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An Under-Frequency Load Shedding Scheme Design for a Large Steelworks with Self-Generation System

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Abstract – This paper presents a load-shedding scheme for a large steelworks with several self-generation units. The power system of the steelworks can be separated from a utility grid in case of disturbances. Also, some substations with generators in the steelworks can be isolated due to the tie line tripping. These situations cause an under-frequency events as the result of the imbalance between generation and load. A system stabilizing controller (SSC) system is the core of the proposed load shedding scheme for the frequency stabilization. The SSC system performs a pre-calculation for load-shedding (LS) quantity before an event and a post-calculation to provide against a deficient load-shedding in the pre-calculated load-shedding. The back-up protection system is used to counteract situations in which the SSC system does not operate normally. Also, the load-shedding by frequency calculation is carried out for subsequent disturbance such as an additional generator tripping. The hardware based proposed scheme has been applied to the steelworks. The several under-frequency events causing a load-shedding are examined through the transient stability analysis by using ETAP. The simulation results show that the proposed scheme effectively stabilizes the frequency within the continuous frequency operation range of generators.

Keywords: UFLS, SSC system, Transient stability, ETAP

1. Introduction

If the power system of a steelworks is separated from a utility substation due to external disturbances, it operates with only self-generation units. In such situation, if the load quantity of the steelworks exceeds the self-generation quantity, the system frequency will decrease, resulting in an under-frequency condition. There are abnormal frequency limits based on worst-case conditions of steam turbines [1].

Each generators have different operating frequency range of their steam turbines. In under-frequency situation deviated from the rated frequency, generators are tripped by the protection relays and schemes at different times. Under overload condition, sequential tripping of generators may result in a power system blackout. Therefore, the shedding of load that exceeds the generation quantity is required.

There have been some approaches on the load shedding scheme of a power system. In [2, 3], the intelligent under-frequency load-shedding (UFLS) scheme is presented for optimally shedding the load. The load-shedding scheme of [4, 5] is based on historical load data and the best time to shed the loads. In [6-8], these works are mainly focused on the load shedding scheme in case of system isolation.

In this paper, fault situations considered are the separation of the power system of a steelworks from utility and the substation separation in the steelworks due to the tie line tripping. After the first separation, the overload-shedding by frequency calculation is also carried out for subsequent disturbance such as an additional generator tripping and sudden increase of load. Under these situations, the load-shedding scheme for stabilizing the frequency operation is represented through transient stability analysis by using ETAP [9].

2. Study System Description

The power deficiency between the generation quantity of generation units in steel plant and plant-load demand is supplied from KEPCO's 345kV power grid. In this steelworks, there are eight substations of 154kV and one 22kV substation with several generators and loads. Each 154kV substation is connected to a double busbar of 22kV through two or three 154/22kV transformers.

The generation units are composed of ten oil-fired type generators, five coke dry quenching (CDQ) type generators, four blast furnace gas (BFG) type generators, two complex off-gas type generators using finex oven gas (FOG), coke oven gas (COG), BFG and three liquefied natural gas (LNG) type generators. The selection of a suitable simulation conditions is necessary to simulate the situations of under-frequency. The peak generation (PG) from 24

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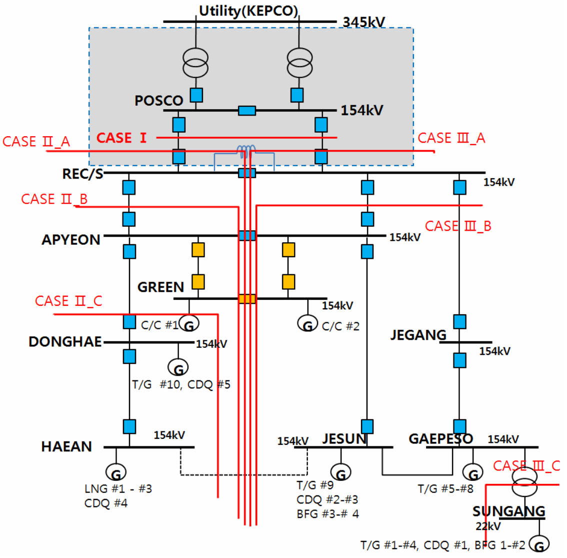

Fig. 1. The schematic diagram of the power system

generators is 1363MW, and average generation (AG) is 1036MW.

