

# Preliminary study of new load shedding method considering LFC control

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**Abstract.** The introduction of a large amount of photovoltaic power generation reduces the load on the entire system when the low frequency load is interrupted, but the photovoltaic power generation connected to the relevant line is also separated, so that it becomes an independent operation in the partial system, and the supply power is also reduced. There is a possibility of reduction. In conventional UFLS, after observing the frequency, the load is cut off in units of several seconds. The load shedding amount is determined by the load ratio of the entire system at that time. In this study, the UFLS model will be added to the existing IEEJ AGC30. The demand and solar power output in the target area are divided into substations to create data, and the solar power output of each substation is taken into account to grasp a more accurate load. The validity of this model is verified by simulating frequency fluctuation and LFC operation.

## 1 Introduction

In recent years, due to the growing global awareness of the realization of a sustainable society and the global warming issues, a large amount of renewable energy power sources such as PV (photovoltaic) power generation system are being introduced in Japan. Since PV changes the power generation output according to the amount of solar radiation, the power demand (net demand), which is the difference between the actual power demand and the PV output, changes greatly every moment. Therefore, it is expected that the future operation and control of the power system will need to be based on grasping the supply and demand status every moment, in addition to the careful planning as before.

In this study, UFLS (Under Frequency Load Shedding) is taken up as an electric power system control technology that can increase the effect more than ever by grasping the state of supply and demand. This is one of the functions realized by the frequency abnormality prevention relay system. When supply shortages occur due to power supply line accidents due to generator dropout or system disconnection due to electric cables disconnection, the frequency drops. For that reason, it is essential to maintain the frequency by optimally performing load shedding [1]. In order to determine the optimum load shedding amount, it is necessary to appropriately grasp the current power demand. However, the net demand seen from substations may be difficult to determine the appropriate load shedding due to the spread of distributed power sources. In the conventional UFLS, after observing the frequency, several time periods are set and the load is shed in turn. The load shedding amount is determined by the ratio of the power demand of the entire system at that time.

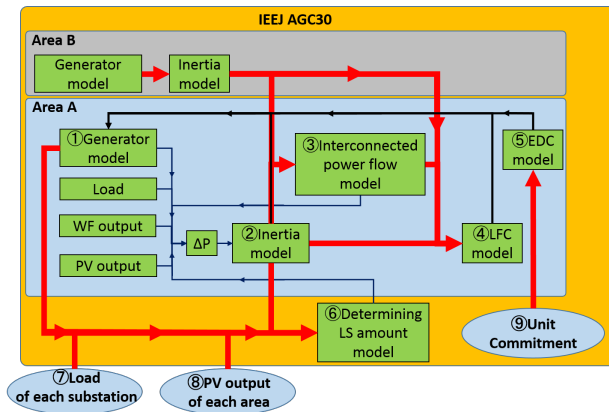
In this study, we propose a new UFLS method based on the grasping of net demand considering PV output. With the proposed method, it can be expected that frequency recovery is performed more quickly than when PV output is not considered. However, UFLS is not the only way to deal with frequency drops. Output increase due to generator GF (Governor Free) operation and LFC (Load Frequency Control) operation also contributes to frequency recovery. Both are the main measures against the changing supply and demand situation every moment. Therefore, it is necessary to consider UFLS, GF, and LFC simultaneously in order to numerically verify the frequency recovery strategy. For this reason, this study verifies the validity of the proposed method by numerical experiments using the IEEJ AGC30 [2], which is a standard analysis model for load frequency control simulation. Since the IEEJ AGC30 is provided as an editable program, the UFLS model is designed and added in this study. The input data has been created by considering the power demand and PV output in the target area by subdividing each substation. We simulated the actual power system and examined its validity through simulations to see and consider what difference occurs in frequency fluctuations and LFC operation value fluctuations.

