International Journal of Smart Home
Vol. 9, No. 5 (2015), pp. 41-50
http://dx.doi.org/10.14257/ijsh.2015.9.5.05

Applying Demand Response Based on TOU and EDRP to Optimal Microgrid Operation

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Abstract

The operation of microgrid is an important research topic due to its high efficiency of energy consumption and various types of energy source. Demand response (DR) programs can be applied to operate microgrid efficiently and economically. This paper deals with an optimal operation a microgrid in grid-connected operation mode. DR programs based on time of use (TOU) program and emergency demand response program (EDRP) are applied in this paper. Mixed integer linear programming is used to the end of simulation. Through the simulation results, the effectiveness of the DR programs based on TOU and EDRP to the microgrid operation are shown.

Keywords: *Microgrid, optimal operation, demand response, TOU, EDRP.*

1. Introduction

Microgrid is composed of distributed generations, renewable energy sources, and loads as a small-scale power system. The operation of microgrid can be divided in two modes: interconnected and islanded modes. In the islanded mode, the critical requirement for the microgrid is to maintain constant frequency such as 50 or 60 Hz. It relates to the balance between the power supply and power demand. On the other hand, in the grid-connected mode, the microgrid operation should be optimal to gain the efficiency and economics [1-5]. In this paper, we concentrate on grid-connected mode to optimize the microgrid operation.

Recently, demand response (DR) is widely applied into the microgrid operation. DR can be classified into two types: price-based DR and incentive-based DR [6]. The price-based DR refers to changes in usage by customers to take the advantage of lower-priced periods. Time of use (TOU) program is one of the price-based DR programs, which presents a rate with different unit prices for usage during different block of time. TOU program has been presented by many authors to transfer loads from peak time to off-peak time for maximizing the customer's benefit such as in [7-10]. By comparison, incentive-based DR programs are decided by utilities, load-serving entities, or a regional grid operator. Emergency demand response program (EDRP) is a type of incentive-based DR program, which provides incentive payments to customers for reducing loads at peak time. Several researchers have been introduced the EDRP to the microgrid operation for reducing loads at peak time [11-15].

In this paper, both TOU and EDRP are used to optimize the microgrid operation for day-ahead generation. From this study, the impact of different type of DR programs on the microgrid operation is demonstrated. Microgrid consists of several types of energy sources such as: controlled distributed generator (CDG), photovoltaic power generator (PV), and battery energy storage system (BESS). Moreover, the electrical loads can be divided into three types, that is: fixed load, shiftable load, and controllable load.

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ISSN: 1975-4094 IJSH

The rest of this paper is organized as follows; Section 2 introduces the mathematical model to be used for optimal microgrid operation. Section 3 presents the case study in this paper. Section 4 shows the simulation results with two types of DR programs. Finally, the conclusion is summarized in Section 5.

2. Mathematical Model for Optimal Operation

2.1. Nomenclature

Before presenting the mathematical models of the microgrid operation, mathematical notations for the models are defined as follows:

t = the identifier of operation interval

T = the number of operation intervals

i = the identifier of CDG

I = the number of the CDG

L_C = losses for charging

L_D = losses for discharging

$u_i(t)$ = on or off mode of the i^{th} CDG at t^{th} interval

C^{CDG_i} = the production cost of the i^{th} CDG [won/kWh]

$SU^{CDG_i}(t)$ = startup cost of the i^{th} CDG at t^{th} interval [won]

$C_{start}^{CDG_i}$ = startup cost of the i^{th} CDG [won]

$C_{Shed}(t)$ = the price for shedding at t^{th} interval [won/kWh]

$PR_{Buy}(t)$ = the buying price from the power grid at t^{th} interval [won/kWh]

$PR_{Sell}(t)$ = the selling price to the power grid at t^{th} interval [won/kWh]

$pen(t_{from}, t_{to})$ = penalty of shifting power from t_{from}^{th} interval to t_{to}^{th} interval [won/kWh]

$P_{adj}^{Load}(t)$ = the total amount of adjusted power load at t^{th} interval [kWh]

$P^{Fix}(t)$ = the amount of power consumed by the fixed load at t^{th} interval [kWh]

$P_{init}^{Shift}(t)$ = the amount of power consumed by the shiftable load at t^{th} interval [kWh]

$P_{adj}^{Shift}(t)$ = the amount of adjusted power consumed by the shiftable load at t^{th} interval after the load shifting [kWh]

$P(t_{from}, t_{to})$ = the amount of power shifted from t_{from}^{th} interval to t_{to}^{th} interval [kWh]