The minimum generations (MG) are MG_1 of 793MW (76.5% of peak generation) and MG_2 of 733MW (70.6% of peak generation). The basic load conditions are average load (AL) and peak load (PL). Some load conditions are arbitrarily adjusted to obtain various overload rate (OLR). In Fig. 1, there are several separation conditions such as Case I, Case II group (II_A~II_C) and Case III group (III_A~III_C). Case I represents the separation condition of the steelworks power system from utility. The others represent the tie line tripping condition among substations.

2.1 Generation units modeling with frequency range

In this paper, oil-fired type, complex off-gas type and LNG-type generators are represented by detailed models with transient and sub-transient circuits on both the direct and quadrate axes. On the other hand, BFG-type and CDQ-type generators are represented by classical model considering only swing equation.

The excitation systems of oil-fired type generators are represented by IEEE421.5-2005 AC5A and DC1 model [10]. On the other hand, the excitation systems of LNG-type and complex off-gas type generators are represented by IEEE421.5-2005 ST1 model [10]. These IEEE standard models are provided by ETAP library. The governor models of oil-fired type, complex off-gas type and LNG-type generators are not IEEE standard models. Therefore, the governor models are represented by users. It is also possible to represent undefined model in the library by using ETAP's user defined model (UDM).

In practical operation, the governor-free mode is chosen to provide against over-frequency state. Because the governors will automatically act to restore the system to rated frequency. The governor-lock mode is chosen to provide against under-frequency state with load-shedding. Because the shedding of load that exceeds the generation quantity is performed by pre-calculation, generators do not need to have power margins for frequency regulation.

Table 1. Generator frequency operation range

Generator	Continuous operation range (Hz)
T/G #1~8	58.2~61.8
T/G #9	58.5~60.5
T/G #10	58.1~61.7
LNG #1~#3	57.5~62.5
C/C #1~#2	58.0~61.8

The continuous frequency operation range of generator in abnormal state is different for each generator. Likewise, the trip frequency is also different. Therefore, it is important to identify the minimum frequency to trip generator. In the steelworks, the continuous frequency operation ranges of generators are different and shown in Table 1. Operation at frequencies other than this range is time-restricted. Complex off-gas type generators(C/C #1, #2) are tripped immediately at 57Hz. This frequency is minimum trip frequency. Therefore, if the system frequency does not decay below 57Hz, it is possible to protect generators under a grid disturbance.

2.2 Load modeling

The magnitude change of active and reactive power of loads depends on the deviation of frequency and voltage and is represented as following equations.

$$P = P_0[P_{poly} + P_{exp1} + P_{exp2}] \tag{1}$$

$$Q = Q_0[Q_{poly} + Q_{exp1} + Q_{exp2}] \tag{2}$$

where $P_{poly} = p_1V^2 + p_2V + p_3$

$$P_{exp1} = p_4V^{a_1}(1 + K_{pf1}\Delta f)$$

$$P_{exp2} = p_5V^{a_2}(1 + K_{pf2}\Delta f)$$

$$Q_{poly} = q_1V^2 + q_2V + q_3$$

$$Q_{exp1} = q_4V^{b_1}(1 + K_{qf1}\Delta f)$$

$$Q_{exp2} = q_5V^{b_2}(1 + K_{qf2}\Delta f)$$

The exponents a_1, a_2, b_1 and b_2 are a constant reflecting voltage influence. The exponents K_{pf1}, K_{pf2}, K_{qf1} and K_{qf2} are a constant reflecting frequency influence. The coefficients p_1~p_5 and q_1~q_5 define the proportion of load components such as constant current load, constant impedance load, constant power load, motor load and the component rate of load affected from voltage and frequency. Mill load is constant power load supplied through inverter. Influence coefficients suggested by [11] are applied to other loads. The applied coefficients are $p_1=p_2=p_3=q_1=q_2=q_3=0$, $a_1=b_1=0$, $p_4=q_4=0.8$, $p_5=q_5=0.2$, $a_2=0.6$, $b_2=2$, $K_{pf1}=K_{qf1}=0$, $K_{pf2}=1.5$ and $K_{qf2}=0.6$.

3. Proposed UFLS Scheme

There are two types of under-frequency relay (UFR) used to protect frequency of the steelworks in the abnormal states. One of these UFRs is provided against a utility outage. The other is used for a load-shedding due to an additional generator trip after the first separation fault.

