Economic Scheduling of Distributed Generators in a Microgrid Considering Various Constraints

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***Abstract*—This paper deals with the economic dispatch problem in a microgrid to provide the optimal power reference of distributed generators. The objective function and the constraints related to the operation of the microgrid are formulated and the solution method for the problem is introduced. The constraints for this problem include i) additional reserve requirement due to the uncertainty in the output of renewable resources, ii) flow limit between the control areas, and iii) additional reserve for the stable operation during the islanded mode. In order to examine the effect of the constraints on the generation cost, some numerical experiments are conducted.**

***Index Terms* — Microgrid, economic dispatch, distributed generator, direct search method**

I. INTRODUCTION

MICROGRID is a low or medium voltage distribution network comprising various distributed generators (DGs), storage devices, and controllable loads that can be operated in either grid-connected or islanded mode [1-2]. There are many research projects about the design, control, and operation of microgrid throughout the world, such as the CERTS microgrid in the USA [2-3], MICROGRID project funded by the European Commission [4], and new energy integration test project accomplished by the NEDO in Japan [5].

In order to increase the efficiency of the use of DGs and to achieve the full benefit from the operation of microgrid, many researches propose the central controller or energy management system (EMS) for the microgrid [4], [6-8]. They use various information such as the local electrical and heat demands, weather, price of electric power, fuel cost, power quality requirements, demand side management requests, and congestion levels to provide the following functions; to provide the power and voltage set point for each DG controller, to insure that heat and electrical loads are met, to insure that the microgrid satisfies operational contracts with the main power system, to minimize emissions and system losses, to maximize the operational efficiency of the DGs, and to provide logic and control for islanding and reconnecting the microgrid during events [2], [7].

This paper presents the formulation and the solution method for the economic dispatch problem to provide the optimal power reference of DGs in a microgrid. Firstly, various technical issues about the control and operation of microgrid are introduced. Secondly, various constraints related to the operation of microgrid are formulated, such as the spinning reserve requirement for the variation of load demand and the output of intermittent sources, the flow limit between the control areas, and the reserve for the stable operation in the islanded mode. Then, the direct search method is introduced as a solution method of the economic dispatch problem including the above constraints. Finally, the numerical experiments with 10 units system show the effect of the constraints on the generation cost.

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II. MICROGRID OPERATIONAL ISSUES

A. Hierarchical control architecture of the microgrid

A hierarchical control architecture proposed in [8] comprises three control levels: i) distribution management system (DMS), ii) microgrid central controller (MGCC), and iii) micro source and load controller (MC and LC). This section briefly describes the functions of each control level.

1) Distribution Management System: DMS deals with the management and control of distribution areas comprising several feeders including several microgrids. The traditional functions of DMS need to be enhanced with new features related to the operation of microgrids connected on the feeders and more generally to the operation with increased penetration of DGs.

2) Microgrid Central Controller: MGCC sends the control signals to GCs and LCs to maximize the microgrid value. To achieve that goal, MGCC generally performs the following functions:

- Electrical load and heat demand forecasting
- Economic scheduling including load shedding
- Security Assessment
- Demand side management functions

3) Micro Source Controller and Load Controller: MCs control the voltage and the frequency of the microgrid in transient conditions using local information. During the grid-connected mode, they follow the demands from the MGCC. When the system is islanded they have the autonomy to perform local optimization. LCs are installed at the controllable loads to provide load control capabilities following demands from the MGCC.

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B. Power control schemes of the distributed generators

Active Power and frequency control strategy of the microgrid mainly depends on the control scheme and the configuration of the DGs. In [3], two active power control schemes of DGs are proposed, such as the unit output power control (UPC) mode and the feeder flow control (FFC) mode. The UPC-mode DGs generate a constant active power according to the power reference, while the output of the FFC-mode DGs are controlled in order that the active power flow in the feeder remains constant. The principle of the UPC mode operation is simple to understand since it is almost the same as the synchronous generator. On the other hand, the FFC mode is more complicated since it is newly introduced with the advent of DGs. This section presents basic concept and the characteristics of the two control modes.

