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Optimal microgrid scheduling to provide operational flexibility in main grid operation

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Abstract

The penetration of renewable energy sources into power systems has been increasing to mitigate the concerns for the environment, global warming, and rising fuel prices. However, the variability and uncertainty of power output from renewable energy sources raise challenging issues for power system operation, which draws attention to the need for operational flexibility. In this paper, we propose an optimal scheduling method for a microgrid that can provide the flexible ramping capability to the main grid. To investigate the effectiveness of the proposed method, a microgrid, which has an energy storage system and small-scale dispatchable generating units in order to not deploy the involuntary load shedding in an emergency condition, is postulated, and numerical simulations are carried out. We consider the energy storage system and dispatchable units as providers for flexible ramping capability and show that the proposed approach enables highly cost-effective distribution system operation. The simulation results verify that scheduling performance can be improved using the proposed method compared with the conventional scheduling method.

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Keywords: Microgrid; Flexible ramping capability; Power system operation; Islanded operation

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1. Introduction

Power system operators worldwide face the increasing amount of energy from renewable energy sources, such as photovoltaic (PV) and wind energy [1]. In terms of global warming, renewable resources can be regarded as a favorable solution, but the uncertainty and variability of renewable sources' power generating capabilities are imposing additional operational burdens on power system operators [2,3]. As a result, many studies have attempted to determine the optimal amount of reserves to deal with the uncertain and variable nature of renewable resources [4,5].

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Recently, to more effectively integrate renewable energy into the power system, some electricity markets have introduced a new type of ancillary service that is called a ramping product [6,7]. The main goal of ramping products is to procure flexible ramping capability (FRC) that is defined as the ability to ramp up/down from one generation level to another level within a pre-specified time interval [8]. If system operators procure FRC in time period t, they can effectively dispatch controllable generators and handle the uncertainties arising in time period $(t + 1)$. In general, thermal generating units provide FRC by reserving a portion of output power. However, various resources (e.g., electric storage of electric vehicles and wind power generators) can be considered as FRC providers as well [9,10]. The volume of upward and downward FRC requirements for a system in time period can be calculated as follows:

$$UFRC_t = \max\left[(NL_{(t+1)} - NL_t) + \alpha_t, 0\right] \tag{1}$$

$$DFRC_t = \max\left[(NL_t - NL_{(t+1)}) + \alpha_t, 0\right] \tag{2}$$

Here, NL_t represents net load that is equal to load minus non-controllable renewable energy output in period t. As can be confirmed in Eq. (1) and Eq. (2), system operators require more upward FRC when it is expected that net load will increase from t to the upcoming time period t. Whereas, if net load is expected to decrease, downward FRC is more desired in order to cover the downward ramping shortage. The additional FRC requirement for the purpose of the uncertainty in net load is represented as σ_t, as shown in Eq. (1) and Eq. (2).

As microgrids progressively pervade power systems [11], optimal operating strategies in microgrids has been widely investigated [12,13]. The method to operate microgrids can be classified according to whether a microgird is operated connected or disconnected from the main grid [14]. However, even though a microgrid is in grid-connected mode, the microgrid operator (MGO) does not solely rely on the main grid for supplying energy to the microgrid and does depend on generating resources in the microgrid. By doing this, the MGO can reduce a load-shedding risk if an emergency arises in the main grid. In this paper, we propose a new operating method for MGOs that enables providing FRC to the main grid. The main grid operator can derive benefit by procuring flexibility, and the MGO also enhance cost-effectiveness in operating the microgrid by the sales of FRC. In general, microgrids have small-scale generators and energy storage systems, both of which are able to ramp up and down very quickly. Therefore, MGOs can readily procure FRC, and a superfluous amount of FRC can be traded with the main grid operator.

The remainder of the paper is organized as follows. Section 2 presents the new proposed formulation that includes the possible sales of ramping products from microgrid to the main grid. Simulations based on the proposed method are given in Section 3, and Section 4 summarizes the results of this work and draws conclusions.

2. Mathematical formulation

The proposed mathematical formulation for the optimal scheduling includes the objective function Eq. (3) and the constraints Eq. (4)–Eq. (15). For the sake of simplicity, network power flow equations and constraints for other ancillary services (*e.g.*, regulation reserve, spinning reserve) are disregarded in this paper. However, the proposed method can be easily generalized to consider those constraints. The formulation is expressed in mixed integer linear programming form, which can be readily solved using commercial software.