## 2 Conventional UFLS

### 2.1. Mechanism of UFLS

The frequency is maintained by always balancing load and power generation. If a large power supply stops suddenly, the balance is lost and the frequency drops. When the frequency exceeds a certain level, the

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**Fig. 1.** Connection between UFLS and the IEEJ AGC30.

generator automatically disconnects from the grid to protect its own equipment. As a result, the frequency decreases in a chained fashion, and eventually all generators stop and blackout occurs. In order to avoid blackout, it is necessary to increase the power generation at high speed or to shed the load before the generator relay operates. Methods for increasing the power generation include increasing the output by the governor-free function of the parallel power supply, increasing the output by LFC, and supporting by interconnected power flow from adjacent areas. However, since it takes time to start the power supply when it is stopped, it is not subject to emergency control. UFLS, which is a mechanism for shed the load, is installed for each substation feeder. UFLS is an urgent measure to recover the frequency by load shedding until the frequency can be controlled by the supply power in response to the rare frequency accident that the frequency drops significantly due to large-scale power loss. In order to prevent chained power trips due to frequency drop, set several time periods, and if each frequency does not recover to the frequency settling value, the load will be shed sequentially, and when the frequency settling value is recovered, UFLS is released.

## 2.2 Previous research

According to UFLS surveys conducted by various power companies in Asia, Europe, Australia, South Africa, the Middle East, and the United States conducted by Lu et. al. [3], the total load limits, number of UFLS blocks, average block size, and trip frequency deviation threshold are different. For example, Mollah et. al. [4] has proposed an automatic UFLS using measured values by PMU (Phasor Measurement Unit). However, conventional UFLS research does not explicitly deal with the massive introduction of renewable energy power generation.

Tang et. al. [5] proposes to determine the load shedding amount of UFLS according to changes in the inertia constant of wind power generation, assuming large-scale introduction of wind power generation. Steven et. al. [6] has shown that there are already feeders that generate more electricity than the load due to the increase in PV in residential areas in recent years. It is raised the problem that if the feeder is shed, it can

make things worse. The study proposes a new method for determining the order of load shedding to take into account distributed generation in the UFLS system.

Thus, a method for explicitly determining the load shedding amount based on the net demand, which is the difference between the actual power demand and the distributed PV output, has not been fully studied.

In this study, we focused on the order of load shedding, considered distributed generation, evaluated the frequency finish with / without UFLS, and compared the possibility of cooperative operation with LFC.

## 3 Proposed UFLS Model

### 3.1. UFLS model and the IEEJ AGC30

Fig. 1 shows the relationship between the determining load shedding amount model and the IEEJ AGC30 in this study.

①Generator model : In general, in the IEEJ AGC30, the frequency deviation is calculated from the difference between the turbine output of the synchronous generator and the total electric output obtained by subtracting the electric output other than the synchronous generator from the total load. This generator model corresponds to a portion for calculating turbine output. In this study, in order to enable simulation in any area in Japan, the number of generator control blocks was increased to 50 for coal, 50 for oil, 50 for LNG, and 80 for GTCC, 50 for constant speed pump and 50 for variable speed pump.

②Inertia model : When an imbalance occurs in the balance between power generation and load in the power system, the grid frequency fluctuates, but it does not change discontinuously, but continuously fluctuates several seconds later than the supply-demand imbalance. This is due to the inertia of the generator and the frequency characteristics of the load, which can be expressed by a first-order lag system. This corresponds to the part where the supply-demand imbalance  $\Delta P$  is obtained from the total output, WF output, PV output, and load of the generator model, and the frequency deviation  $\Delta f$  is calculated through the model.

③Interconnected power flow model : In this study, based on the results of previous studies [7], [8], [9], a model using the synchronizing power coefficient is adopted as the standard model. This corresponds to the part for calculating the interconnected power flow  $\Delta P_T$  from the frequency deviation calculated from the inertia model of the own area and the other area.