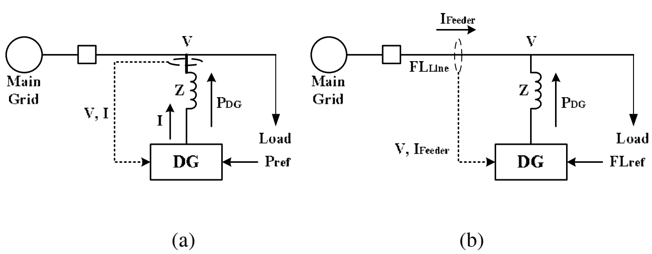

Fig. 1. Power control mode of DGs: (a) unit output control mode, (b) feeder flow control mode

1) UPC mode: The objective of this mode is to regulate the power injected by the unit to a desired value (P_{ref}) [3]. For this, the voltage (V) at the point where the unit is interconnected and the current (I) injected by the DG are measured as shown in Fig. 1 (a). The active power injected by the unit (P_{DG}) is calculated from the voltage and current, and fed back to the controller.

When the microgrid is connected to the main grid, the unit can hold its output power constant regardless of the variation of loads because the mismatches are compensated by the corresponding power injection from the grid. However, when the microgrid is disconnected from the main grid, i.e. the operation state of a microgrid changes to the islanded mode, DGs should participate in matching the power demand in place of the main grid. In many researches, the power vs. frequency (P – f) droop control is adopted in order that the DGs share the power demand [2-4]. If we assume that the droop is R, the frequency (f) and the active power output of a DG (P) can be determined as follows.

$$f' = f^0 - R\left(P' - P^0\right) \qquad (1)$$

2) FFC mode: In this control mode, the output power of a DG is controlled in order that the active power flow in the feeder where the unit is installed remains constant. When a load increases during the grid-connected mode, DG increases its output to maintain a constant feeder flow. Using this control mode, the power supplied from the grid will remain unchanged although the loads change inside the microgrid. Therefore, the microgrid looks like a controllable load from the utility point of view. For this mode, the voltage (V) at the unit is installed and the line current (I_{Feeder}) are measured to calculate the power flow in the feeder (FL_{Line}) as presented in Fig. 1 (b). The flow vs. frequency droop controller is also proposed for the power sharing of the FFC-mode DGs during the transition mode. In this controller, the droop constant has the same magnitude as the UPC mode with negative sign [3].

III. Economic Dispatch Problem In a Microgrid

The MGCC tries to minimize the total energy costs for the whole microgrid. The total cost includes the generation costs of DGs, the cost of the energy purchased from the main grid to supply the loads, and/or the profit provided by selling energy to the main grid [9]. When the market prices are high, which usually means the peak demand in the main grid, DGs should produce more power in order to minimize the global cost. In the opposite conditions, it is beneficial for the DGs to reduce the power output. However, when there are many DGs in a microgrid, it is very complicated to decide the optimal DG outputs to minimize the operation cost of the microgrid. Therefore, this section provides the formulation and the solution method for the optimal dispatch problem in a microgrid.

A. Configuration of the microgrid

The FFC-mode DGs can automatically follow the variation of load, thus the microgrid can be controlled as a true controllable load as seen from the utility side [2-3]. If there are more than two FFC-mode DGs in a microgrid, the microgrid can be divided into several control areas. Fig. 2 depicts the configuration of the microgrid used in this study. It consists of several control areas, where the variation of loads and the output of non-dispatchable DGs in each area are compensated by the DGs in the same area. For this, we assume that the first DG in each area is operated in the FFC mode while the others are operated in the UPC mode. In this configuration, any variation in an area can be compensated by the FFC-mode DG and the flow between the two successive areas remains unchanged during the predetermined time period.

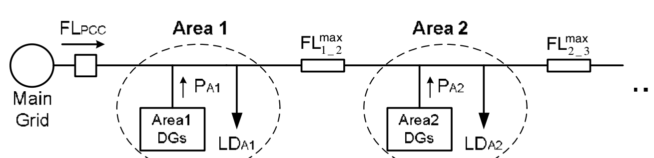

Fig. 2. Configuration of the microgrid with multiple control areas

B. Basic economic dispatch problem

The objective of the economic dispatch (ED) problem in the power system is to minimize the total generation cost while satisfying the power balance and generation limit of units, which can be formulated as follows [10]:

$$\min F_T = \sum_{g=1}^{N_{gen}} F_g(P_g) \tag{2}$$

subject to

$$\sum_{g=1}^{N_{gen}} P_g = \sum_{d=1}^{N_{load}} LD_d \tag{3}$$

$$P_g^{\min} \le P_g \le P_g^{\max} \tag{4}$$

where,

- g index of generation units
- d index of loads
- N_{gen} number of units
- $F_g(\cdot)$ cost function of unit g
- P_g generation of unit g
- N_{load} number of loads
- LD_d power demand of load d
- $P_g^{\max}$ maximum generation limit of unit g
- $P_g^{\min}$ minimum generation limit of unit g

