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Article

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Coordinated operation schedule of microgrids in consideration of penetration of variable renewable energy sources

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Abstract

Operation schedule for microgrids has an important role to manage the electric power supply and demand efficiently. This paper presents a problem formulation and its solution method to obtain a coordinated operation schedule of controllable components in the microgrids. In the problem formulation, uncertainty originated from variable renewable energy sources is introduced. By utilizing characteristics of the formulated problem, dimension of its solution space is reduced, and thus a combined solution method of binary particle swarm optimization and quadratic programming is applicable in the proposed solution method. Validity of the authors' proposal is verified through discussions on numerical results.

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Keywords: Microgrids; Supply–demand management; Binary particle swarm optimization (BPSO); Quadratic programming (QP); Uncertainty

1. Introduction

In association with the growth in penetration of renewable energy sources (RESs), microgrid, which is a localized group of electrical power sources and loads, has been attracting attention as one of the most realistic sustainable energy systems in terms of efficient use of the RESs. If we appropriately operate components in the microgrids, this concept provides the possibility of grid independence to consumers with improving/keeping efficiency, reliability, and quality in the power supply and demand management. With a view to achieving this goal, several researches and development on microgrid-related techniques are actively carried out [1,2], and demonstrative field tests have been promoted [3,4].

There are two types in the microgrid components: one is controllable component, and another is uncontrollable one. Controllable generation systems (CGs) and energy storage systems (ESSs) compose the former. In contrast, the

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Nomenclature

t	time ($t = 1, \ldots, T$)
i	number of CGs ($i = 1, \ldots, NG$)
j	number of ESSs ($j = 1, \ldots, NS$)
$u_{i,t}$	ON/OFF state variable of CGs (ON: 1, OFF: 0) and an element of vector u_t and u
$g_{i,t}$	output of CGs and an element of vector g_t and g
$g_{i,t}^{max}$	maximum capable output of CGs at t
$g_{i,t}^{min}$	minimum capable output of CGs at t
G_i^{max}	maximum output of CGs
G_i^{min}	minimum output of CGs
$u_{i,t}^{on}$	consecutive operating duration of CGs
$u_{i,t}^{off}$	consecutive suspending of CGs
MUT_i	minimum value of operating duration of CGs
MDT_i	minimum value of suspending duration of CGs
ΔG_i^{up}	ramp-up rate of CGs
ΔG_i^{down}	ramp-down rate of CGs
$s_{j,t}$	output of ESSs and an element of vector s_t
$q_{j,t}$	state-of-charge (SOC) of ESSs
η_j	overall efficiency of ESSs
$s_{j,t}^{max}$	maximum capable output of ESSs at t
$s_{j,t}^{min}$	minimum capable output of ESSs at t
S_j^{max}	maximum output of ESSs
S_j^{min}	minimum output of ESSs
Q_j^{max}	maximum SOC of ESSs
Q_j^{min}	minimum SOC of ESSs
e_t	trading electricity and an element of vector e.
e_t'	imbalance (surplus/shortage)
d_t	forecasted net load
d_t^{max}	maximum assumable value of net load
d_t^{min}	minimum assumable value of net load
$f(d_t)$	probability density function of net load
A_i, B_i, C_i	fuel cost coefficients
SC_i	start-up cost of CGs
M_t	price of electricity trading
I_t	imbalance penalty
θ_1, θ_2	cognitive factors representing trust for each particle and swarm
r_1, r_2	random numbers in range [0, 1]

latter consists of electrical loads in consumer-side. Variable renewable energy-based generation systems (VREGs), whose outputs strongly depend on the weather condition, are also categorized in the latter. Since the VREGs take a significant portion of power sources in the microgrids, it becomes difficult to maintain the balance of power supply and demand with few adverse effects on the traditional main power grid. This is the reason why the operation scheduling method for the microgrids is crucially required.

In the case that we focus on operation of the CGs, its scheduling problem can be formulated as a combined problem of the unit commitment (UC) and the economic load dispatch (ELD). The UC-ELD problem, as is well known, is regarded as a mixed integer (MIP) problem and can be solved by traditional optimization-based

and/or intelligent optimization-based solution methods. Dynamic programming methods [5,6] and branch-and-bound methods [7,8] are typical examples of the former. Metaheuristics [9–12] and evolutionary computation algorithms [13,14] are involved in the intelligent methods. Although various algorithms have been applied to the problem formulation around the world, there is no established solution method until now. In addition, the target problem becomes more complicated because installation of the ESSs brings new variables in it [15–18].