3.1 UFR for separation mode from utility grid

The operational purpose of UFR for the isolation of steelworks grid from utility is to prevent the possibility of faults can be expanded to the loss of self-generators due to continuous under-frequency caused by a utility service outage. The UFR for separation from utility operates as follows. First step is alarms. Step 2, 3 and step 1-2 derivative action play a role for the isolation of the steelworks power system from utility grid after a certain time delay when the frequency setting point for each of the steps is reached.

3.2 SSC system

The basic feature of an SSC system is the prevention of grid blackout through the generator protection and the grid stabilization by a fast overload-shedding in the under-frequency state. The load-shedding command of SSC system is performed by using the result of pre-calculation, post-calculation and frequency calculation. When the power system of the steelworks is operating normally, the SSC system always compare the load and generation quantity in advance. The result is used to determine the target of load-shedding according to system disturbance event such as the steelworks grid separation from utility and a separation among substations in the steelworks. Also, the status of the system is periodically monitored and the pre-calculation of the quantity of load-shedding is repeatedly performed by the SSC system, but a trip signal does not occur. If the frequency less than or equal to the Step2 setting value of UFR is detected due to excess of load compared to generation quantity when a disturbance event upsets the power balance, the required load-shedding signal is generated. The loads to be shed are determined according to a fixed priority. The method of load shedding is the mill trip (MT) which initiates immediately shedding of fluctuating load and then the shedding of general loads.

The output of load-shedding pre-calculated by SSC system is performed only one time. The post-calculation and frequency calculation provide against a deficient load-shedding or an additional generator trip. The flow chart of SSC system is shown in Fig. 2.

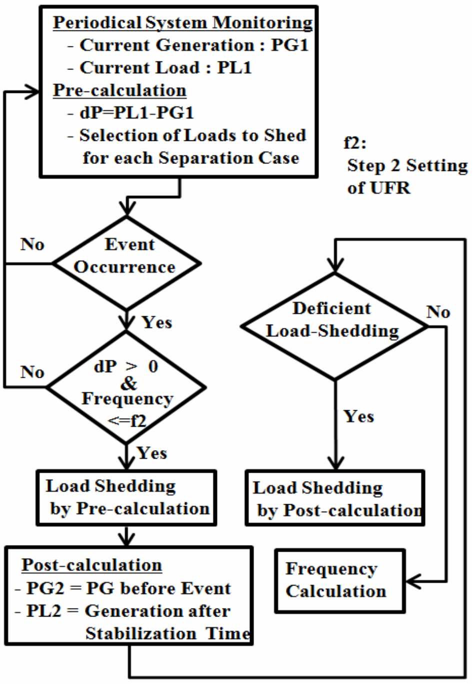

Fig. 2. Flow chart of SSC system

3.3 UFR for SSC system with frequency calculation

If the SSC system is normal, the frequency of the steelworks grid can be restored to normal state by the load-shedding of SSC system due to a first isolation fault. Because there is a possibility of deficient load-shedding in the operation of SSC system under the real operation condition, the immediate operation of frequency calculation circuit after pre-calculated load-shedding can cause an excessive load-shedding. Therefore, the load-shedding by frequency calculation is carried out for only subsequent disturbance after the restoration of normal frequency, which means the quantity of generation equals to that of load. The possible subsequent disturbance is an additional trip of generator or a sudden increase of load equivalent to generator's trip. Because the additional trip of generator incurs under-frequency situation, UFR should be set to counteract this situation.

3.4 SSC backup protection system

The SSC system may encounter situations in which it can't operate normally. So, an SSC back-up protection system is required to counteract those situations. If under-frequency signal due to excess of load compared to generation is detected under the situations in which the SSC system can't operate, the SSC back-up protection system exports the load-shedding command according to the predetermined shedding steps regardless of the current amount of loads. The pre-calculation of the SSC back-up system is impossible and the load-shedding is performed by the selected four steps frequency of 8-step UFR.

4. Case Study

The frequency protection scheme described in the previous sections has been tested on the separation cases of Fig. 1. In the determination of load-shedding amounts in Tables of this paper, the priority of load to shed and the rapid decline of frequency decay rate are mainly considered. And the load shedding quantity is obtained by a number of computer simulations with the mentioned considerations.

4.1 UFR setting for separation mode from utility (Case I)

The minimum trip frequency of generators in the steelworks is 57Hz. Therefore, if the system frequency does not decay below 57Hz, it is possible to protect generators under a grid disturbance. The cases to simulate under-frequency condition due to the outage of KEPCO are shown in Table 2. The assumed utility outage is the loss of 345kV bus in Fig. 1. The load conditions of AG-20, AG-30 and AG-140 are arbitrarily adjusted to obtain various rate of overload.

