HIERARCHICAL OPERATION AND CONTROL FOR MICROGRIDS

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ABSTRACT

This paper addresses the hierarchical operation and control for a microgrid. In particular, the authors focus on supply and demand control of the microgrid. The microgrid has been actively introduced to distribution networks with renewables such as solar photovoltaic (PV for short) systems and wind energy conversion systems (WECS for short) [1]-[10]*. Operation and control methods of the microgrid are complex because renewables have uncertain factors affected by weather. For this reason, effectual operation and control methods have not been proposed yet. In this paper, the authors have evaluated the proposed operation and control methods by the numerical simulation and a real time simulator. The simulation outcome shows the cost minimum operation and frequency stability by the proposed hierarchical operation and control.*

INTRODUCTION

The subject addressed is the hierarchical operation and control for a microgrid. The microgrid has been actively introduced to distribution networks with renewables such as solar photovoltaic systems and wind energy conversion systems around the world [1]-[10]. The features of the microgrid are as follows [11]:

(1) The microgrid basic concept is the local production for local consumption. Therefore, line loss is negligible and few communication infrastructures are required.

(2) In grid-connected modes, the microgrid realizes efficient operation with integrating operation of generators including renewables, storages, and controllable loads.

(3) In stand-alone modes, the microgrid supplies the electricity to important loads independently of bulk power systems. It enhances the reliability and reduces the risk of failure of power supply.

In the meantime the problem is that the renewables have uncertain factors affected by weather and the operation and control methods of microgrid are complex. For this reason effectual operation and control methods have not been proposed yet.

In this paper, the authors propose the hierarchical operation and control for the microgrid depicted in Figure 1. The microgrid is consisting of internal combustion engines (ICE for short), loads, PVs, WECSs, and batteries.

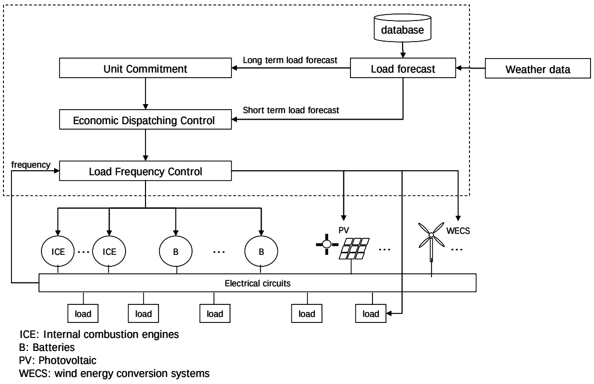


Figure 1 A diagram of the proposed hierarchical operation and control for a microgrid.

The forecast function computes the forecasted supply and demand of loads and ICEs from the information of the historical database. The unit commitment and the economic dispatching control (EDC for short) are carried out based on the forecasted results for minimizing the fuel cost. For the range of higher fluctuation cycle, the load frequency control (LFC for short) is carried out.

The advantages of the proposed hieratical operation and control structure are as follows:

(a) ICEs and batteries are operated and controlled. The renewables are treated as disturbance, but they are controlled by the LFC in a positive manner.

(b) In the optimal operation layers, look-ahead unit commitment and economic dispatching control minimize the cost function with some constraints. These layers have an ability to guarantee economic efficiency.

(c) In the frequency control layer, it also has an ability to stabilize the frequency of the microgrid.

The authors have evaluated the proposed operation and control methods by the numerical simulation and a real time simulator. The simulation outcome shows the cost minimum operation and frequency stability by the proposed hierarchical operation and control.

A BRIEF DESCRIPTION OF THE HIERARCHICAL SUPPLY AND DEMAND OPERATION AND CONTROL

The ICEs and batteries in the microgrid are operated and controlled by the proposed method in response to the range of the fluctuation cycle caused by the output fluctuation of loads and renewables such as PVs and WECSs to maintain the supply and demand varying from hour to hour at all times. In a general way, we will control equipment in the microgrid in response to the range of the fluctuation cycle. For the range of the fluctuation of a few minutes cycle, the governor control of each ICE is effective. For the range of the fluctuation of a half hour cycle, load frequency control is effective. For the range of the fluctuation of a few hours cycle, economic dispatching control considering economic efficiency, the upper and lower limits of output, and the upper and lower change rate limits of output of ICEs and batteries is effective. For the hourly supply and demand planning, a unit commitment which has functions similar to the economic dispatching control is effective.