$$\begin{aligned} \min \sum_{t\in\Omega_t}\sum_{g\in\Omega_g}\left\{C_g^{NL} + C_g^{LP}\cdot p_{gt}\right\} + \sum_{t\in\Omega_t}\left\{\lambda_t^{buy}\cdot p_t^{buy} - \lambda_t^{sell}\cdot p_t^{sell}\right\} \\ -\sum_{t\in\Omega_t}\sum_{g\in\Omega_g}\left\{\lambda_t^{upramp}\cdot mur_{gt} + \lambda_t^{dnramp}\cdot mdr_{gt}\right\} - \sum_{t\in\Omega_t}\sum_{e\in\Omega_e}\left\{\lambda_t^{upramp}\cdot mur_{et} + \lambda_t^{dnramp}\cdot mdr_{et}\right\} \end{aligned} \tag{3}$$

$$\sum_{g\in\Omega_g} p_{gt} + \sum_{e\in\Omega_e} p_{et}^{disch\arg e} + p_t^{buy} = NL_t + \sum_{e\in\Omega_e} p_{et}^{ch\arg e} + p_t^{sell}, \tag{4}$$

$$\sum_{g\in\Omega_g} ur_{gt} + \sum_{e\in\Omega_g} ur_{et} \geq UFRC_t, \tag{5}$$

$$\sum_{g\in\Omega_g} dr_{gt} + \sum_{e\in\Omega_e} dr_{et} \geq DFRC_t, \tag{6}$$

$$P_g^{\min} \leq p_{gt} - dr_{gt} - mdr_{gt}, \tag{7}$$

$$p_{gt} + ur_{gt} + mur_{gt} \le P_g^{\max}, \tag{8}$$

$$soe_{et} = soe_{e(t-1)} + \eta \cdot p_{e(t-1)}^{charge} - \frac{1}{\eta} \cdot p_{e(t-1)}^{discharge}, \tag{9}$$

$$(p, soe, ur, dr, mur, mdr) \in F \tag{10}$$

$$p_t^{buy} \le M \cdot \gamma_t^{buy}, \tag{11}$$

$$p_t^{sell} \le M \cdot \gamma_t^{sell}, \tag{12}$$

$$\gamma_t^{buy} + \gamma_t^{sell} \le 1, \tag{13}$$

$$p_t^{buy} + \sum_{g \in \Omega_g} mur_{gt} + \sum_{e \in \Omega_e} mur_{et} \le \overline{F}, \tag{14}$$

$$p_t^{sell} + \sum_{g \in \Omega_g} mdr_{gt} + \sum_{e \in \Omega_e} mdr_{et} \le \overline{F}, \tag{15}$$

In the formulation, index g and e represent generating unit and electric storage, respectively. The objective function minimizes the operating cost which can be calculated as the total energy cost minus the revenue of ramping products sale. Here, the total energy cost means the summation of the generation cost in the microgrid and the net cost associated with energy trading with the main grid. The load in the microgrid can be supplied either by the generating resources in the microgrid or by the main grid. Eq. (4) represents the power balance equation, and the upward and downward FRC requirements for the microgrid are represented as Eq. (5) and Eq. (6), respectively. The operating limits for generating units are given in Eq. (7) and Eq. (8). State-of-energy of storage can be calculated as Eq. (9). All the other constraints for generating units and electric storage (e.g., the constraints for the power output of storage, the state-of-energy of storage constraints for the beginning and the end of the planning horizon) are concisely represented in Eq. (10). The binary variable represented as γ_t^{buy} (γ_t^{sell}) in Eq. (11) (Eq. (12)) has a value of one if an MGO decides to buy (sell) energy from the grid. The parameter represented as M indicates a large positive number in the constraints. Due to the Eq. (13), an MGO cannot buy and sell the energy in the same time period. Eq. (14) and Eq. (15) constrain the amount of transferred power flow between the microgrid and the main grid. In this paper, it is assumed that the maximum allowable power flow, represented as $\overline{F}$, is predefined. However, the determination of the value $\overline{F}$can also be incorporated in the optimization problem.

3. Numerical study

The simulation was conducted on the microgrid that has PV, gas turbine generator (GT), two types of combined heat power plants (CHP), and electric energy storage. The scheduling horizon was set to 24 h day with hourly intervals. The load data and specifications of the system were taken from [14]. The optimization problem was solved using GAMS/GUROBI software with the winter weekday data, and the optimality gap was set to 0.1%. In the conventional approach, the ramping products price was set to zero so that the MGO is indifferent to providing FRC to the main grid. The transfer power limit between the microgrid and the main grid is assumed to 200kW which is 17.6% of the peak load.

Table 1. Comparison of operating cost under different ramping products price [$].