The UFR setting values of Table 3 is used to separate steelworks grid from KEPCO when KEPCO grid is under-frequency state. The values of Table 3 are determined on basis of the simulation results which is obtained by using Table 2. If the under-frequency event due to the KEPCO grid outage is occurred, steelworks grid is disconnected from KEPCO grid by UFR with setting values of Table 3. In sequence, the SSC system performs the load-shedding by pre-calculation. Then, it is possible to restore the frequency to normal after the separation of steelworks grid from utility by UFR.

The frequency response for steelworks-utility grid separation due to the loss of 345kV bus of Fig. 1 is shown in Fig. 3. It is possible to secure the margin of about 0.4Hz against the critical frequency of 57Hz by the UFR setting of Table 3.

Table 2. Simulation cases for separation mode

Grid condition	Generation (MW)	Load (MW)	OLR (%)	LS (MW)	MT (MW)
AGPL	1036	1533	48	497	385
AGAL	1036	1423	37.4	387	334
MG_1AL	793	1423	79.4	630	334
MG_2AL	733	1423	94.2	690	334
AG-20	1036	1243	20	207	155
AG-30	1036	1346	30	310	257
AG-140	1036	2486	140	497	385

Table 3. UFR setting for Case I

Step	Setting value (Hz)	Time delay (s)
1	59.0	Instantaneous
2	58.4	1.2
3	57.9	0.3
Step1-2 derivative	59.0 → 58.4	0.6

The UFR setting values for the SSC system frequency calculation of Case I are shown in Table 4. The load-shedding quantity in Table 4 is determined on the base of the additional generation loss of 275.6MW under the operating condition of MG_2AL causing the maximum rate of frequency decline.

Because generator T/G #10 is disconnected from grid and start to house load operation at 58Hz with time delay (15s), the last step of UFR is determined into 58.1Hz. In the real operation of the steelworks grid, the sudden loss of 275.6MW generation is not common outage. Therefore, the system frequency can be stabilized by the UFR setting of Table 4. If the additional trip of generators is occurred in

Table 4. UFR setting for frequency calculation of Case I

Step	Setting value (Hz)	LS(MW)	Accumulation(MW)
2	59.3	25	25
3	59.1	30	55
4	58.9	38	93
5	58.7	39	132
6	58.5	40	172
7	58.3	43	215
8	58.1	60	275

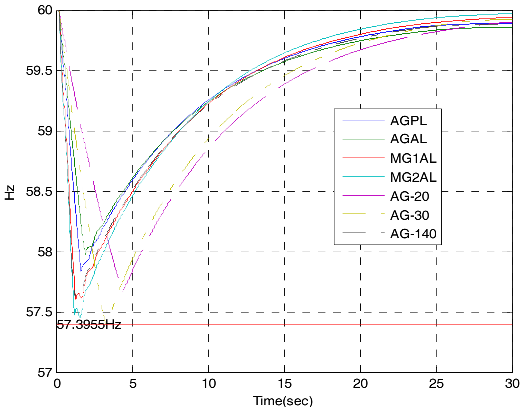

Fig. 3. The frequency response for steelworks-utility grid separation due to the loss of 345kV bus

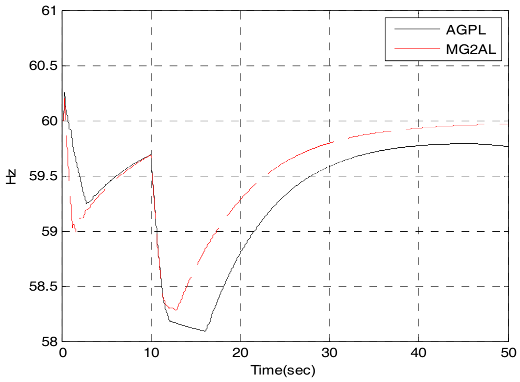

Fig. 4. The frequency response for frequency calculation after steelworks-utility grid separation