④LFC model : Since it is difficult to predict short cycle fluctuations among load fluctuations, the generator is operated as quickly as possible by automatic control. Conversely, for mid-cycle load fluctuations of several minutes to 20 minutes, the fluctuation amount is calculated at the central load dispatching station, and control is performed by the LFC that operations the generator to follow the fluctuation amount. In order to maintain the frequency of the power system and the power flow of the interconnection line at specified

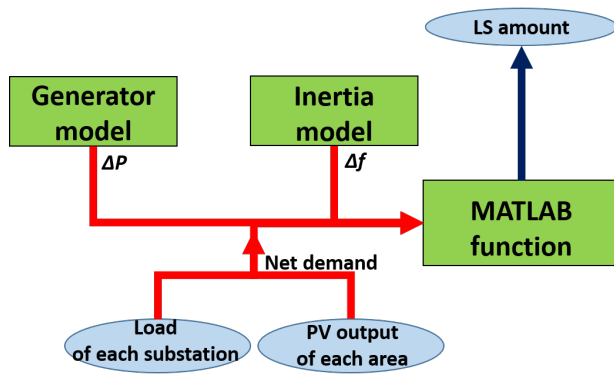


Fig. 2. Determining LS amount model.

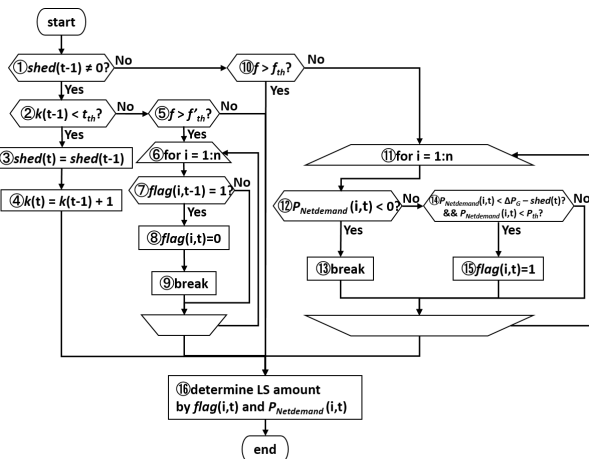


Fig. 3. The flowchart of MATLAB function in determining LS amount model.

values, it corresponds to the part that detects the frequency fluctuation and the amount of change in the interconnected power flow and controls the output of the generator.

⑤ EDC model : Load fluctuations which has long-cycle 20 minutes or more can be predicted in advance because of the large variation. For this predicted value, the generator output of each generator is determined by EDC in consideration of economy. By automatically adjusting the generator output, the balance between supply-demand can be maintained following demand fluctuations while considering economic efficiency. The amount of adjustment for each generator that is most economical while satisfying constraints such as securing LFC capacity and generator operation output band under the operation / stop status of the generator determined by UC (Unit Commitment) corresponds to the part that decides.

⑥ Determining LS (Load Shedding) amount model : In this model, the generator output abnormality is detected from ①, and the abnormality of frequency deviation is detected from ②. This model corresponds to the part that immediately detects the abnormal generator output fluctuation and shuts off the same amount of load when the abnormal frequency is detected by inserting the data of ⑦ and ⑧ in advance.

⑦ Load of each substation : This corresponds to data indicating how much load drops when a substation is shut down.

⑧ PV output of each area : This corresponds to data indicating how much supply is lost when a substation is shut down.

⑨ UC : This corresponds to the part that determines the start and stop of the generator by solving the supply cost minimization problem and the supply-demand balance constraint. It takes into account the output upper and lower limit constraints, output change speed constraints, minimum operation / stop time constraints, system-wide reserve / adjustment constraints, pumped storage power storage capacity and output upper and lower limit constraints.

### 3.2. Determining LS amount model

Fig.2 is a model for determining load shedding. This section describes the input to the MATLAB function.

$\Delta f$  : Frequency deviation

$\Delta P$  : Difference in generator output before and after one step

$P_{Netdemand}$  : Net demand of each area

Fig. 3 is a chart showing the response in the MATLAB function in the load shedding decision model. Each variable in the figure is defined as follows.