	5% of energy price	10% of energy price	20% of energy price
Proposed	1475	1450	1385
Conventional	1501	1501	1501
Savings [%]	26 (1.76%)	51 (3.52%)	116 (8.38%)

Table 1 shows the cost-effectiveness of the proposed method under different ramping products price conditions. As can be seen in the table, the MGO can reduce operating cost by providing FRC for the main grid. It is interesting to note that the savings increase dramatically as the ramping products price goes up. The reason for this is that not only the ramping price is changed but also the optimal scheduling of the microgrid is changed in a way to extend the benefits from increased ramping price. See the change in the output of generating unit and in the state-of-energy of storage in Figs. 1 and 2, respectively. The advantage of supplying FRC to the main grid can be clearly seen from Table 2 that summarizes the components of the operating cost. In the proposed method, the MGO can generate profits of $147 by providing FRC. Note that the total energy cost is increased as much as $31 in the proposed scenario

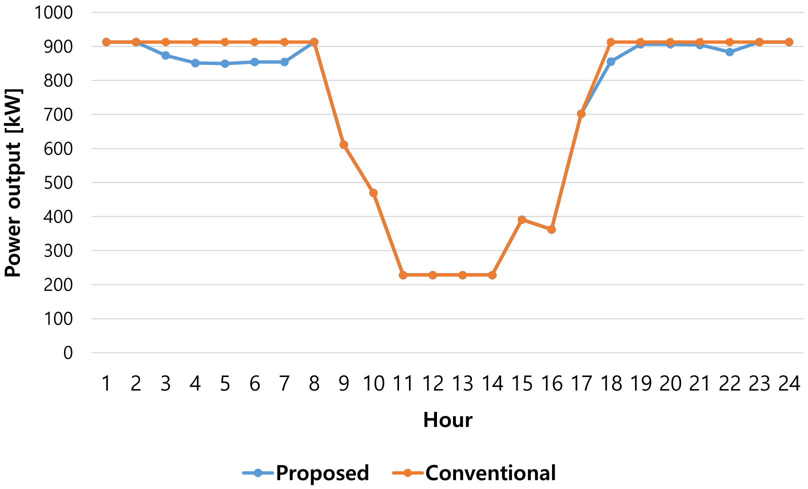

Fig. 1. Power output of CHP #2 for the scheduling day [kW].

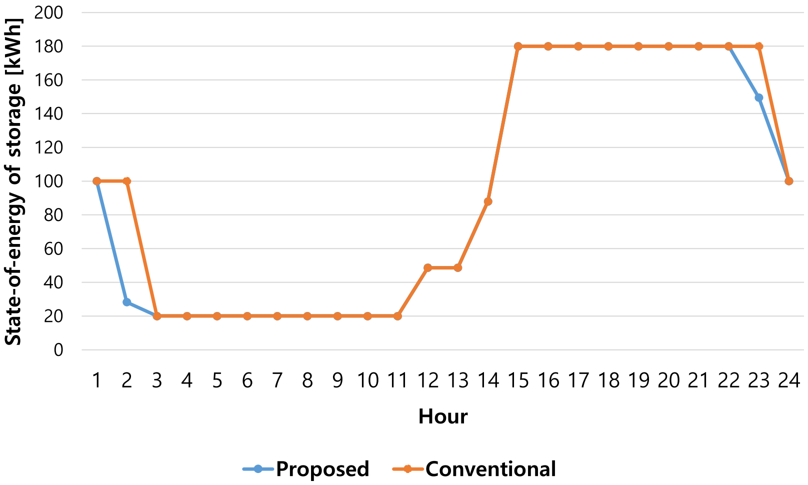

Fig. 2. State-of-energy of electric storage for the scheduling day [kWh].

Table 2. Components of operating cost if ramping products price is 20% of energy price [$].

	Total energy cost	FRC cost	Operating cost	Savings
Proposed	1532	−147	1385	116 (8.38%)
Conventional	1501	N/A	1501	

by the reason of the change in the microgrid scheduling. However, the profits from selling ramping products far outweigh the increased total energy cost.

Table 3 summarizes the total generated volume of energy by each generating unit for the entire scheduling time period. It can be seen that less energy is produced in the microgrid, and accordingly less energy is sold to the grid, if it is possible for the MGO to provide FRC for the main grid. The reason for the decreased energy production is due to the flow limit of the tie-line connecting the microgrid and the grid. In the proposed model, a portion of the line transfer capacity is reserved for the purpose of FRC provision, which leads to the curtailed amount of available trading energy through the tie-line.

Table 3. Total generated energy in the microgrid for the scheduling horizon [kWh].

	GT	CHP #1	CHP #2
Proposed	600	3311	16,753
Conventional	600	5597	17,142

4. Conclusion

In this paper, we proposed a model that enables FRC in a microgrid to be effectively used for the main grid. With the proposed method, the MGO can reduce the operating cost while the main grid operator can secure operational flexibility at the expense of buying FRC from the microgrid. Because the microgrid scheduling highly depends on the ramping products price, the optimization problem was solved based on various conditions. We have found that the MGO can minimize the operating cost by reserving a portion of tie-line capacity for providing FRC if the ramping products price is high. When we conduct the numerical study, the tie-line capacity was defined in a conservative way. We expect that if the transfer capacity between the microgrid and the main grid increases, the proposed model can create further cost savings.

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