Table 5. UFR setting for SSC back-up protection system

Step	Setting value (Hz)	LS(MW)
2	59.3	55
4	58.9	65
6	58.5	100
8	58.1	136

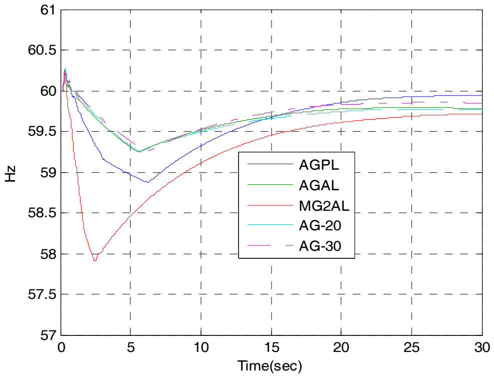

Fig. 5. The frequency response for steelworks-utility separation due to a tie line fault

the situation of frequency restoration (more than 59.3Hz) after a first separation, the load-shedding is performed by UFR of Table 4. The frequency response is shown in Fig. 4. Even if the load-shedding is performed up to step 8 of Table 4, the frequency does not decay below 58Hz.

The UFR setting values for the SSC back-up protection system of Case I are shown in Table 5.

The load-shedding quantity in Table 5 is determined on the base of the operating condition of MG_2AL. The frequency response by the SSC back-up protection for steelworks-utility separation due to a tie line fault is shown in Fig. 5. There is a sufficient margin against the critical frequency of 57Hz.

4.2 UFR setting for a tie-line separation (Case II)

There are three subcases such as Case II_A, Case II_B and Case II_C in the Case II. When a fault on a tie-line among substations of steelworks occurs, the fault is cleared by opening the circuit breakers at the ends of the tie-line. At this time, the under-frequency load-shedding of an isolated substation is performed by the SSC system pre-calculation. The UFR setting values for the SSC system frequency calculation and the SSC back-up protection system are determined under the operating condition of MG_2AL causing the maximum rate of frequency decline for each sub-case. The simulation conditions for each subcase are shown in Table 6.

The additional generation losses for each sub-case are 143.5MW, 143.5MW and 18MW. The UFR setting values on the base of these values for the SSC system frequency calculation are shown in Table 7.

The 4-step load-shedding frequency of Table 7 is selected from 8-step UFR of Table 4. The simulation result for the individual separation of Case II due to a tie-line fault is shown in Fig. 6. The frequency response is quickly stabilized with the normal load-shedding by the SSC system.

Table 6. Simulation conditions for MG_2AL and Case II

Subcase	Generation (MW)	Load (MW)	OLR (%)	LS (MW)	MT (MW)
Case II_A	274	534.8	95.2	260.8	140.3
Case II_B	274	437.4	59.6	163.4	100.8
Case II_C	131.5	212.8	61.8	81.3	39.5

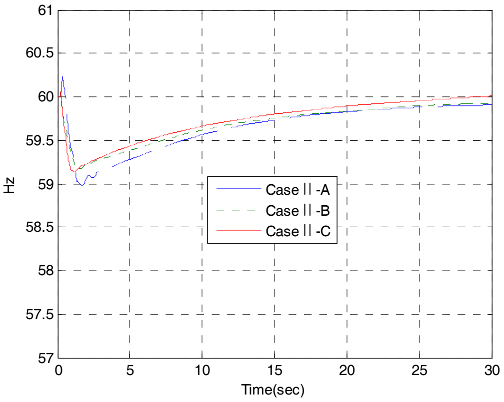

Fig. 6. The frequency response for Case II due to fault

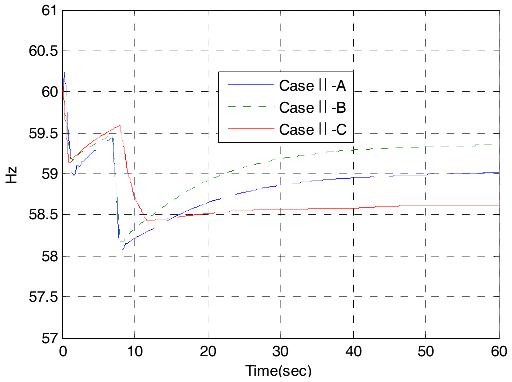

Fig. 7. The frequency response for frequency calculation of Case II

If the additional loss of generators is occurred in the situation of frequency restoration after a first separation due to a tie-line fault, the load-shedding is performed by UFR of Table 7. In the frequency response shown in Fig. 7, the frequency is not decayed to the critical frequency of 57Hz. The final frequencies are stabilized within the continuous frequency operation range of generators. In Case II, the considered additional trip quantity is not common outage in a real operation. Therefore, the system frequency can be stabilized by the UFR setting of Table 7.