UNIT COMMITMENT

The unit commitment for the hourly supply and demand planning is a mixed integer programming that decides the start-stop operation and outputs states of the ICEs, and batteries. The number of combination of this problem explosively increases according to the number of the ICEs and batteries. It is impossible to evaluate the objective function values of all combinations. Therefore, we introduce the following approximate procedures to shorten the computing time for state decision of the combination of the ICEs and batteries.

STEP1: Approximately minimizing outputs of all ICEs and batteries by a quadratic programming ignoring constraints of lower limits of output.
STEP2: Deciding states that are starts or stops of machines. If the output of machine is under the lower output limits in the STEP1, these machine are presumed the stop state. In this STEP, the states of all machines are decided.
STEP3: Minimizing outputs of selected ICEs and batteries in STEP1 & STEP2 by a quadratic programming.

The proposed method minimizes the ICEs operational and start-up cost expressed by equation (1). The ICEs operational cost is approximately assumed by a quadratic function.

$$\text{Minimize} \sum_{t=1}^{T} \sum_{k=1}^{N} \left(a_k P_k^2(t) + b_k P_k(t) + u_k(t) c_k \right) + \sum_{i=1}^{N} \Delta u_k K_k \quad (1)$$

where,
$P_k(t)$: the output of k_{th} ICE at time t.
$u_k(t)$: the state of k_{th} ICE at time t (0: stop, 1: start).
a_k, b_k, c_k: the coefficients of fuel cost characteristic of the k_{th} ICE.
Δu_k : the state of k_{th} ICE (0: stop, 1: start).
K_k: the start-up cost of k_{th} ICE.

Constraints are the balance of supply and demand, the upper and lower limits of output of ICEs, the upper and lower change rate limits of output of ICEs, the minimum continuous stop/start time of ICEs, reserve power, the upper and lower limits of discharge and charge power of batteries, the upper and lower limits of the state of charge for batteries. For batteries, the loss of discharge and charge are considered in operation.

ECONOMIC DISPATCHING CONTROL

The proposed economic dispatching control computes optimal output of each ICE based on the unit commitment results. The quasi-optimal solving method applying the Lagrange's method of undetermined multipliers has been proposed [12]. This method minimizes cost function with the upper and lower limits/ change rate limits of output of ICEs in the arbitrary future duration.
The formulations of the EDC are expressed by equation (2) – (5).

$$\text{Minimize} \sum_{i=1}^{T} f_i \quad (2)$$

$$f_i = \sum_{k=1}^{N} \left(\frac{a_k}{2} P_k(t+i)^2 + b_k P_k(t+i) + c_k \right)$$

Constraints are follows.

$$\sum_{i=1}^{T} P_k(t+i) = \hat{P}(t+i) \qquad (i=1,\ldots,T) \quad (3)$$

$$\underline{P_k}(t+i) \le P_k(t+i) \le \overline{P_k}(t+i) \qquad (i=1,\ldots,T) \quad (4)$$

$$-\delta_k \le P_k(t+i+1) - P_k(t+i) \le \delta_k \quad (i=1,\ldots,T) \quad (5)$$

where,
$P_k(t)$: the output of k_{th} ICE at time t.
a_k, b_k, c_k: the coefficients of fuel cost characteristic of the k_{th} ICE.
$P(t)$: the amount of the forecasted load demand at time t.
$P_k(t+i)$, $P_k(t+i)$: the upper and lower limits of output of k_{th} ICE at time t.
δ_k : the change rate limits of output of k_{th} ICEs.
N: the number of the ICE.
T: the duration time of the optimization from the current time to T steps.

We apply the Lagrange's method of undetermined multipliers to equation (2) – (5). We compute an optimal solution at every control step by following procedures.