$t$  : Simulation time (A (t-1) : value of function A one step before)

$shed$  : LS amount

$t_{th}$  : Time interval between the occurrence of LS and the next action

$k$  : Elapsed time after LS

$f$  : Frequency deviation

$n$  : Number of substations

$flag$  : Connect / Shed flag

$\Delta P_G$  : Generator output deviation

$f'_{th}$  : Frequency threshold for reclosing

$f_{th}$  : Frequency threshold for shedding

$P_{th}$  : LS threshold

The detailed response is as follows.

① It is determined whether the load is interrupted at the previous time.

② It is determined whether  $t_{th}$  has elapsed from the previous load interruption at the previous time.

③ If  $t_{th}$  [s] has not elapsed in ②, determine with the same amount of shutoff as the previous time.

④ Increases the elapsed time after blocking by 1 [s].

⑤ If  $t_{th}$  has elapsed in ②, determine if the frequency is greater than  $f'_{th}$ .

⑥ If the frequency is greater than the threshold in ⑤, repeat the loops from ⑦ to ⑨ for the number of substations.

⑦ It is determined whether the shed flag is set at the previous time.

⑧ If the shed flag is set in ⑦, connect it.

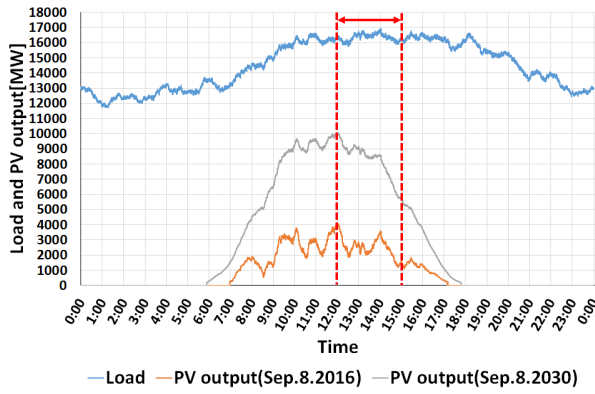


Fig. 4. Load and PV output data.

⑨ If the shed flag is set in ⑦, after performing ⑧, the loop in ⑥ is forcibly terminated.

⑩ If the load is interrupted at the previous time in ①, determine whether the frequency is greater than  $f_{th}$ .

⑪ Repeat from ⑫ to ⑮ loop for the number of substations.

⑫ Determine if net demand is negative.

⑬ If the net demand is negative at ⑫, the ⑪ loop is forcibly terminated.

⑭ If the net demand is positive in ⑫, it is determined "whether the net demand is smaller than the difference between  $\Delta P_G$  and the temporarily determined LS amount" and "whether the net demand is smaller than the LS amount threshold."

⑮ If "the net demand is smaller than the difference between  $\Delta P_G$  and the temporarily determined LS amount" and "the net demand is smaller than LS amount threshold  $P_{th}$ " in ⑭, the shed flag is set.

⑯ Determine the LS amount from  $flag$  and  $Net_{demand}$ .

## 4 Case Study

### 4.1. Conditions

The simulation targeted the Kyushu Electric Power Inc area. The target years were 2016 and 2030, and the time section was 3 hours from 12:00 to 15:00. Load, PV output, and WF output data were supplemented by spectral extrapolation method [2] based on each actual value (each 1 hour value), and each 1 second value was created and used. We selected September 8 (load peak value: 16607MW), which is a sunny day on summer days when load is relatively high. Table 1 shows the generator settings in the Kyushu Electric Power Inc. area. Fig. 4 shows the load data on September 8, 2016 and the PV output on September 8, 2016 and September 8, 2030.

Since detailed data for each substation cannot be observed, load data for each municipality was estimated by the following method.

$$p_i = p a_i / a \quad (1)$$

where  $i$  is the municipality number,  $p$  is the demand for the entire area,  $p_i$  is the load for each municipality,  $a$  is the area population, and  $a_i$  is the population of each municipality. Using the load data created by equation (1), the load data each 1 second value for each municipality was created. Similarly, PV output data for each municipality was created using PV output data.

$$P_{netdemand} = P_{demand} - P_{PV} \quad (2)$$

where  $P_{demand}$  is demand,  $P_{PV}$  is PV output, and  $P_{netdemand}$  is net demand. The net demand data  $P_{netdemand}$  obtained by equation (2) was sorted in descending order and used as the input for the determining LS amount model.

