Protective Relay Setting of the Tie Line Tripping and Load Shedding for the Industrial Power System

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Abstract—This paper presents the proper underfrequency relay settings to enhance the operation of industrial power systems with cogeneration facilities. A cogeneration unit was installed in the plant in 1996 to supply the power demand of the plant. The cogeneration unit always faces the shutdown problem when a severe fault occurs on the nearby Taipower network. It is, therefore, necessary to investigate the plant protective relay settings to prevent a whole plant blackout when the contingency occurs. The transient stability analysis has been performed by considering both the detailed models of the cogenerators with the governor and exciter control systems and the external utility power system. The underfrequency relay settings for tie line tripping and load shedding are designed to prevent the tripping of the cogeneration units so that the electricity service to the critical loads of the industrial customer can be maintained in case serious external disturbances such as short circuit faults occur. In this study, the scheme of underfrequency relay settings has been developed for the power system of a large synthetic rubber manufacturer with a large cogeneration unit. Three study cases have been selected for the transient stability analysis to verify the effectiveness of the proposed protective relay setting.

Index Terms—Load-shedding scheme, transient stability.

I. INTRODUCTION

Due to the economic development in Taiwan, the power shortage during the summer peak periods has been a very serious problem for Taiwan Power Company (Taipower) in recent years. Furthermore, the environmental protection issue has introduced the difficulty of land acquisition for new generation plants. The system spinning reserve has reduced to be less than 5% and the interruptible load control has to be implemented by Taipower during recent years. To assure the quality of electricity supply, the cogeneration system has been considered by large industrial customers such as textile, paper mill, petrochemical, cement and steel manufacturers in Taiwan. In addition, with the high energy efficiency by producing the electricity and steam at the same time, a significant energy cost saving can be obtained by the cogeneration system for the industrial customers. Therefore, most of the energy-intensive industrial customers have installed the cogenerators or taken serious consideration for the implementation of the cogeneration units.

From the viewpoint of power system operation, it becomes necessary for the industrial customers with the cogeneration units to be connected to the utility network so that the mismatch between the load and cogeneration in the plant can be provided by the utility. Most of all, the industrial power system can also be effectively backed up by the utility power system for the plant internal contingency so that the reliability and stability of power service can be obtained. Since Taipower network is an isolated power system with radial structure, system fault always introduces serious power outages or power quality problems and causes serious damage to the industrial customers. To solve this problem, it has become a critical issue for the industrial customers with cogeneration facility to develop the protective and load-shedding scheme. By the proper design of protective relay system, the tie line with the utility power system can be tripped in time so that the industrial cogeneration units can survive from the system and the continuity of electricity service to the critical loads can be achieved.

To derive an effective load-shedding scheme, the transient stability analysis for all the potential fault cases of the external utility power system have to be performed [1]. According to the computer simulation, the frequency settings of the protective relays for the tie line tripping are defined so that the industrial customer can be isolated to minimize the impact of system disturbance. Furthermore, the frequency settings and the corresponding loads to be interrupted for different stages of load shedding have to be determined to restore the normal operation condition of the industrial customer. In this manner, the vital and essential loads in the plant can, therefore, be operated without power interruption to alleviate the production loss and personnel hazard.

II. DESIGN OF RELAY SETTINGS FOR TIE LINE TRIPPING AND LOAD SHEDDING

To find the proper relay setting for tie line tripping and load shedding to enhance system performance of an industrial power system, the computer simulations of load flow analysis, short circuit analysis and stability analysis for various load conditions have to be executed. Fig. 1 shows the overall process of protective relay setting and load shedding design. The proper mathematical models and accurate parameters of the study power network, the generator, exciter, and governor control systems of the cogeneration unit and loads have to be identified. The external utility system is often represented as an equivalent generation unit with very large inertia constant. The load shedding performed by the
Fig. 1. Flow chart of protective relay setting and load-shedding scheme design.

underfrequency relay and the tie line tripping by the underfrequency, overfrequency, and directional overcurrent relays under various system operations and fault scenarios are investigated. By this manner, the effectiveness of the proposed relay settings can, therefore, be verified by the computer simulation.

III. NETWORK CONFIGURATION OF THE INDUSTRIAL POWER SYSTEM

In this paper, a large synthetic rubber manufacturer (SRM) has been selected for computer simulation to demonstrate the design process of protective relay settings for both the tie line tripping and load shedding scheme. The cogeneration unit was installed in the plant in 1996 to supply the power demand of the plant. The network configuration of the whole study power system is illustrated in Fig. 2. To solve the transient stability analysis more accurately for underfrequency relay setting, two large industrial customers with cogeneration units in the same industrial park are also included in the transient stability analysis. To simplify the simulation, the external Taipower system is represented as the equivalent generation unit in the figure.