$P_{ini}^{Control}(t)$ = the amount of power consumed by the controllable load at t^{th} interval [kWh]

$P_{adj}^{Control}(t)$ = the amount of adjusted power consumed by the controllable load at t^{th} interval after the load shedding [kWh]

$P_{Shed}(t)$ = the amount of shedding power at t^{th} interval [kWh]

$P^{RDG}(t)$ = the output produced from renewable distributed generator (RDG) at t^{th} interval [kWh]

$P^{CDG_i}(t)$ = the output produced from the i^{th} CDG at t^{th} interval [kWh]

$P_{Buy}(t)$ = the amount of power purchased from the power grid at t^{th} interval [kWh]

$P_{Sell}(t)$ = the amount of power sold to the power grid at t^{th} interval [kWh]

$P_{Charge}^{BESS}(t)$ = the amount of power charged at t^{th} interval [kWh]

$P_{Dis}^{BESS}(t)$ = the amount of power discharged at t^{th} interval [kWh]

$P_{\max}^{BESS}$ = maximum power capacity of the BESS [kWh]

P_{Ini}^{BESS} = initial power capacity of the BESS [kWh]

$P_{SOC}^{BESS}(t)$ = state of charge (SOC) of BESS at t^{th} interval [kWh]

$P_{\max}^{IF}(t)$ = maximum total amount of power shifting from another interval to interval t [kWh]

$P_{\max}^{OF}(t)$ = maximum total amount of power shifting from interval t to another interval [kWh]

$P_{\min}^{CDG_i}$ = minimum production capacity of the i^{th} CDG [kWh]

$P_{\max}^{CDG_i}$ = maximum production capacity of the i^{th} CDG [kWh]

2.2. Classification of Loads

For applying DR programs to microgrids, we consider three types of loads depending on the controlled loads, which are: fixed load, shiftable load, and controllable load [1-2]:

- Fixed load (or non-controllable load): a demand that must be supplied to avoid user's dissatisfaction.
- Shiftable load: the load profile for these devices can be shifted from one period to another period for reducing demand load at peak hours.
- Controllable load: loads can't move to an interval from another and they must be on or off.

2.3. Objective Function

The objective function is established to minimize the operation costs of microgrid as shows in equation (1). Total incentive payment to the customers to adjust their load patterns is considered as the cost of DR program and included in the objective function.

$$\text{Minimize} \sum_{t=1}^{T}\left(\sum_{i=1}^{I}\left(C^{CDG_i}\cdot P^{CDG_i}(t)+SU^{CDG_i}(t)\right)\right)$$

$$+\sum_{t=1}^{T}\left(PR_{Buy}(t)\cdot P_{Buy}(t)\right)-\sum_{t=1}^{T}\left(PR_{Sell}(t)\cdot P_{Sell}(t)\right) \tag{1}$$
$$+\sum_{t=1}^{T}C_{Shed}(t)\cdot P_{Shed}(t)-\sum_{t=1}^{T}\sum_{t_{to}=1,t_{to}\neq t_{from}}^{T}(pen(t_{from},\ t_{to})\cdot P(t_{from},\ t_{to}))$$

The first term of the above equation is the production cost and the startup cost of CDG units, the second term is the cost by buying electricity from the utility grid, the third term is the income by selling electricity to the utility grid, the fourth term is the cost for load shedding, and the final term is the penalty for shiftable loads.

2.4. Constraints

Power generation capacity of the CDG is expressed by (2):

$$P_{\min}^{CDG_i}\cdot u_i(t)\le P^{CDG_i}(t)\le P_{\max}^{CDG_i}\cdot u_i(t) \tag{2}$$

On–off mode binary constraint:

$$u_i(t)=\begin{cases}1 & if\ P^{CDG_i}>0\\ 0 & otherwise\end{cases} \tag{3}$$

The startup cost of CDG units is calculated as equations (4) and (5):

$$SU^{CDG_i}(t)=C_{start}^{CDG_i}\cdot[u(t)-u(t-1)] \tag{4}$$

$$SU^{CDG_i}(t)\ge 0 \tag{5}$$

The power balance between power supply and power load is shown in equation (6). When the BESS is discharged, it can be considered as the power supply to the microgrid. On the other hand, the BESS can be considered as the load when it is charged.

$$P^{RDG}(t)+\sum_{i=1}^{I}P^{CDG_i}(t)+P_{Buy}(t)-P_{Sell}(t)+P_{Dis}^{BESS}(t)-P_{Charge}^{BESS}(t)=P_{adj}^{Load}(t) \tag{6}$$

where, $P_{adj}^{Load}(t)=P^{Fix}(t)+P_{adj}^{Shift}(t)+P_{adj}^{Control}(t)$

For t = 1, equations (7)-(10) show the initial amounts of charging and discharging, which consider SOC of the BESS.

