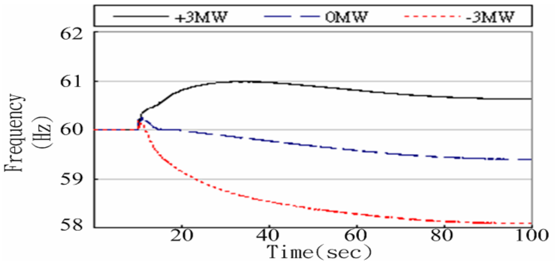

Fig. 9. Frequency response for constant pressure operation in *Case A*.

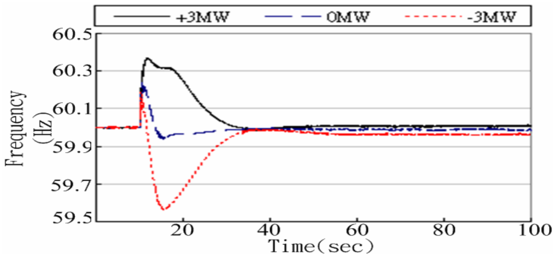

Fig. 10. Frequency response for constant frequency operation in *Case A*.

Case C. Steam generation deficiency of the cogeneration system

The power output of cogenerator and total in-plant load are 26MW and 35MW, respectively. Figure 14, 15 and 16 show the system responses of the cogeneration system after tie-line tripping. Due to the deficiency of power generation in the plant, the system frequency of the isolated system has dropped to the minimum value of 59.2Hz. The steam valve is opened to increase the power output of cogenerator to restore the system frequency around 60Hz by constant frequency operation. With proper control of the steam valve, the decay of steam pressure will result in the limitation of the turbine power output. By activating the load shedding scheme proposed in this paper, the steam pressure can be controlled to be stable at 0.94p.u, and the power output of cogenerator will be reduced to 25MW after one and half minutes.

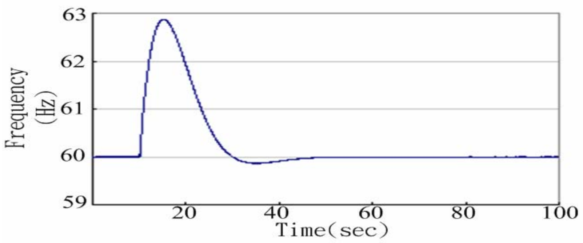

Fig. 11. Frequency response of cogeneration system in *Case B*.

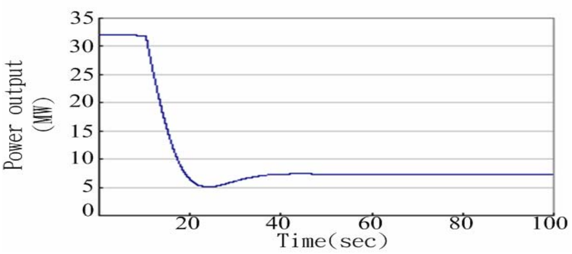

Fig. 12 Power output of cogenerator in *Case B*.