C. *Constraints formulation*

The basic ED problem is extended to include the additional constraints related to the operation of a microgrid. The constraints implicated in this study are as follows:

- Reserve for the variation in load demand
- Reserve for the variation in the output of DGs with intermittent energy sources
- Flow limit between two successive areas
- Reserve for the stable operation in the islanded mode

1) Power balance constraints: The output of DGs with renewable energy sources such as photovoltaic (PV) cell and wind turbines (WT) is driven by weather, not by the loads of the system [3]. Therefore, these intermittent sources cannot be used as a dispatchable source. In the ED problem, these sources are dealt with as negative loads and the output of them is assumed to be predictable within some range of uncertainty. For this, the MGCC has to forecast the generation from the renewable power sources and heat demand as well as the power demand and electricity prices for every time step [11-12].

The power balance condition is modified as (5) considering the power output of the non-dispatchable sources and the power injected by the main grid.

$$\sum_{g=1}^{N_{gen}} P_g + FL_{PCC} = \sum_{d=1}^{N_{load}} LD_d - \sum_{k=1}^{N_{ND}} P_{ND_k} \tag{5}$$

where

- P_{NDk}, N_{ND} output power of non-dispatchable DG and the number of these units
- FL_{PCC} power injected by the main grid

2) Spinning reserve requirement constraints: There are normally uncertainties in the forecast of the load demand and the prediction of wind velocity and irradiance. Therefore, the load demand and the output of intermittent sources will vary continuously. In order to compensate the variations and operate the system stably, additional reserve on a system is necessary. In this paper, the increased up (or down) spinning reserve is calculated as a percentage of the predicted load and the output of the non-dispatchable sources. It is assumed that the load demand varies within *r%* of the forecasted value and the output of the non-dispatchable sources change within *u%* of the predicted value. If the up/down spinning reserve is shared by all dispatchable DGs in the area, the constraints can be formulated as follows [13].

$$USR_i = \sum_{g\in A_i} US_g \ge r\%\times \sum_{d\in A_i} LD_d + u\%\times \sum_{k\in A_i} P_{ND_k} \tag{6}$$

$$DSR_i = \sum_{g\in A_i} DS_g \ge r\%\times \sum_{d\in A_i} LD_d + u\%\times \sum_{k\in A_i} P_{ND_k} \tag{7}$$

where

- USR_i up spinning reserve requirement of area i
- DSR_i down spinning reserve requirement of area i
- US_g up reserve contribution of the dispatchable DG g
- DS_g down reserve contribution of the dispatchable DG g

In a microgrid with the proposed configuration, where all the variations in an area are picked up only by FFC-mode DG, the constraint formulation should be modified. The spinning reserve requirement is reflected as the decrease in the maximum limit and the increase in the minimum limit of the first DG in an area as presented in (8) and (9).

$$P_{i1} \le P_{i1}^{\max} - \left(r\%\times \sum_{d\in A_i} LD_d + u\%\times \sum_{k\in A_i} P_{ND_k} \right) \tag{8}$$

$$P_{i1} \ge P_{i1}^{\min} + \left(r\%\times \sum_{d\in A_i} LD_d + u\%\times \sum_{k\in A_i} P_{ND_k} \right) \tag{9}$$

3) Inter-area flow limit constraints: The additional constraints due to the limit of the inter-area flow can be formulated as (10) – (12). It is assumed that the number of areas in a feeder is 'n' in this formulation. As presented in (10), the power flow from/to the main grid can be defined as a decrease/increase in the load of the first area.

$$P_{A_1} = LD_{A_1} - FL_{PCC} + FL_{1\_2} \qquad for\ Area_1 \tag{10}$$

$$P_{A_i} = LD_{A_i} + FL_{i\_i+1} - F_{i-1\_i} \qquad for\ Area_i \quad i = 2,\cdots,n\text{-}1 \tag{11}$$

$$P_{A_n} = LD_{A_n} - FL_{n-1\_n} \qquad for\ Area_n \tag{12}$$

with

$$-FL_{i-1\_i}^{\max} \le FL_{i-1\_i} \le FL_{i-1\_i}^{\max} \qquad i = 2,\cdots,n \tag{13}$$

where

- P_{A_i} sum of power output of DGs in Area i
- LD_{A_i} sum of load demand in Area i
- FL_{i_j} transfer power from Area i to Area j
- $FL_{i\_j}^{\max}$ limit of the flow from Area i to Area j