$$0\le P_{Charge}^{BESS}(1)\cdot(1-L_C)\le P_{\max}^{BESS}-P_{Ini}^{BESS} \tag{7}$$

$$0\le P_{Dis}^{BESS}(1)\le P_{Ini}^{BESS}\cdot(1-L_D) \tag{8}$$

$$P_{SOC}^{BESS}(1)=P_{Ini}^{BESS}-P_{Dis}^{BESS}(1)/(1-L_D)+P_{Charge}^{BESS}(1)\cdot(1-L_C) \tag{9}$$

$$0\le P_{SOC}^{BESS}(1)\le P_{\max}^{BESS} \tag{10}$$

For 1 < t ≤ T, equations (11) and (12) show the amounts of charging and discharging. Equations (13) and (14) show the SOC of BESS at interval *t*. It means that the BESS should be operated within the allowable range.

$$0\le P_{Charge}^{BESS}(t)\cdot(1-L_C)\le P_{\max}^{BESS}-P_{SOC}^{BESS}(t-1) \tag{11}$$

$$0\le P_{Dis}^{BESS}(t)\le P_{SOC}^{BESS}(t-1)\cdot(1-L_D) \tag{12}$$

$$P_{SOC}^{BESS}(t)=P_{SOC}^{BESS}(t-1)-P_{Dis}^{BESS}(t)/(1-L_D)+P_{Charge}^{BESS}(t)\cdot(1-L_C) \tag{13}$$

$$0\le P_{SOC}^{BESS}(t)\le P_{\max}^{BESS} \tag{14}$$

The shiftable load can be moved to cheaper intervals. It is dependent on the generation costs and trading prices. Equations (15)-(16) express inflow power and outflow power constraints for shifting power from t_{from}^{th} interval to t_{to}^{th} interval.

Shiftable power inflow constraint:

$$\sum_{t_{from}=1, t_{from}\neq t}^{T} P(t_{from},\ t) \leq P_{\max}^{IF}(t) \tag{15}$$

Shiftable power outflow constraint:

$$\sum_{t_{to}=1, t_{to}\neq t}^{T} P(t,\ t_{to}) \leq P_{\max}^{OF}(t) = P_{ini}^{Shift}(t) \tag{16}$$

Equation (17) shows penalty of transferring shiftable load from t_{from}^{th} to t_{to}^{th} interval:

$$pen(t_{from},\ t_{to}) = \begin{cases} \infty & if\ \ customer\ don't\ permit\ shiftable\ load\ to\ t_{to}^{th} \\ 0 & otherwise \end{cases} \tag{17}$$

Equation (18) shows the amount of adjusted power that is consumed by the shiftable load at t^{th} interval after shifting load.

$$P_{adj}^{Shift}(t) = P_{ini}^{Shift}(t) + \sum_{t_{from}=1, t_{from}\neq t}^{T} P(t_{from},\ t) - \sum_{t_{to}=1, t_{to}\neq t}^{T} P(t,\ t_{to}) \tag{18}$$

The amount of power reduced in the peak time is shown in equations (19) and (20).

$$P_{Shed}(t) = P_{ini}^{Control}(t) - P_{adj}^{Control}(t) \tag{19}$$

$$0 \leq P_{Shed}(t) \leq P_{ini}^{Control}(t) \tag{20}$$

3. Case Study

The microgrid shows in Fig. 1 is used in this paper, which consists of a photovoltaic power generation, two CDGs, and a BESS. The operation of microgrid is in the grid-connected mode. Table 1 shows the variable, startup costs and the minimum, maximum capacity of CDG units. The photovoltaic power and load data are given in Tables 2 and 3, and the power trade prices are shown in Fig. 2.