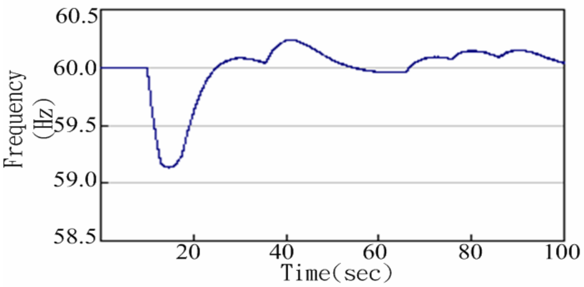

Fig. 13. Frequency response in *Case C*

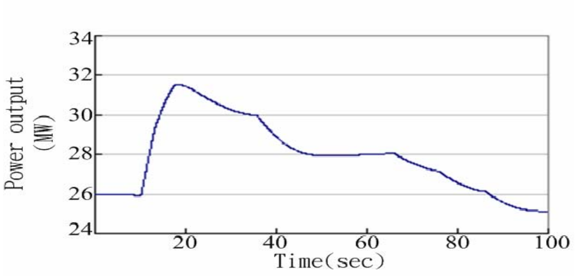

Fig. 14. Power output of cogeneration system in *Case C.*

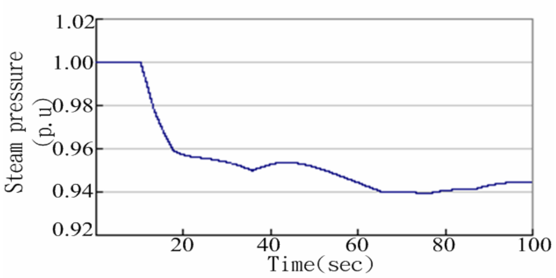

Fig. 15. Steam pressure of cogeneration system in *Case C.*

6. TRANSIENT STABILITY ANALYSIS OF THE INCINERATOR COGENERATION SYSTEM

To investigate the transient stability of the incinerator plant, the cogeneration system with the neighboring Taipower network in Fig. 17 has been used for computer simulation of transient stability analysis. The 161kV tie-line is connected to Taipower Nankung substation which also serves other large customers in the heavy industrial park. The Talin power plant of Taipower provides 420MW to serve the load of Linyuan substation which is connected to Kaokang EHV substation. The rest of Taipower system has been represented as the equivalent generator unit connected to Kaokang substation. The mathematical models with two damping coils along the p and q axes by taking into account the magnetic flux saturation effect are considered for all generators. The governor and exciter systems of Taipower generators are also included to simulate the transient response more accurately for the fault contingency of external Taipower system.

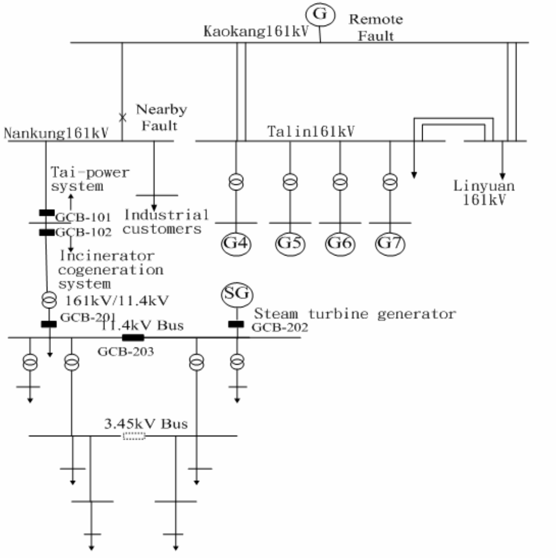

Fig.16. One line diagram of the study power system.

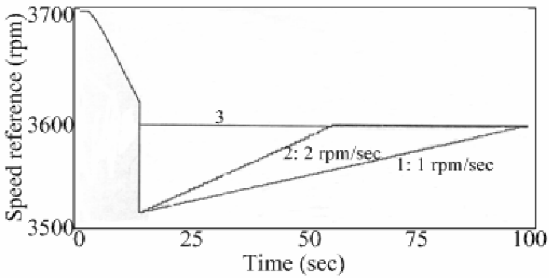

Fig. 17. Three different speed reference settings.

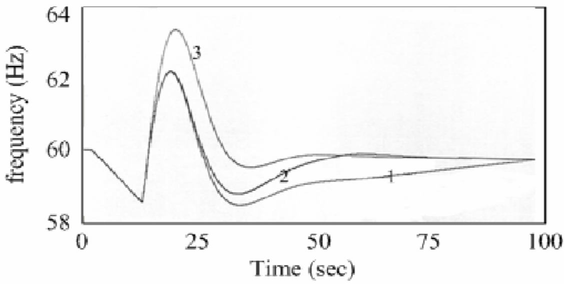

Fig. 18. Frequency response in *Case D.*

Case D. Nearby fault of external power system

For the nearby power contingency, a bolted ground fault on the 161kV transmission line in Fig. 17 has been assumed for computer simulation. By the operation of circuit breaker to clear the fault, the Nankung substation becomes an isolated system. With large industrial loads to be served, the cogeneration system frequency has been dropped to be below 58.6Hz to activate the tie-line tripping by under frequency relay to result in the islanding operation of the incinerator plant. At the same time, the governor system was changed from constant pressure operation to constant frequency operation by the governor controller. With three different speed reference settings as shown in Fig. 18, the corresponding system frequency of the islanding system during the transient period has been illustrated in Fig. 19. It is found that the over shooting of system frequency has been reduced to 62Hz by setting the initial speed reference as the actual speed with ramping rate of 2rpm/sec after tie-line tripping.