The authors propose a problem formulation and its solution method to obtain a coordinated operation schedule for the microgrid components. In the problem formulation, uncertainty originated from the VREGs is introduced. Furthermore, electricity trading with the traditional grid is considered to provide operational alternatives for microgrid operators. Meanwhile, by utilizing characteristics of the formulated problem, a combined method of binary particle swarm optimization (BPSO) and quadratic programming (QP) is employed in the solution method. Through numerical simulations and discussions on their results, validity of the authors' proposal is verified.

2. Problem formulation

As shown in Fig. 1, microgrids are normally composed by (1) CGs, (2) ESSs, (3) VREGs and (4) electrical loads. Operation scheduling problem of the microgrids is to determine start-up/shut-down timing and output share of Component 1, and charging/discharging state of Component 2 in response to the value of net load for each time interval. The net load is calculated by the sum of output of Component 3 and electricity consumption of Component 4. Here, if the microgrid operators cannot procure electricity to maintain the balance of power supply and demand, the resulting electricity surplus/shortage has to be eliminated by the trading electricity with an extra payment, called imbalance penalty. However, it is often convenient to trade electricity with the traditional grid as compared to adjusting the microgrid operation. From this aspect, the electricity trade is also regarded as an optimization target in this paper.

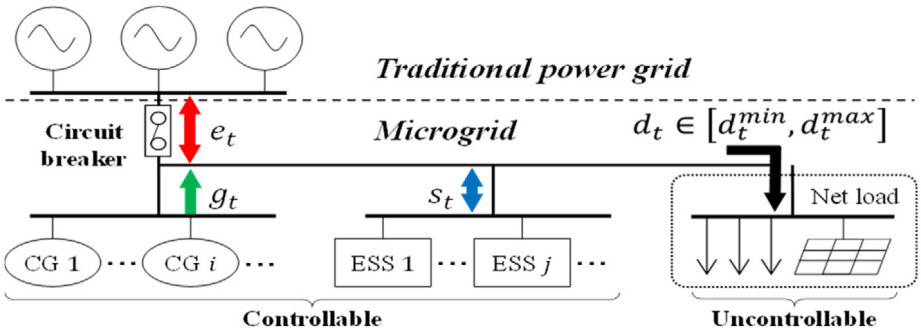

Fig. 1. Microgrid model.

The optimization variables are defined as

$$u_{i,t} \in \{0, 1\}, \quad \text{for } \forall i, \forall t, \tag{1}$$

$$g_{i,t} \in \left[G_i^{min}, G_i^{max}\right], \quad \text{for } \forall i, \forall t, \tag{2}$$

$$s_{j,t} \in \left[S_j^{min}, S_j^{max}\right], \quad \text{for } \forall j, \forall t. \tag{3}$$

$$e_t \in \mathbb{R}, \quad \text{for } \forall t. \tag{4}$$

The objective function is represented as

$$min. \sum_{t=1}^{T} \int_{d_t^{min}}^{d_t^{max}} \left[C_t\left(u_t, g_t\right) + M_t e_t\right] f\left(d_t\right) dd_t, \tag{5}$$

$$C_t\left(u_t, g_t\right) = \sum_{i=1}^{NG} \left\{\left(A_i + B_i g_{i,t} + C_i g_{i,t}^2\right) + SC_i\left(1 - u_{i,t-1}\right)\right\} u_{i,t}. \tag{6}$$

Now, reserve margin is secured automatically depending on the calculation result of (5). The other operational constraints can be expressed by the following equations.