STEP1: Reading forecasted load demand.
STEP2: Computing a feasibility region.
STEP3: Discriminating the occurrence of the imbalance of supply and demand. If the occurrence has happened, we ensure the reserve power and re-compute the feasibility region.
STEP4: Computing an optimal output of each ICE and battery, and fuel cost applying the Lagrange's method of undetermined multipliers considering change rate limits of output in the feasibility region of the STEP3.

LOAD FREQUENCY CONTROL

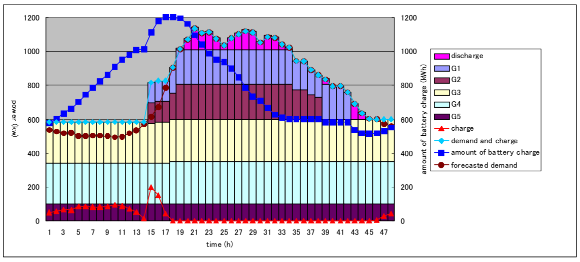
The load frequency control is consisted of basic PI control, and the input signals are the system frequency and the power flow of the tie line, and the output signals are power reference value of ICEs and batteries. This load frequency control has functions of normal control, suppressive control of PVs and WECSs output, disconnecting function of PVs and WECSs.

PERFORMANCE EVALUATION BY A NUMERICAL SIMULATION AND A REAL TIME SIMULATOR

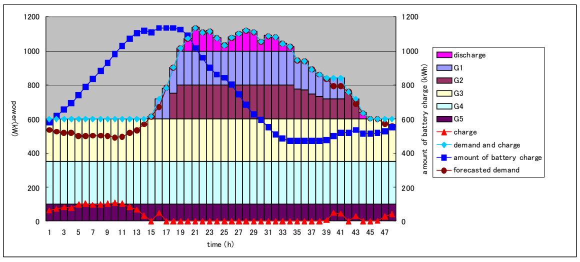
We have evaluated the proposed unit commitment and economic dispatching control by a numerical simulation. The proposed load frequency control has evaluated by a real time simulator. The real time simulator can consider a measurement delay, error, and noise. Therefore, we can estimate the performance of the proposed load frequency control in practical conditions.

Unit Commitment

We have carried out off line numerical simulations. The followings are simulation conditions:
(a) A Microgrid has five (5) ICEs and one (1) battery.
(b) Computing a look-ahead planning which is optimal solution every 30 minutes for a day (48 points for optimization).
(c) Execution by the Pentium 4, 3GHz CPU, and 1GB memory personal computer.
Figure 2 shows an exact solution and an approximate solution computed by the versatile software program and the proposed method respectively. Table 1 shows a comparison between the exact solution and the approximate solution.



(a) An approximate solution computed by the proposed method.



(b) An exact solution computed by a versatile software program.

Figure 2 Simulation results of the unit commitment.

Table 1 A comparison between two methods.

	Exact solution	Approx. solution
Cost	100.00 %	100.31 %
Computing time	9,907 second	13 second

When the cost of the exact solution is assumed 100%, we have obtained 100.31% cost as the approximate solution. From a practical perspective concerning the cost, there is not a great difference between two methods. Meanwhile, the computing time of the approximate solution is 762(= 9,907/13) times faster than the exact solution. This result shows the effectiveness of the proposed unit commitment.

Economic Dispatching Control

We have also carried out off line numerical simulations. The followings are simulation conditions:
(a) A microgrid has ten (10) ICEs and one (1) battery.
(b) Table 2 shows the generator characteristics and load data.
(c) Computing a look-ahead planning which is optimal solution every 5 minutes for 3 hours (180 points for optimization).
(d) Execution by the Pentium 4, 3GHz CPU, and 1GB memory personal computer.
Figure 3 shows ICEs outputs of each machine. It takes 0.15 second per step. This result shows the effectiveness of the proposed EDC.