The UFR setting values for the SSC back-up protection system are shown in Table 8.

The frequency response by the SSC back-up protection

Table 7. UFR setting of frequency calculations for Case II

Step	Setting value (Hz)	LS(MW)			Accumulation(MW)		
		II_A	II_B	II_C	II_A	II_B	II_C
2	59.3	35	35	4	35	35	4
4	58.9	35	35	4	70	70	8
6	58.5	37	37	5	107	107	13
8	58.1	34	34	5	141	141	18

Table 8. UFR setting for SSC back-up protection system for CASEII

Step	Setting value (Hz)	LS(MW)			Accumulation(MW)		
		II_A	II_B	II_C	II_A	II_B	II_C
2	59.3	30	15	9	30	15	9
4	58.9	30	15	9	60	30	18
6	58.5	30	15	11	90	45	29
8	58.1	30	17	12	120	62	41

Table 9. Simulation conditions for MG_2AL and Case III

Subcase	Generation (MW)	Load (MW)	OLR (%)	LS (MW)	MT (MW)
Case III_A	458.9	888.2	93.5	429.3	193.6
Case III_B	458.9	720.1	56.9	261.2	133.2
Case III_C	82.4	116.3	41.1	33.9	15.1

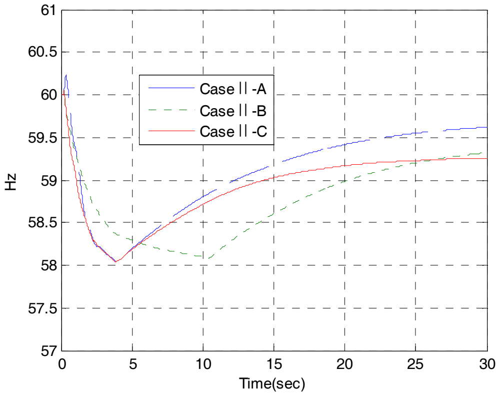

Fig. 8. The frequency response for SSC back-up protection system of Case II

for CASE II due to a tie line fault is shown in Fig. 8. The final frequencies are stabilized within the continuous frequency operation range of generators.

4.3 UFR setting for a tie-line separation (Case III)

There are three sub-cases such as Case III_A, Case III_B and Case III_C in the Case III. The UFR setting values for the SSC system frequency calculation and the SSC back-up protection system are determined under the operating condition of MG_2AL causing the maximum rate of frequency decline for each sub-case. The simulation conditions for each sub-case are shown in Table 9.

The additional generation losses for each sub-case are 132.1MW, 132.1MW and 30.1MW. The UFR setting values on the base of these values for the SSC system frequency calculation are shown in Table 10.

In the individual separation of Case III due to a tie-line fault, the under-frequency load-shedding of an isolated

Table 10. UFR setting of frequency calculation for Case III

Step	Setting value (Hz)	LS(MW)			Accumulation(MW)		
		III_A	III_B	III_C	III_A	III_B	III_C
2	59.3	30	30	6	30	30	6
4	58.9	30	30	8	60	60	14
6	58.5	34	34	8	94	94	22
8	58.1	36	36	7	130	130	29