• Balance of power supply and demand:

$$d_t = \sum_{i=1}^{NG} g_{i,t}u_{i,t} + \sum_{j=1}^{NS} s_{j,t} + e_t + e'_t, \text{ for } \forall t. \tag{7}$$

• Maximum and minimum outputs of CGs:

$$g_{i,t}^{min} \le g_{i,t} \le g_{i,t}^{max}, \text{ for } \forall i, \forall t.$$
$$(g_{i,t}^{min} = max\left(G_i^{min}, g_{i,t-1} - \Delta G_i^{down}\right); g_{i,t}^{max} = min\left(G_i^{max}, g_{i,t-1} + \Delta G_i^{up}\right)) \tag{8}$$

• State duration for CGs:

$$\text{If } 0 < u_{i,t}^{on} < MUT_i \text{ then } u_{i,t} = 1; \text{If } 0 < u_{i,t}^{off} < MDT_i \text{ then } u_{i,t} = 0, \text{ for } \forall i, \forall t. \tag{9}$$

• Ramp rate for CGs:

$$\Delta G_i^{down} \le g_{i,t} - g_{i,t-1} \le \Delta G_i^{up}, \text{ for } \forall i, \forall t. \tag{10}$$

• State for ESSs:

$$Q_j^{min} \le q_{j,t} \le Q_j^{max}, \text{ for } \forall j, \forall t.$$
$$(q_{j,t} = q_{j,t-1} - \eta_j s_{j,t} \text{ (Charging)}; q_{j,t} = q_{j,t-1} - \frac{1}{\eta_j} s_{j,t} \text{ (Discharging)}) \tag{11}$$

• Maximum and minimum outputs of ESSs:

$$s_{j,t}^{min} \le s_{j,t} \le s_{j,t}^{max}, \text{ for } \forall j, t \in TS_j.$$
$$(s_{j,t}^{min} = max\left(S_j^{min}, q_{j,t-1} - Q_j^{max}\right); s_{j,t}^{max} = min\left(S_j^{max}, q_{j,t-1} - Q_j^{min}\right)) \tag{12}$$

By (7), the ESSs contribute to saving operation cost of the CGs and/or payment for trading electricity.

In the case that the time interval, Δt, and the ramp-up and the ramp-down of CGs, ΔG_i^{up} and ΔG_i^{down}, satisfy the conditions, $\Delta t \ge MUT_i + MDT_i$ (for $\forall i$), $\Delta G_i^{up} \ge G_i^{max} - G_i^{min}$ (for $\forall i$) and $\Delta G_i^{down} \ge G_i^{max} - G_i^{min}$ (for $\forall i$), the constraints (9) and (10) become inactive [19,20]. Since these conditions are often satisfied in the operation scheduling problems of microgrid, the authors ignore these constraints in this paper.

3. Solution method

The formulated problem is a complicated MIP problem having the discrete and the continuous optimization variables. The former is the state of CGs, u, and the latter consists of the outputs of the CGs, g, and the ESSs, s, and the trading electricity, e, as shown in (1)–(4). Since it is extremely difficult to solve the problem exactly, the intelligent optimization-based algorithm becomes one of the most effective alternatives. In practice, several metaheuristics and evolutionary computation techniques were applied to the similar problem frameworks including genetic algorithm [9], simulated annealing [10,11], tabu search [19], particle swarm optimization [12,20] and evolutionary programming [13,14]. In this paper, a BPSO is selected to ease the problem difficulty brought by the UC problem. The ELD problem for each UC candidate, which is created by searching paradigm of the BPSO, is solved using a QP solver.

3.1. Application of quadratic programming

The target optimization problem has four optimization variables, (u, g, s, e). This is a reason why the target problem becomes complicated. To improve compatibility between the target problem and its solution method, the authors redefine the optimization variables as

$$u'_{h,t} \in \{0, 1\}, \text{ for } \forall h, \forall t, \tag{13}$$
$$g'_{h,t} \in \left[G_h'^{min}, G_h'^{max}\right], \text{ for } \forall h, \forall t, \tag{14}$$

where h is the number of controllable component ($h = 1, \ldots, NG, \ldots, NG + 2$); $u'_{h,t}$ is the state of controllable components, which is an element of vector u'_t and u'; $g'_{h,t}$ is the output of controllable components, which is an

element of vector g'_t and g; G'^{max}_h and G'^{min}_h are the maximum and the minimum outputs of controllable components. In (13) and (14), the ESSs are aggregated into large-scale one to emphasize perspicuity of the formulation. The $(NG+1)$th component means the aggregated ESS, and the $(NG+2)$th component is the trading electricity. Now, Eq. (7) can also be expressed by

$$d_t = \sum_{h=1}^{NG+2} g'_{h,t} u'_{h,t} + e'_t, \ \text{for } \forall h, \forall t. \tag{7'}$$