The amount of power exchanged between the main grid and microgrid (FL_{PCC}) is restricted by the inter-area flow limit. From (5), (10), and (13), the maximum and minimum limit of the FL_{PCC} can be determined as follows.

$$LD_{A_1} - FL_{1\_2}^{\max} - \sum_{g\in A_1} P_g^{\max} \le FL_{PCC} \le LD_{A_1} + FL_{1\_2}^{\max} - \sum_{g\in A_1} P_g^{\min} \quad (14)$$

4) Constraints for the stable islanded mode operation: When a microgrid switches to the islanded mode, the increased/decreased power in each area is transmitted to the first (nearest to the main) area to compensate the loss of main. If the power flow in the inter-area line is remained near its maximum value during the grid-connected mode, then the power cannot be transmitted during the transition and it may make the system unstable. Some researches propose load shedding algorithm for the stable operation in case of the contingencies [4], [14]. However, this paper assumes that all the loads should be supplied by the DGs without the curtailment for the stable operation in the islanded mode. For this purpose, DGs should have the same amount of reserve as the power flow from/to the main grid (FL_{PCC}). Furthermore, the inter-area flow limit during the grid-connected mode should be decreased. The value of limit depends on the FL_{PCC} and the contribution of each area to the reserve. This section provides the formulation of constraint for the stable islanded mode operation.

During the transition, the power picked up by the unit g is proportional to the inverse of droop, R_g. Therefore, the contribution to the reserve of unit g (ΔP_g^{IM}) can be determined as follows.

$$\Delta P_g^{IM} = \frac{1/R_g}{\sum_{k=1}^{N_{gen}} 1/R_k} \times \left| FL_{PCC} \right| \quad (15)$$

The amount of power shared by area i (ΔP_{Ai}^{IM}) can be calculated by the sum of the contributions of all units in area i as follows.

$$\Delta P_{A_i}^{IM} = \frac{\sum_{g\in A_i} 1/R_g}{\sum_{k=1}^{N_{gen}} 1/R_k} \times \left| FL_{PCC} \right| \quad (16)$$

The constraints can be formulated differently whether the power is initially imported from or exported to the main grid. When the microgrid supplies power to the main grid during the grid-connected mode, DGs will decrease their output during the transition. Therefore, all DGs should have additional down spinning reserve and it can be reflected as the increase in the minimum limit of the unit g as follows.

$$P_g^{\min} + \Delta P_g^{IM} \le P_g \le P_g^{\max} \quad (17)$$

Since DGs decrease their output, the downward flow between areas will be increased during the transition. Therefore, in order not to exceed the inter-area flow limits during the islanded mode, the downward flow should be maintained at sufficiently lower than the limit during the grid-connected mode. The additional flow from area *i–1* to area *i* is the sum of the contribution to the reserve of area *i* and its downward areas. Accordingly, the downward flow limit should be decreased by the amount of additional flow, whereas the upward flow limit remains unchanged.

$$-FL_{i-1\_i}^{\max} \le FL_{i-1\_i} \le \left(FL_{i-1\_i}^{\max} - \sum_{a=i}^{n} \Delta P_{A_a}^{IM} \right) \quad i = 2,\cdots,n \quad (18)$$

On the contrary, if the power is imported from the main grid during the grid-connected mode, DGs will increase their output when it is disconnected from the main grid. As opposite to the former case, DGs should have additional up spinning reserve and the upward flow will be increased in the inter-area lines. Therefore, the maximum limit of unit g should be decreased and the upward flow limit should be decreased as follows.

$$P_g^{\min} \le P_g \le P_g^{\max} - \Delta P_g^{IM} \quad (19)$$

$$-\left(FL_{i-1\_i}^{\max} - \sum_{a=i}^{n} \Delta P_{A_a}^{IM} \right) \le FL_{i-1\_i} \le FL_{i-1\_i}^{\max} \quad i = 2,\cdots,n \quad (20)$$

D. Solution Method

Various mathematical approaches and optimization techniques have been developed as the solution method of ED problem. Ref [15] proposes an algorithm for the ED problem with transmission constraints. The algorithm is called Direct Search Method (DSM) and applied to the ED problems with various constraints, such as wind-thermal coordination dispatch and generation-reserve dispatch [13], [16-17]. The attractive properties of the DSM are as follows:

- The algorithm is very simple and easy to implement;
- Various inequality and equality constraints can be included;
- It can handle various kind of fuel cost functions even non-differentiable one.