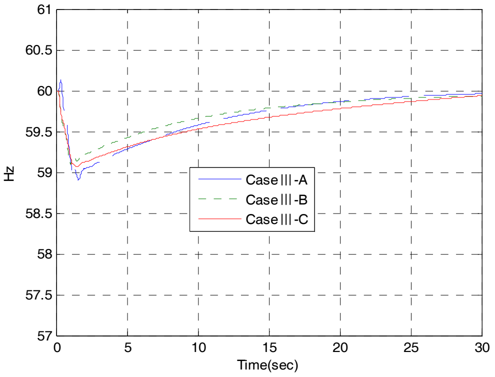

Fig. 9. The frequency response for Case III due to fault

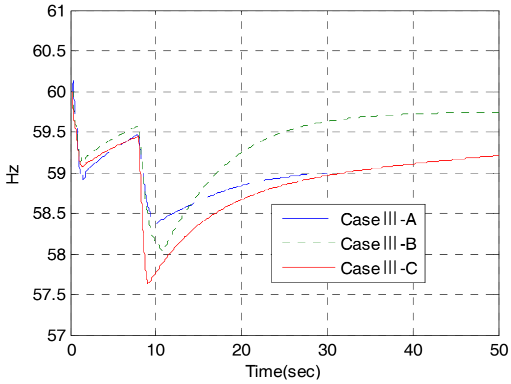

Fig. 10. The frequency response for frequency calculation of Case III

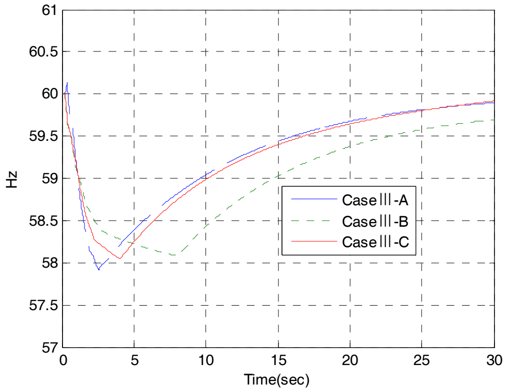

Fig. 11. The frequency response for SSC back-up protection system of Case III

Table 11. UFR setting for SSC back-up protection system for Case III

Step	Setting value (Hz)	LS(MW)			Accumulation(MW)		
		III_A	III_B	III_C	III_A	III_B	III_C
2	59.3	50	30	4	50	30	4
4	58.9	55	30	4	105	60	8
6	58.5	60	32	5	165	92	13
8	58.1	70	34	5	235	126	18

Table 12. Stabilization time for steelworks-utility separation

	Separation by UFR	Separation due to fault
Stabilization Time (s)	9.6	2.8

Table 13. Stabilization time for steelworks-utility separation

	II_A	II_B	II_C	III_A	III_B	III_C
Stabilization Time (s)	4.3	2.3	2.3	4.4	2.4	3.5

substation is performed by the SSC system pre-calculation. The simulation result is shown in Fig. 9. The frequency response is quickly stabilized with the normal load-shedding by the SSC system.

If the additional loss of generators is occurred in the situation of frequency restoration after a first separation due to a tie-line fault, the load-shedding is performed by UFR of Table 10. The frequency response for Case III is shown in Fig. 10. The final frequencies are stabilized within the continuous frequency operation range of generators

The UFR setting values for the SSC back-up protection system are shown in Table 11.

The frequency response by the SSC back-up protection for Case III separation due to a tie line fault is shown in Fig. 11. The final frequencies are stabilized within the continuous frequency operation range of generators.

4.4 Stabilization time for the frequency calculation

The stabilization time to initiate the frequency calculation (load limitation calculation) is decided as the reaching time to 59.3 Hz of frequency with addition 0.2s. In the tables below, the stabilization time is selected for the cases of load-shedding by the normal operation of the SSC system (100% shedding of pre-calculated loads). The results of tables are values based on the maximum value among the stabilization times required for each separation conditions.

However, there is a possibility of deficient load-shedding in the operation of the SSC system under the real operation condition of steelworks. When the quantity of the deficient load-shedding is small, the stabilization time should be increased than compared to the results of Table 12 and 13. On the contrary to this, when the quantity of the deficient load-shedding is large, the stabilization time should be decreased than compared to the results of Table 12 and 13 or almost close to 0s. In this situation, the load-shedding by the SSC frequency calculation result in an excessive load-shedding. Therefore, the load-shedding by the frequency calculation should be carried out for only subsequent disturbance after the restoration of normal frequency.

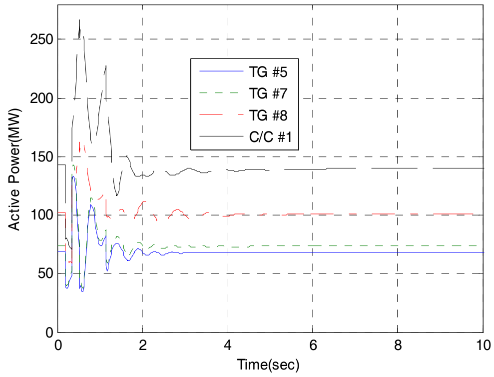

Fig. 12. The active power swing of Case I (MG_2AL)

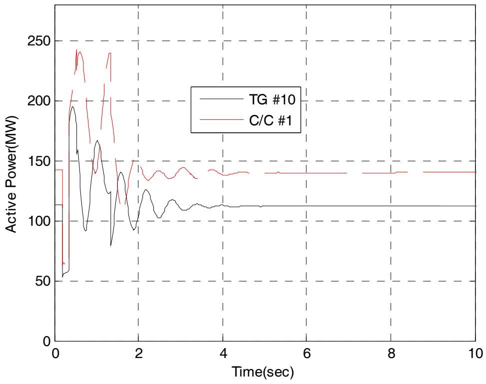

Fig. 13. The active power swing of Case II_A (MG_2AL)