A. Equivalent Network of Taipower System

For the transient stability analysis of an industrial power system, it becomes impractical to include all generation units of the external utility system because the units are far away from the study industrial customer and less impact will be resulted. Besides, the computer simulation by considering the detail models of all Taipower generators is very complicated. For this reason, an equivalent generation unit G1 with very large inertia constant \( H = 1000 \) s is used to represent the whole Taipower system in this study. The Kangshan substation, which is served by another Taipower 345-kV EHV substation, provides the 161-kV electricity to Formosa Plastics Corporation (FPC) which is very close to the study network. There are four cogeneration units with a total capacity of 400 MVA in FPC, which will be combined together to form an equivalent generation unit G2 in Fig. 2. Four transformers with 200-MVA capacity in the Kangshan substation are used to transform the voltage level from 161 to 69 kV to supply the power to all the customers in the industrial park. Except for the Derchan feeder to serve the study industrial customer, the other 11 69-kV feeders are represented by the equivalent loads at buses 108 and 101. The Derchan feeder is connected to bus 110 and provides electricity to SRM and the other four large industrial customers. One of the four customers has a cogeneration unit with 20.25-MVA capacity and is represented as G3 in the figure. The total loads of the nearby customers are integrated and represented as the equivalent load at bus 102. According to the load survey, the
The power demand of the Derchan feeder is very stable as shown in Fig. 3 because of the continuous production process of the chemical plants. The peak and off-peak load demands are 39 and 27 MW, respectively.

B. SRM Industrial Power System

For the SRM industrial power system to be studied in this paper, there are three plants and one cogeneration unit manufactured by Asea Brown Boveri (ABB) with rated voltage 4.16 kV, rated capacity 18.25 MVA, and the maximum real power output is 14.6 MW. It is a steam-extraction-and-condensing-type unit with both the high-pressure and medium-pressure steam is extracted for the rubber production process. The rest of the steam is then fed into the steam turbines for power generation. According to the Taipower time-of-use (TOU) tariff, the electricity charge during system peak period is five times that during the off-peak period. The power generation cost of the cogeneration system during the off-peak period is higher than the Taipower energy charge. Therefore, the cogeneration unit is operated with the minimum mode by generating 30% of its rated output power and the power deficiency is then imported from Taipower during the off-peak period. On the other hand, the cogeneration is operated with the maximum mode and the surplus power is sold to Taipower during the daytime peak period to achieve the most cost benefit of the cogeneration unit. Table I shows the typical data of bus loading and cogeneration output during system peak, shoulder, and off-peak periods. The equivalent loading and the cogeneration output of the other large industrial customers are also included. In this table, three operation scenarios of the industrial customers in the study network are selected for computer simulation. LF1 is the operation scenario during system peak with all the plants fully operated. The cogeneration output is 12.4 MW and the total factory load demand is 12.04 MW, which implies that the surplus power of 0.36 MW has been sold to Taipower. LF2 is the operation scenario during system peak with one plant in SRM shut down. The cogeneration output is 9.52 MW and the total factory demand is 8.59 MW with 1-MW surplus power to be sold to Taipower. LF3 is the operation scenario during system off peak with one plant in SRM shut down. The cogeneration output is 6.86 MW and the total load demand is 8.37 MW, which means that the deficit power of 1.51 MW has been purchased from Taipower.

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Table I. System Bus Data and Cogeneration Output for Three Load Conditions
In this study.

relay with frequency setting at 59.1 Hz are, therefore, proposed
low-frequency condition. To solve the problem, the directional power
cogenerator unit when the tie line is tripped at the plant lightly
frequency shutdown problem due to the governor action of the
protective scheme, the cogeneration unit will encounter the low-
load characteristics in the factory.

V. TIE LINE TRIPPING STRATEGY

When a fault occurs in the external utility power system, the disturbance of system voltage and frequency may cause the shutdown of the cogeneration unit due to the tripping of boiler auxiliary facility and the action of relays for the unit protection. In this paper, the frequency setting of tie line tripping is derived based on the transient stability analysis of the study system by considering the mathematical model of cogeneration unit and load characteristics in the factory.

A. Overfrequency Relay (81H)

For the study of the industrial power system, the high-frequency problem may be introduced by the tripping of circuit breakers at the Kangshan substation and the total generation is larger than the total load demand within the isolated system served by the Derchen feeder. It will cause the shutdown of large coal-fired generators and result in serious system frequency decay. With the dramatic frequency and power swing, there exists the possibility of a whole industrial power system blackout. It is suggested that the overfrequency relay 81H with frequency setting of 60.5 Hz without time delay should be implemented to trip the tie line as soon as possible.