In this study, the DSM is modified to solve the ED problem in a microgrid considering various constraints presented in the previous section. The solution procedure of the DSM can be summarized as follows [15].

Step 1) Estimate a feasible initial solution with a simple procedure based on average full load cost.

Step 2) Calculate the incremental costs and decrement costs of the units without violating the maximum or minimum limits by increasing or decreasing their outputs by the predetermined step ΔP.

Step 3) A unit with minimum incremental cost (assume unit *i*) is selected to increase its output by ΔP, and a unit with maximum decrement cost (assume d, $d \neq i$) is selected to reduce its output for satisfying the load balance equation.

Step 4) Only the incremental cost of unit i and the decrement cost of unit d are recalculated if they do not violate their maximum or minimum limits.

Step 5) Examine all units to check the convergence. If no improvement can be achieved, i.e. the minimum incremental cost is larger than the maximum decrement cost, then, stop the procedure; otherwise, go to step 3.

IV. Numerical Experiments

To examine the effect of the constraints on the generation cost, a 10 unit test system is used [16]. Because it is very difficult to get the cost data of the new energy sources, the cost function of the conventional power units are used in this study. Although the ratings of the conventional units are higher than those of typical DGs, the algorithm can be verified without limiting the generality. The power output limits and the cost data are listed in Table I. The cost function of the units is assumed for the simplicity to be a quadratic function as follows.

$$F_g\left(P_g\right) = a_g + b_g \times P_g + c_g \times P_g^2 \qquad (21)$$

TABLE I
THE 10 UNITS SYSTEM DATA

DG	Cost data			Output limit	
	a_g	b_g	c_i	P^{max}	P^{min}
G1	15	2.2034	0.0051	60	10
G2	25	1..9161	0.00396	80	20
G3	40	1.8518	0.00393	100	30
G4	32	1.6966	0.00382	120	25
G5	29	1.8015	0.00212	150	50
G6	72	1.5354	0.00261	280	75
G7	49	1.2643	0.00289	320	120
G8	82	1.2163	0.00148	445	125
G9	105	1.1954	0.00127	520	250
G10	100	1.1285	0.00135	550	250

For the test, we divide the test system into three areas. The units and the load demand of each area are as listed below. The first unit in each area is assumed to be operated in the FFC mode. The load demands are expressed as a percentage of the total demand.

- Area 1: units = G9, G1, G5 and load = 25%
- Area 2: units = G10, G2, G7 and load = 40%
- Area 3: units = G8, G3, G4, G6 and load = 35%

A. *Scenario 1 – Effect of load variation and flow limit*

In the first test, we investigate the effect of the inter-area flow limit and the reserve for variation of load on the generation cost. The generation cost is calculated under various conditions of load level, reserve requirement, and inter-area flow limits. Fig. 3 shows the results according to various reserve requirement and inter-area flow limit at the load level of 2200 MW. In this test, we assume that 100 MW power is imported from the main grid.

The cost increases as the flow limit becomes smaller because the units with higher cost have to increase their output due to the flow limit. In the test system, the load demand in area 1 is relatively lower than other areas. Therefore, it is more efficient that the power generated in area 1 is transmitted to the other areas. However, when the inter-area flow is limited, the units in area 2 and 3 with higher incremental cost increase their output. Accordingly, the total generation cost becomes larger.

The cost also increases as the 'r' becomes larger, i.e. the reserve requirement for the load variation increases. It is because the outputs of the FFC-mode DGs, which have lower cost, are restricted to provide the reserve for the load variation.

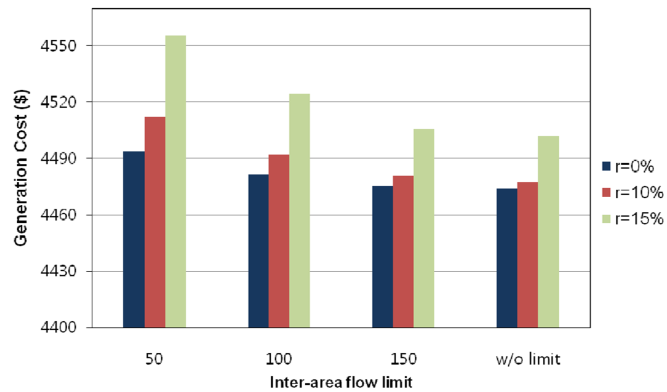

Fig. 3. The generation cost according to the various reserve requirements and inter-area flow limits