Table 1. Production Characteristics of CDG Generator

Item	Cost (won/kWh)		Capacity (kW)	
	Variable	Startup	Minimum	Maximum
CDG1	35	150	0	300
CDG2	100	200	0	100

Table 2. Photovoltaic Power Generation [2]

Hour	1	2	3	4	5	6	7	8	9	10	11	12
Output (kWh)	0	0	0	0	5	7	13	15	17	20	22	25
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Output (kWh)	23	20	14	10	8	0	0	0	0	0	0	0

Table 3. Load Data

Hour	1	2	3	4	5	6	7	8	9	10	11	12
Electrical load (kWh)	400	400	395	397	420	455	460	475	490	510	550	600
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Electrical load (kWh)	600	575	560	550	550	555	540	530	500	490	450	450

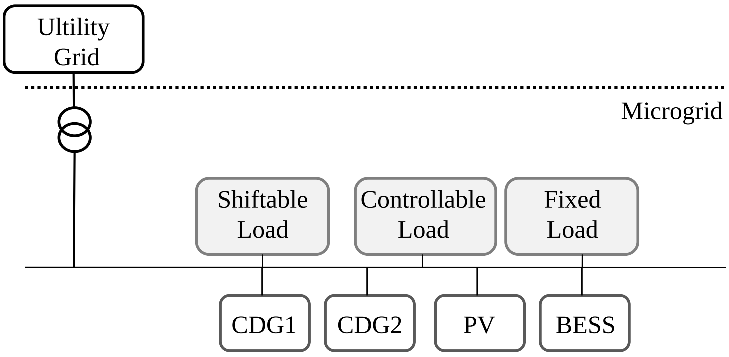

Figure 1. Test microgrid

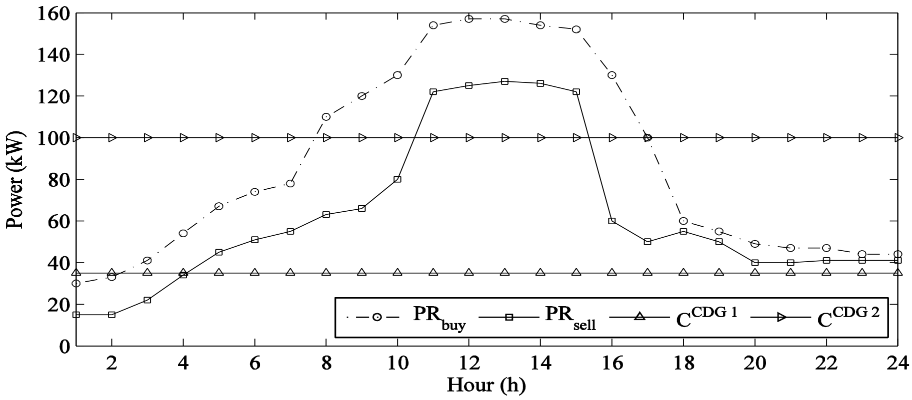

Figure 2. Power Trade Prices

4. Simulation Results

In this paper, we considered the incentive of 120 won per 1 kWh, which is used in the EDRP program. The original load and adjusted load after applying TOU program are shown in Fig.3. It can be seen that the loads can be shifted from expensive periods (peak hours) to cheap periods (off-peak hour) depending on the different prices in each periods. As a result, it can be created a new peak in the cheaper periods.

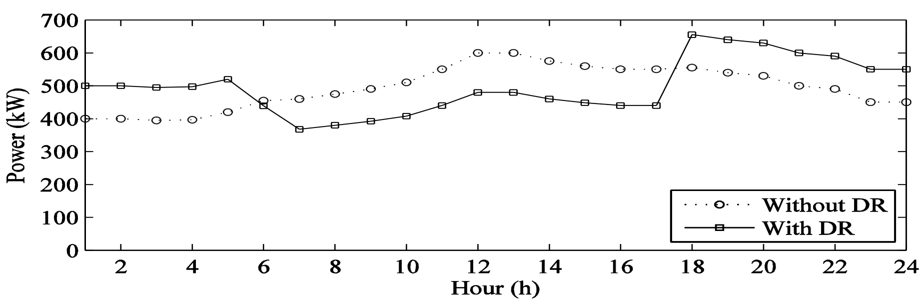

Figure 3. Applying DR Program based on TOU

Figure 4 shows the adjusted loads after implementing EDRP program. At the peak periods (from 8 a.m. to 5 p.m.), the buying price from power market is very high. After implementing EDRP program, amounts of controllable load can be reduced and paying to customers an intensive.