Case E. Severe fault of external power system

For the severe fault, such as the tripping of EHV 345kV transmission line, the whole Taipower system is separated to form the southern and northern subsystems. Because of the large amount of power flows carried from the south to the north, the tripping of transmission lines will introduce serious unbalance between power generation and load demand in each subsystem. With such large amount of power generation surplus in southern Taiwan, the system frequency increases dramatically in a short time period.

To test the over frequency protection of the cogeneration system, the load tripping at Linyuan bus and the constant power generation of Talin power plant have been assumed in the study system for computer simulation by transient stability analysis. Figure 20 and 21 show the system responses of cogeneration system with different timing to change the governor control strategy.

When the fault occurs, the system frequency is increased to activate the tie-line tripping of the incinerator cogeneration system. The change of governor system from the constant steam pressure to the constant frequency control has to be made at the system frequency of 61.5Hz to reduce the power output of cogenerator in time as shown by line 1. On the other hand, the isolated cogeneration system will collapse if the constant frequency control of governor system is applied at the system frequency of 62.5Hz due to the turbine over speeding.

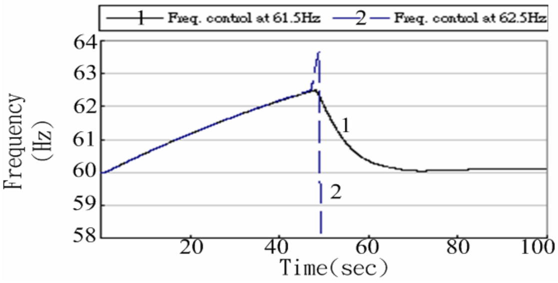

Fig. 19. Frequency response with different models of governor system in *Case E*.

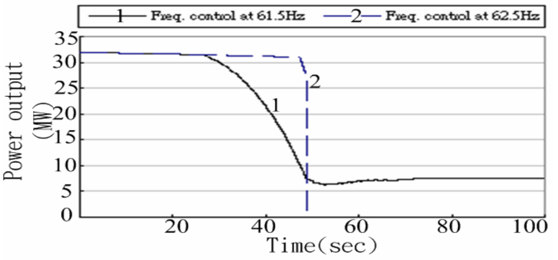

Fig. 20. Turbine power output with different models of governor system in *Case E*.

7. CONCLUSION

The adaptive control strategy of governor system for the incinerator cogeneration has been demonstrated by transient stability analysis. The design of load shedding scheme based on the under steam pressure protection has been proposed to maintain the system frequency and boiler steam pressure for the incinerator cogeneration system after tie-line tripping. For the external system disturbance, the fluctuation of steam pressure, the governor control system and the boiler control system of the cogenerator will affect the system response. To maintain the boiler steam pressure by considering the unstable heat value of trash burn in the incinerator plant, the PID controllers of the governor system for the constant frequency operation and constant pressure operation are coordinated with each other. The power output of the turbine generator fluctuates with trash heat value by applying the constant steam pressure control for normal operation. After tie-line tripping to isolate the fault contingency of external system, the constant frequency control will override the constant pressure control loop so that the system frequency of the islanding system can be maintained.

The frequency response and power output of cogenerator for different case studies have been simulated. The transient stability analysis of incinerator cogeneration system by considering the unstable steam generation due to dynamic change of heat value of trash has been performed. It is concluded that the proper load shedding and the adaptive governor control by changing from constant steam pressure to constant frequency are very critical for the incinerator plant to maintain power system stability after tie-line tripping.

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