When we fix the states of controllable components on each time, $u'_{h,t}$, the target problem can be relaxed as a special type of optimization problem that has a quadratic objective function and several variables subject to linear constraints. The sets of coefficients, $(A_{NG+1}, B_{NG+1}, C_{NG+1})$ and $(A_{NG+2}, B_{NG+2}, C_{NG+2})$, are set by $(0, 0, 0)$ and $(0, M, 0)$, respectively. Therefore, the QP solvers can be applied after creating u'.

3.2. Application of binary particle swarm optimization

Particle swarm optimization (PSO) is a computational algorithm that optimizes a problem by iteratively trying to improve a solution candidate for a given measure of quality. An initial set of randomly created solutions propagates in the design of search space towards the optimal solution over a number of iterations based on large amount of information that is fitted and shared by all members of the swarm. Each particle x has a position, p^n_x, and a velocity, v^n_x, in iteration n $(n = 1, 2, \ldots, N)$ and flies through on the search space for finding their best positions and velocities. The inertia weight factor, ω, controls the iteration size. With regards to the target problem, the following equations describe the solution updating mechanism. In (15), asterisk means "optimal".

$$p^n_x = u'; \ p^{n+1}_x = p^n_x + v^{n+1}_x; \ v^{n+1}_x = \omega v^n_x + \theta_1 r_1 \left[p^*_x - p^n_x\right] + \theta_2 r_2 [\left(\min_{x \epsilon X} p^*_x\right) - p^n_x]. \tag{15}$$

Although the PSO has succeeded in many continuous problems, it has some difficulties to handle the discrete optimization problems. Therefore, BPSO, which is an extended PSO, is applied to the UC problem in this paper. To modify the ON/OFF states of CGs, the authors employ a sigmoid function as shown in (16).

$$\text{If } 0.5 < \frac{1}{1 + e^{-u'_{h,t}}} \text{ then } u'_{h,t} = 1; \text{ else } u'_{h,t} = 0, \ \text{for } \forall h, \forall t. \tag{16}$$

As described in 3.1, the target problem can be relaxed as a QP problem by fixing u'. That is, we can reduce the dimension of solution space from (u, g, s, e) to u', and thus expect to improve the searching ability of applied algorithms.

4. Numerical simulations

Numerical simulations were carried out on the microgrid model, which was already shown in Fig. 1, to verify the validity of authors' proposal. Parameters of the microgrid model were set as follow: $T = 24$, $\Delta t = 1$, $NG = 3$, $\sum_{i=1}^{3} G^{max}_i = 48.0$ (MW), $S^{max} = 1.8$ (MW), $S^{min} = -1.8$ (MW), $Q^{max} = 10.4$ (MWh) and $Q^{min} = 2.6$ (MWh). Initial SOC of the aggregated ESS was set randomly, and it had to be recovered to the original level at the end period.

As shown in Fig. 2, photovoltaic generation systems (PVs) are emphasized as the VREG, and the maximum values of electric load and aggregated PV output are set to 39.6 [MW] at 19:00 and 9.0 [MW] at 12:00, respectively. To simplify analysis of the numerical results, the uncertainty originated from the PVs was only considered. Specifications of each CG made with reference to [19,20] are summarized in Table 1.

4.1. Numerical conditions

The authors determined the following five operation schedules by the proposed solution method.

Case 1: Operation schedule for the CGs only.
Case 2: Case 1 considering the reserve margin (±5% of the electric load and ±10% of the PV output)
Case 3: Operation schedules for the CGs and the ESSs.

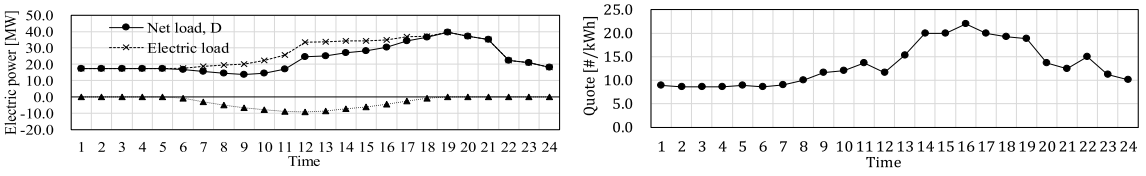

Fig. 2. (a) Net load in ideal condition; (b) Electricity price.