4.5 Stabilization time for post-calculation

A post-calculation is necessary because there is a possibility of deficient load-shedding in carrying out load-shedding by the SSC system. The post-calculation should be carried out after the stabilization of active power swing. That is, the stabilization time for the post-calculation of the SSC system is decided based on the time in which active power swing is stabilized after the first shedding of pre-calculated loads by the SSC system. In the post-calculation of the SSC system, the generation quantity takes the data of pre-fault. In post-calculation, it is impossible to determine the load quantity to shed in advance. But, the load can be found equal to the power output of generator at the time the power swing of generator is stabilized after pre-calculated load-shedding. The active power swing of generators in MG_2AL grid condition of Case I is shown in Fig. 12.

The active power swing of generators in MG_2AL grid condition Case II_A is shown in Fig. 13. In Fig. 12 and 13, the active power is almost stabilized within 2.5s after the starting of a fault. In all other simulation cases, the stabilization time is within 2.5s. Therefore, if the deficient load-shedding occurs, the system frequency can be recovered through the load-shedding by the post-calculation of the SSC system after the stabilization time of 2.5s.

5. Conclusion

In this paper, the frequency operation plan for the power system of a large integrated steelworks with self-generation facilities has been represented in detail with the SSC system and the SSC back-up protection system. The developed load-shedding scheme for the under-frequency situations has been applied to the steelworks power system to verify the effectiveness. In the simulation for the steelworks power system, the transient stability analysis has been performed by the software package ETAP. In the simulation results, if the SSC system and the SSC back-up protection system is operated normally when the under-frequency conditions are occurred due to a several disturbance, the frequency of steelworks grid can be stably kept within the continuous frequency operation range of generators. With the proposed triple protection schemes, it is sufficiently possible to operate even minimal mill plant under the system isolation state. It is concluded that the proposed load-shedding scheme installed as hardware can effectively provide against the under-frequency conditions.

References

[1] IEEE Power Engineering Society, "IEEE Guide for Abnormal Frequency Protection for Power Generating," IEEE Std. C37.106-2003.

[2] P. Wang and R. Billinton, "Optimum Load-shedding Technique to Reduce the Total Customer Interruption Cost in a Distribution System," Generation, Transmission and Distribution, IEE Proceedings, vol. 147, pp. 51-56, 2000.

[3] D. Hazarika and A. K. Sinha, "Method for Optimal Load Shedding in Case of Generation Deficiency in a Power System," International Journal of Electrical Power & Energy System, vol. 20, issue 6, pp. 411-420, Aug. 1998.

[4] P. Mahat, C. Zhe and B. Bak-Jensen, "Underfrequency Load Shedding for an Islanded Distribution System With Distributed Generators," IEEE Trans. Power Delivery, vol. 10, no. 25, pp. 911-918, 2010.

[5] E. E. Aponte and J. K. Nelson, "Time Optimal Load Shedding for Distributed Power Systems," IEEE Trans. Power System, vol. 21, no.1, pp. 269-277, 2006.

[6] P. M. Anderson and M. Mirheydar, "An Adaptive Method for Setting Underfrequency Load Shedding Relays," IEEE Trans. Power Systems, vol. 7, no. 2, pp. 647-655, May. 1992.

[7] C. Concordia, L.H. Fink and G. Poullikkas, "Load Shedding on An Isolated System," IEEE Trans. Power Systems, vol. 10, no. 3, pp. 1467-1472, Aug. 1995.

[8] P. Mahat, C. Zhe and B. Bak-Jensen, "Under-frequency Load Shedding for an Islanded Distribution System with Distributed Generators," IEEE Trans. Power Delivery, vol. 10, no. 25, pp. 911-918, 2010.

[9] ETAP, Operation Technology Inc. http://etap.com/

[10] IEEE Power Engineering Society, "IEEE Recommended Practice for Excitation Models for Power System Stability Studies," IEEE Std. 421.5-2005.

[11] IEEE Task Force on Load Representation for Dynamic Performance, "Load Representation for Dynamic Performance Analysis," IEEE Trans. Power Systems, vol. 8, no. 2, pp. 472-482, May. 1993.

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