As a simulation verification method, two generators are stepped out at 13:00, and the difference in frequency fluctuation at that time is compared with the difference in the finish of LFC and EDC depending on the presence or absence of UFLS. Similarly, we conducted a simulation to compare the difference in the finish depending on the PV introduction rate. If the time interval  $t_{th}$  from the time when the LS occurs until the next operation occurs is too short, the load is returned without waiting for the recovery of the frequency fluctuation, and the frequency deteriorates. Therefore, the time interval until the next operation was set to  $t_{th} = 450$  [s]. As described above, the LS amount threshold  $P_{th}$  is set in this simulation. The LS that hinders the activities of important cities will cause a large loss, so that a load larger than this  $P_{th}$  is excluded from the LS candidates. In this study,  $P_{th} = 300$  [MW].

Table 1. Generation setting of Kyushu Electric Power Company Inc.

Fuel type	Inertia [s]	Total output [MW]	Number of units	LFC
Oil	8.0	2655	7	-
Coal	8.0	4737	12	On
GTCC	11.0	4404	18	On
Constant speed pump	10.0	1100	4	-
Variable speed pump	0	1200	4	-
Hydropower	8.0	1593	2	-
Nuclear	8.0	4140	4	-

### 4.2. Results

Fig. 5 shows the load shedding in 2016 and 2030, respectively. Immediately after detecting a step-out for two generators at 13:00, the same amount of LS occurred. It can be seen that the LS amount is reduced in 2030 than in 2016. After that, the LS amount decreases stepwise, and the load is gradually recovering.

Figs. 6-9 show the simulation results of September 8, 2016.

Fig. 6 shows the frequency variation. At 13:00, when the UFLS is not installed, the frequency drops by -0.9Hz, but when the UFLS is installed, the frequency is

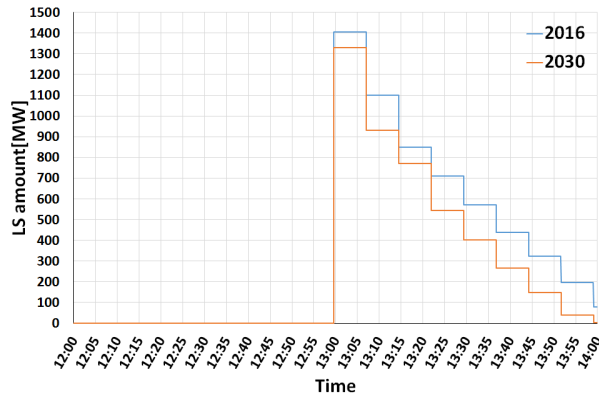


Fig. 5. LS amount.

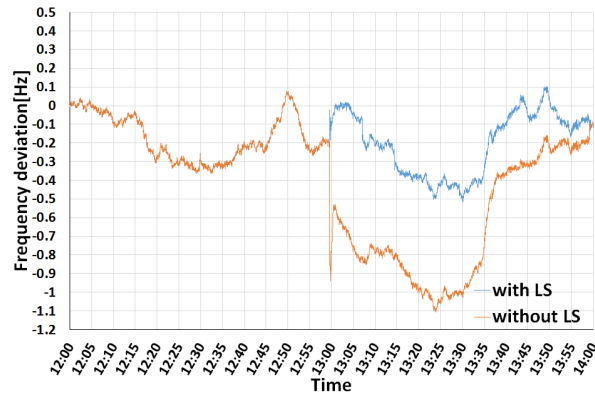


Fig. 6. Frequency deviation with/without UFLS (Sep.8.2016).