B. *Scenario 2 – Effect of reserve for the stable islanded mode operation*

This simulation examines how the reserve for the islanded operation affects the generation cost by calculating the cost under various load levels and the amount of power from the main grid. In this test, the inter-area flow limit is selected to 50 MW arbitrarily. The simulation results with various conditions are summarized in Table II. In this test system, the cost increases due to the additional reserve when the microgrid exports power to the grid while the cost is almost unchanged when the power is imported from the grid.

TABLE II
EFFECT OF THE RESERVE FOR THE ISLANDED MODE OPERATION

Load (MW)	FL_{PCC} (MW)	Generation cost ($)	
		w/o reserve	with reserve
1800	-100	4002.00	4004.63
	-50	3886.98	3889.20
	0	3774.96	3774.96
	50	3666.90	3666.90
	100	3562.82	3562.82
2000	-100	4473.71	4478.08
	-50	4354.53	4357.63
	0	4238.66	4238.66
	50	4126.63	4126.63
	100	4018.58	4018.91
2200	-100	4964.18	4971.24
	-50	4840.98	4845.38
	0	4721.65	4721.65
	50	4605.78	4605.82
	100	4493.75	4494.75

To understand the effect more deeply, we will analyze the results of two cases at the load level of 2000 MW: i) 100 MW power is imported from the main grid and ii) the microgrid exports 100 MW power to the grid.

Fig. 4 shows how the generation pattern and the inter-are flow change when considering the reserve. When the power is imported, the optimal power output of each area is 450, 725.8, and 724.2 MW, respectively (see Fig. 4 (a)). If the reserve is considered, the dispatch pattern of the units in area 2 and 3 change slightly because the upward flow limit between area 2 and 3 is reduced to 8.7 MW. On the contrary, the generation pattern in the area 1 is unchanged because the downward flow limit is not changed. Therefore, the generation cost is almost unchanged although the constraint is included.

When the power is exported, the optimal power output of each area without considering the reserve is 637.8, 731.4, and 730.8 MW, respectively as shown in Fig. 4 (b). If the reserve is considered, the power flow from area 1 to area 2 is restricted to -24.9 MW. This means the units in area 1 with relatively lower cost should reduce the output for the stable operation in the islanded mode. Instead, the units in area 2 and 3 have to increase the output by about 43 and 19 MW, respectively. These changes in the dispatch pattern increase total generation cost.

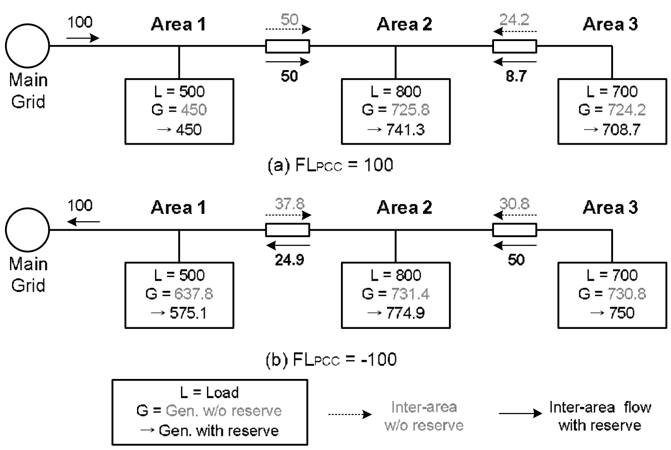

Fig. 4. Change in the generation of each area and the inter-area flow: (a) power is imported from the grid, (b) microgrid exports power to the main grid

V. Conclusion

This paper presented the formulation and the solution method for the economic dispatch problem considering various constraints related to the operation of the microgrid. Some constraint formulations are modified to be suitable for the microgrid and the formulation of the constraint related to the stable operation in the islanded mode is also proposed. The simulation results using 10 units test system show the effect of constraints on the generation cost. The cost increases as the flow limit becomes smaller and the reserve requirement for the load variation increases. The cost also increases due to the additional reserve for the stable islanded mode operation, but it depends on the configuration of the microgrid and whether the power is imported from or exported to the grid. With the proposed algorithm, we can operate the microgrid economically during the grid-connected mode as well as maintain the stability during the islanded mode.

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