B. Underfrequency Relay (81L)

An underfrequency relay (81L) was used by the industrial customer for the tripping of the tie line. It is activated when the frequency drops below 58.8 Hz with 0.1-s time delay. By this protective scheme, the cogeneration unit will encounter the low-frequency shutdown problem due to the governor action of the cogenerator unit when the tie line is tripped at the plant lightly loaded condition. To solve the problem, the directional power relay 32 P with setting of 3 MW and another low-frequency relay with frequency setting at 59.1 Hz are, therefore, proposed in this study.

C. Directional Overcurrent Relay (67)

To further enhance the system stability, a directional overcurrent relay with setting T/L: 1/0.15 is considered to trip the tie line when the fault current flow from the industrial customer to Taipower is twice the magnitude of the rated load current within 0.4 s. In this manner, the critical motor loading in the plant can be prevented from unnecessary tripping.

VI. TRANSIENT STABILITY ANALYSIS OF THE INDUSTRIAL POWER SYSTEMS

To analyze the impact of an external Taipower fault to the industrial power system with cogeneration unit, a computer simulation of the study system for the nearby contingency cases has to be carried out. In this paper, several actual fault cases at the Kangshan substation and Derchan feeder that serve the industrial customer have been considered. By screening these contingencies, three cases are selected for load-flow analysis and transient stability analysis to verify the effectiveness of the proposed load-shedding scheme. The settings of underfrequency relays for tie line tripping and load shedding are designed based on the simulation results so that the stable operation of the cogeneration unit can be restored and the critical loads can be maintained for all possible system contingencies.

A. Case 1

This case simulates the contingency when a three-phase short circuit occurs at bus 105 in Fig. 2. Many large generation units in the Taipower system have been shut down, and very serious system frequency decay has resulted. The fault is cleared after 0.2 s by tripping the transmission line 103–105. The low-frequency relay setting of tie line trip is to be evaluated according to the computer simulation of system frequency response. The underfrequency protective relay for the tie line tripping is activated at frequency 58.8 Hz. The three load conditions in Table I are considered for transient stability analysis. Fig. 4 shows the response of system frequency and Fig. 5 shows the mechanical output power during the transient disturbance. For the system off peak and the light load condition in the plant (LF3), dramatic frequency decay has been found and the tie line is tripped after 1.4 s. The study system becomes isolated and the stable operation of the plant is restored after transient disturbance. For the system peak and plant heavy-load condition (LF1), the system frequency decays slowly and the tie line is tripped after 4.2 s. Before the tie line tripping, the power output of the cogeneration unit has reached its rated capacity of 14.6 MW due to the governor action. This implies that the power generation of the cogeneration unit will be greater than the total plant demand after the tie line tripping. Because of the large amount of power generation surplus in the isolated power network, the system frequency rises up to 60.7 Hz and power generation will be reduced by 7 MW due to the governor action. According to the computer simulation, the frequency is then reduced further to 58 Hz and then restored to 60 Hz after transient frequency oscillation. For the case of system peak with low level of output power by the cogeneration unit (LF2), the system frequency drops slowly.
and causes the tie line tripping after 5 s. The system frequency rises up to 61.7 Hz in a short time period and the steam valve of the cogeneration unit is then closed completely by the governor action. The frequency will then drop to 48 Hz after tie line tripping because of the dramatic generation shortage. With such a low frequency, the cogeneration unit will be shut down and a whole plant blackout will result. To prevent the tripping of the cogeneration unit for this study case, a reverse-power 3-MW power setting is proposed in series with a low-frequency relay with 59.1-Hz frequency setting. In this way, very fast tie line tripping can be achieved to save the industrial power system.

B. Case 2

In this paper, an actual previous contingency case that happened before has been selected for computer simulation. It was a three-phase fault occurring at bus 101 of the Kangshan substation and it was cleared after 1.4 s. The simulation is executed to investigate the effectiveness of the proposed protective relay...
Fig. 6. Voltage response at bus 1 for Case 2.

Fig. 7. Frequency response at bus 1 for Case 2 (with directional overcurrent relay setting for tie line tripping and load-shedding scheme). The reverse-current relay with 0.8-s delay to trip the tie line is applied. Figs. 6 and 7 show the voltage and frequency response. Although the voltage has dropped to 0.7 pu, the induction motors will not be deenergized by 3E relays because the voltage dip only lasted for a very short time period. The cogeneration unit will supply a very large amount of reactive power during the faulted period due to the response of excitation system to the low voltage level. With the excessive surplus of the reactive power after tie line tripping, the system voltage magnitude will be increased to 1.2 pu. However, the duration of voltage disturbance is very short due to the quick response of the excitation control. By the proposed frequency setting for tie line tripping, the system frequency variations will be within the range of 59.3–60.3 Hz and the stable operation of the industrial power system can be obtained.