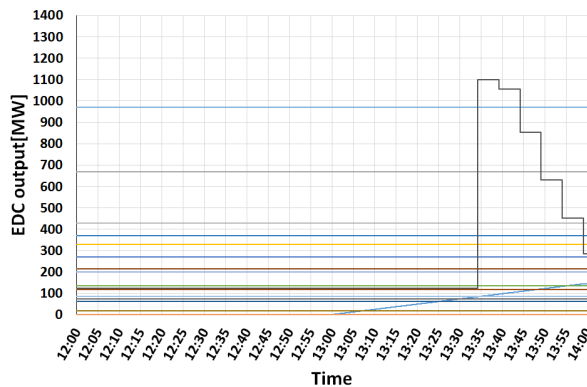


Fig. 7. EDC output (Sep.8.2016).

suppressed to the lowest point -0.4Hz at the time of the accident. The frequency recovery after the accident is faster when UFLS is implemented. Fig. 7 shows the EDC output operation value. The EDC output operation value was constant regardless of with/without UFLS. This is because EDC is used for applications that respond to long-cycle fluctuations based on the start and stop of generators optimized in advance by UC. Figs. 8 and 9 are LFC output operation values with / without UFLS, respectively. The output operation to the GTCC generator gradually increases from 12:00 when UFLS is present, and a operation value of 650 MW is issued at 14:00, whereas when UFLS is not present, 13:00 Subsequent operation values suddenly rise. This is because in the case without UFLS, the output of the activated generator is raised to cope with the shortage of

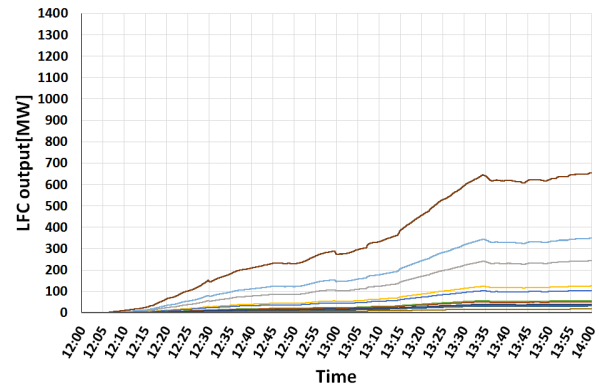


Fig. 8. LFC output with UFLS (Sep.8.2016).

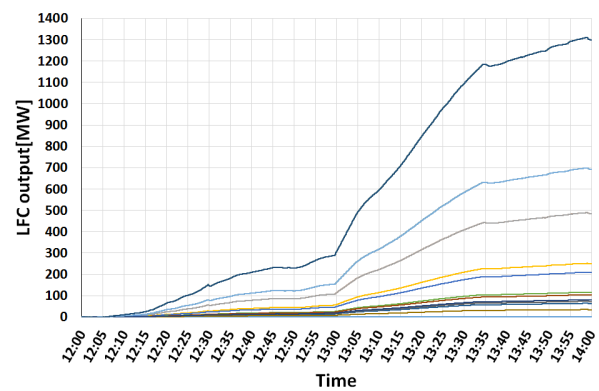


Fig. 9. LFC output without UFLS (Sep.8.2016).

supply power, but it is not necessary to issue a sudden LFC output operation by UFLS measures.

Figs. 10-13 are the simulation results of September 8, 2030. As in 2016, the frequency fluctuation is better when UFLS is installed. However, more PV was introduced than in 2016, and the fluctuation after 13:30 has increased (Fig. 10). The EDC output operation value, as in 2030, was also constant with / without UFLS (Fig. 11). In the case of UFLS, the LFC output operation value is raised immediately after the accident and the operation is lowered from 13:30 when the frequency is restored (Fig. 12). On the other hand, when UFLS is not used, the operation to the coal generator is slightly larger than when UFLS is used, and the GTCC operation value is also increased after 13:30 (Fig. 13). Without UFLS, It is difficult to recover the frequency without increasing the output operation of many generators. But, the number of generators that issue LFC output operations can be reduced by implementing UFLS.

## 5 Conclusion

In this study, we proposed a new LS method that can be applied to actual systems where PV mass introduction is progressing. The proposed method incorporates a new LS model that simulates load and PV output of each area.