Table 2 Characteristics of ICEs

Gen. #	Coefficients of fuel cost			Upper limit	Lower limit	Change rate limit
	a	b	c			
#1	0.2	500	1000	100	40	5
#2	0.3	1000	2000	250	100	3
#3	0.3	1000	2000	250	100	3
#4	0.4	1500	3000	300	120	7
#5	0.4	1500	3000	300	120	7
#6	2.5	2500	2400	120	24	5
#7	2.6	2500	2400	120	24	5
#8	2.8	2500	2400	120	24	5
#9	1.2	3800	12000	200	40	7
#10	1.4	3800	12000	200	40	7

Load Frequency Control

We evaluated the proposed LFC by a real time simulator. Figure 4 shows the PV output, battery output, and frequency. The frequency stays around 60Hz stably. This result shows the effectiveness of the proposed LFC.

CONCLUSIONS

In this paper, we have proposed the hierarchical operation and control for a microgrid. In particular, we focus on supply and demand control of the microgrid. We have evaluated the proposed operation and control methods by the numerical simulation and a real time simulator. The simulation outcome shows the cost minimum operation and frequency stability by the proposed hierarchical operation and control.

Applying the proposed method to practical system will be the future woks.

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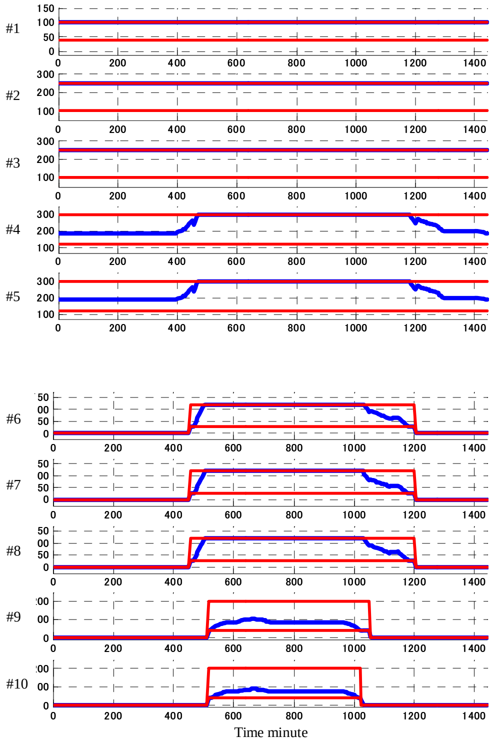
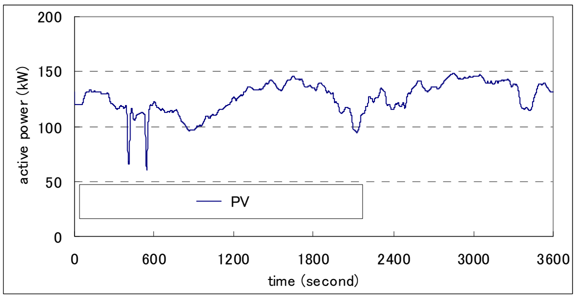
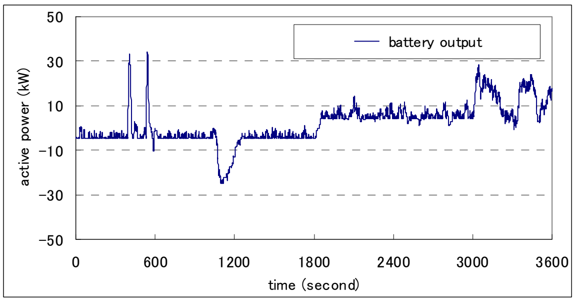


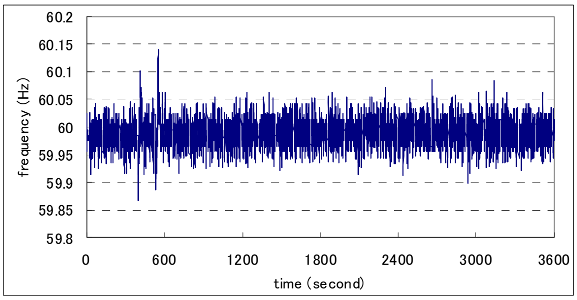
Figure 3 Simulation results of the EDC.



(a) PV output.



(b) Battery output.



(c) Frequency.

Figure 4 Simulation results of the LFC.