If the directional over current relay for the tie line tripping is not implemented for the same fault condition, the Derchan feeder will be tripped after 1.5 s by the circuit breaker in the Kangshan substation. Because the cogeneration output is much less than the total load demand of all industrial customers served by the feeder, the system frequency decays very quickly and the low-frequency relay will be activated to trip the tie line at 58.8 Hz after 1.8 s and
three stages of load shedding have to be executed. Fig. 8 shows the system frequency response for the three operation conditions. By the low-frequency protection of the cogeneration unit at 57.5 Hz with 3-s time delay, the cogeneration unit will maintain its stable operation and the system frequency will be restored to 60 Hz after the execution of the proposed load shedding scheme.

C. Case 3

This study case simulates a three-phase short circuit fault at bus 110 and the Derchan feeder is tripped after 1.0 s. According to the proposed scheme, the tie line is tripped by the directional current relay at 0.8 s and the industrial customer becomes isolated even before the tripping of the Derchan feeder. Fig. 9 shows the frequency response for three load conditions. It is found that the lowest frequency for LF2 and LF3 is greater than 58.7 Hz and no load shedding will be executed. For LF1, the frequency will drop to 58 Hz after performing three stages of load shedding and it is then restored to 60 Hz. Because a dramatic voltage drop will be introduced for the nearby fault, it is suggested that the tie line should be tripped as soon as pos-

![Fig. 8. Frequency response at bus 1 for Case 2 (without directional overcurrent relay).](image1)

![Fig. 9. Frequency response at bus 1 for Case 3.](image2)
If the directional overcurrent relay does not detect the fault and trips the tie line in time for Case 3, the Derchan feeder will be tripped after 1.1 s and then the underfrequency relay for the tie line tripping of the industrial customer is operated. Fig. 10 shows the frequency response at bus 1 and Fig. 11 shows the mechanical input power of the cogeneration unit. Because the voltage drop is so serious that the motor loads will be deenergized due to 3 E relay operation. The load demand in the plant is reduced significantly and the cogeneration output power is decreased due to the governor action. However, the frequency still rises to 60.5 Hz to operate the overfrequency relay for the tie line tripping at 1.3 s. For the conditions of LF1, LF2, and LF3, the lowest frequencies reached are 51.5, 54.5, and 56 Hz and the time duration for the frequency to drop below 57.5 Hz are 3.3, 2.3, and 1.6 s, respectively. During the disturbance process, the cogeneration output is reduced to 0 MW and then increased gradually. For LF1, the cogenerator is tripped and system blackout is introduced. For LF2 and LF3, there also ex-
ists the potential of system collapse. To enhance the system stability, it is recommended that the tie line of the industrial system should be tripped for the nearby fault contingency by applying the directional overcurrent relay with a setting of T/L: 1/0.15.

VII. CONCLUSIONS

In this paper, the transient stability analysis has been performed for a large industrial customer with cogeneration unit. The protective relay settings for the tie line tripping and load shedding have been proposed. Since the capacity of the cogeneration output power is larger than the total load demand in the plant, the tie line with Taipower should be tripped in a fast manner to maintain the stable operation of the isolated industrial power system. Three study cases with different load levels are considered for the computer simulation. It is found that the tie line tripping and load shedding by underfrequency relays is proved to be very effective and reliable. When a nearby fault occurs, the system voltage will drop so significantly that the magnetic switches of the control circuits will be deenergized to trip the auxiliary loads of the cogeneration unit. It is suggested that time-delay devices should be considered for the critical loads in the plant. To improve the system voltage level during the system fault disturbance, the directional overcurrent relay should be implemented with a proper setting to enhance the tie line tripping capability. The overfrequency relay with setting at 60.5 Hz and underfrequency relay with setting at 58.8 Hz should also be applied to trip the tie line in a very fast manner for the external utility fault condition. The underfrequency relay with setting at 59.1 Hz in series with reverse-power relay will provide a good alternative to improve the industrial power system stability.

In an actual Taipower fault contingency on May 19, 1997, many industrial customers had encountered serious production loss and environmental pollution problems due to the abrupt power service interruption. With the proposed tie line tripping strategy and load-shedding scheme, the cogeneration unit of the study industrial system is operated successfully to serve the critical loads in the plant. It is concluded that the effectiveness of the cogeneration unit to provide the emergency backup power can be obtained by the proper design of the protective relays for the tie line tripping and load shedding.

REFERENCES