In the case study, it was assumed that the generator was disconnected due to an accident, and the proposed model was evaluated from the viewpoint of subsequent LS response, frequency fluctuation, and LFC operation value fluctuation. As a result, it was found that the

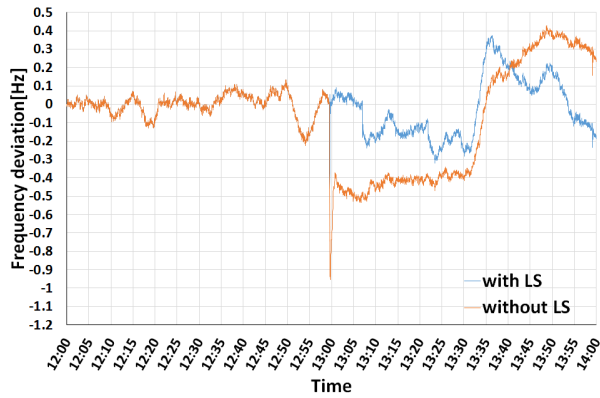


Fig. 10. Frequency deviation with/without UFLS (Sep.8.2030).

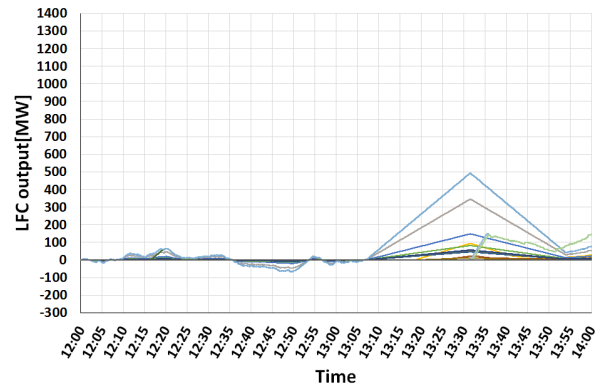


Fig. 12. LFC output with UFLS (Sep.8.2030).

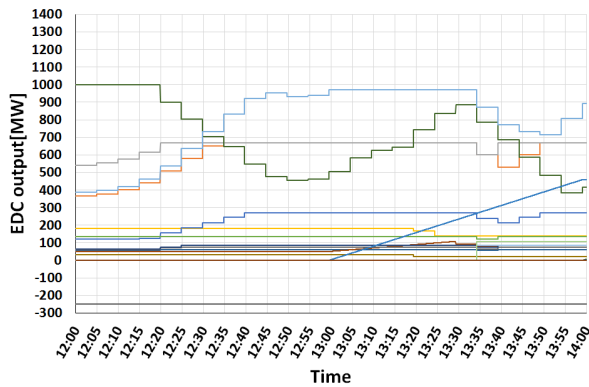


Fig. 11. EDC output (Sep.8.2030).

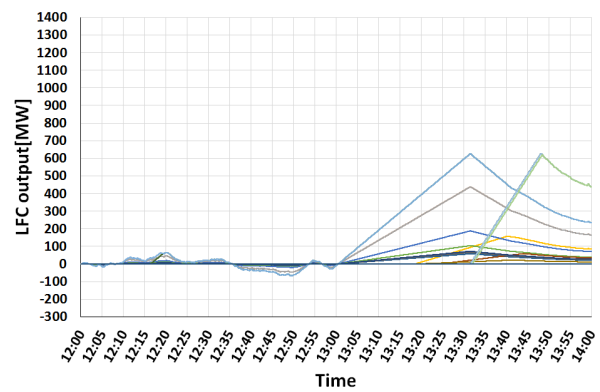


Fig. 13. LFC output without UFLS (Sep.8.2030).

proposed model can be operated in cooperation with LFC, and the stability of the system can be further enhanced by adopting this UFLS model.

As a future issue, when running LS, there may be a difference between the net demand perceived and the load that was actually LS. I would like to simulate and evaluate how much that difference affects.

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