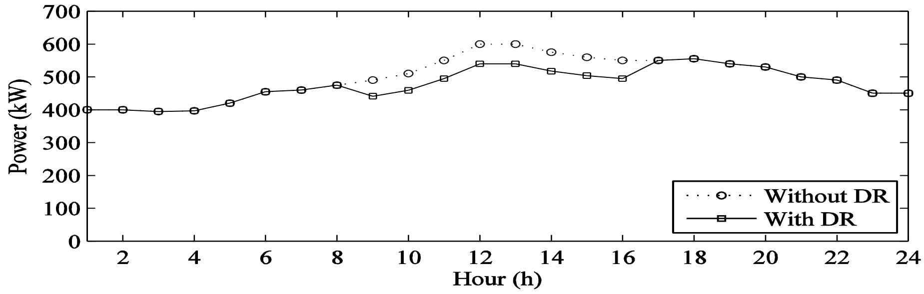

Figure 4. Applying DR Program based on EDRP

Figure 5 illustrates the adjusted loads after applying both TOU and EDRP to optimize microgrid operation. At the peak periods, the reduction load in this case is larger than that in case of applying only TOU. Although the utilities have to pay an incentive to the customers because of theirs reduction loads, the total operation cost still lower than the original case. The effectiveness of the DR programs based on TOU and EDRP are demonstrated in Table 4. It can be seen that the total operation cost can be reduced to about 16.45 % by using DR programs based on TOU and EDRP. The generation scheduling of the microgrid operation after using DR programs based on TOU and EDRP is shown in Table 5.

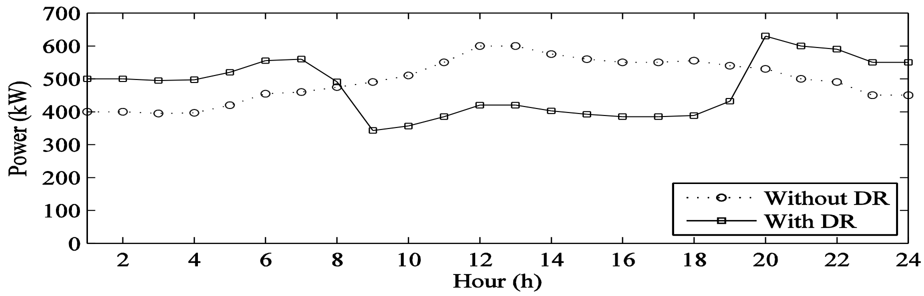

Figure 5. Applying DR Program based on TOU and EDRP

Table 4. Total Cost in Case of with and without DR Program

	Total cost (Won)	Reduced (%)
Without DR	633881	0
DR based on TOU	533707	15.8
DR based on TOU and EDRP	528791	16.58

Table 5. Generation Scheduling with DR Program based on TOU and EDRP

Hour (h)	P^{RDG} (kWh)	P^{CDG_1} (kWh)	P^{CDG_2} (kWh)	P_{Buy} (kWh)	P_{Sell} (kWh)	P^{BESS}_{SOC} (kWh)	P^{BESS}_{Charge} (kWh)	P^{BESS}_{Dis} (kWh)	P_{Shed} (kWh)	P^{Load}_{adj} (kWh)
1	0	0	0	552.6	0	100	52.63	0	0	500
2	0	0	0	500	0	100	0	0	0	500
3	0	300	0	195	0	100	0	0	0	495
4	0	300	0	197	0	100	0	0	0	497
5	5	300	0	215	0	100	0	0	0	520
6	7	300	0	132	0	100	0	0	0	439
7	13	300	0	55	0	100	0	0	0	368
8	15	300	65	0	0	100	0	0	0	380
9	17	300	75	0	0	100	0	0	0	392
10	20	300	88	0	0	100	0	0	0	408
11	22	300	100	0	37	100	0	0	55	385
12	25	300	100	0	5	100	0	0	60	420
13	23	300	100	0	98	0	0	95	60	420
14	20	300	100	0	17.5	0	0	0	57.5	402.5
15	14	300	100	0	22	0	0	0	56	392
16	10	300	100	0	0	0	0	0	30	410
17	8	300	100	32	0	0	0	0	0	440
18	0	300	0	355	0	0	0	0	0	655
19	0	300	0	340	0	0	0	0	0	640
20	0	300	0	330	0	0	0	0	0	630
21	0	300	0	300	0	0	0	0	0	600
22	0	300	0	290	0	0	0	0	0	590
23	0	300	0	250	0	0	0	0	0	550
24	0	300	0	250	0	0	0	0	0	550

5. Conclusion

This paper presented a mathematical model for optimizing microgrid operation considering DR programs based on TOU and EDRP. From simulation results, we found that a significant reduction of the operation cost can be gained by applying DR programs. By combining both TOU and EDRP, both customers and utilities also gain the benefit. In the view point of customers, they can receive an incentive from utilities by reducing their loads at the peak periods. By comparison, in the view point of utilities, they can reduce a significant operation costs.

Acknowledgements

This work was supported by the Power Generation & Electricity Delivery Core Technology Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea. (No. 20141020402350).

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