Table 1. Specification of CGs (# means "any currency unit is applicable").

i	A_i (#)	B_i (#/MW)	C_i (#/MW^2)	SC_i (#)	G_i^{max} (MW)	G_i^{min} (MW)
1	12,000.0	3,800.0	1.2	3,000.0	20.0	4.0
2	7,800.0	3,100.0	1.8	1,000.0	16.0	3.2
3	2,400.0	2,500.0	2.8	500.0	12.0	2.4

Case 4: Case 3 considering the reserve margin (same with Case 2)
Case 5: Operation schedules for the CGs and the ESSs in consideration of the uncertainty.

Case 2 is essentially same with the traditional UC-ELD problems. Case 4 means the conventional problem formulation, and Case 5 is the proposed formulation. In accordance with the result of trial and error, parameters for the BPSO were set as follow: $|X| = 40$, $N = 300$, $\omega = 0.9$, $\theta_1 = 2.0$ and $\theta_2 = 2.0$.

4.2. Results and discussions

Table 2 summarizes the numerical results. In all operation schedules, the balance of power supply–demand for the forecasted net load was maintained by the sum of the output shares of CGs and aggregated ESS and the trading electricity with the traditional grid. Furthermore, in Cases 1–4, the numerical simulations were succeeded within a few minutes. In contrast, Case 5 required several hours to complete its process because evaluation of the solution candidates became complicated by (4)–(7). Therefore, improvement of the computation time remains as an important issue of the authors' proposal.

Table 2. Comparison of numerical results.

Case	Cost for forecasted net load		Expected cost	
1	1,930,868	0 (Base)	1,941,446	0 (Base)
2	1,956,575	+1.33%	1,956,986	+0.80%
3	1,907,744	−1.12%	1,924,593	−0.87%
4	1,932,835	+0.10%	1,924,417	−0.88%
5	1,914,542	−0.85%	1,921,193	−1.04%

As summarized in Table 2, the operation schedule of Case 3 was the best result from the view of operation cost for the forecasted net load. It also means that the aggregated ESS was operated effectively to reduce the operation cost. However, its expected cost became worse than those of Cases 4 and 5 because the schedule has potential risk for the imbalance penalty by unexpected change in the aggregated PV output. On the other hand, the operation schedules in Cases 4 and 5 secured the margin, which contributes to reducing the expected costs, in exchange for increase of their operation costs for the forecasted net load. Moreover, the result of Case 5 improved the expected operation cost as compared to that in Case 4. From these results, we can conclude that the authors' proposal was functioned well. For reference, the optimal operation schedules for Cases 4 and 5 are displayed in Fig. 3.

5. Conclusions

This paper presented a problem formulation to obtain a coordinated operation schedule for the microgrid components in consideration of the uncertainty originated from the VREGs. In addition, the BPSO-QP based solution method was proposed for solving the formulated problem effectively. Through numerical simulations and

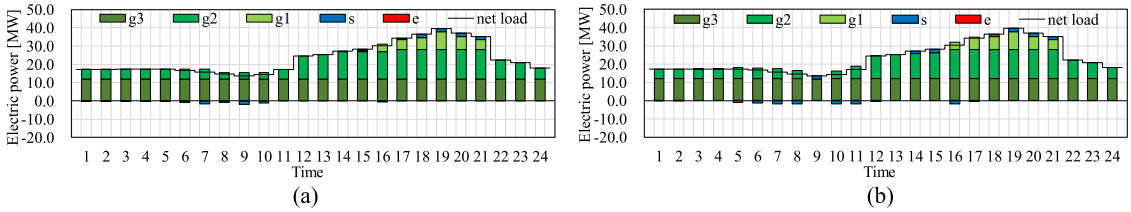

Fig. 3. (a) Optimal solution in Case 4 (conventional formulation); (b) Optimal solution in Case 5 (proposed formulation)

discussions on their results, validity of the authors' proposal was verified. However, it is undeniable that the proposed method has room for discussion on its calculation time. This problem will be solved in future works.

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