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Operation Planning of Reserve in Microgrid Considering Market Participation and Energy Storage System

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Abstract – Innumerable microgrids would be operated independently by individual operators in a future smart grid. This kind of decentralized power system requires entirely different operation scheme in the actual power system and electricity market operation. Especially, frequency regulation is very important for successive energy trade in this multi-microgrid circumstance. This paper presents an optimal energy and reserve market participation strategy and operation strategy of energy storage system (ESS) by a microgrid operator (MGO). For definite evaluation of the proposed strategy, we postulate that the MGO should participate in the Power Exchange for Frequency Control (PXFC) market, which was devised by Maria Ilic and her coworkers and is suitable to the decentralized operation circumstances. In particular, optimal reserve capacity of the frequency control market and optimal market participation ratio of ESS between frequency control market and energy market are derived theoretically and evaluated by simulations utilizing Nordic Pool Elspot price data.

Keywords: Ancillary service market, Decentralized operation, Electricity market deregulation, Energy storage system, Multi-microgrid operation

1. Introduction

Distributed generators (DGs) have been growing their portion in the distribution system more and more [1-2]. Although these kinds of resources, which are represented by renewable generators like wind turbines and photovoltaic systems, are more environmentally friendly and economical than traditional fossil fuel, it has been pointed out that there may be a problem in the appearance of the decentralized generation by many DGs [3]. It is microgrid concept that is intensively studied nowadays to handle this decentralized operation circumstances [4-6]. A microgrid is an electric distribution system which consists of small subsystems with many generation facilities and associate loads, and energy storage system (ESS). It could be operated intentionally in the islanded mode, disconnecting from the main grid and securing energy by running its own DGs or ESS and issuing demand response or load shedding programs.

As electricity market has been established and expanded its domain into ancillary service market like automatic generation control (AGC), market diversity in multi-microgrid circumstance would increase much more. And roles, responsibilities, and rights of a MGO would be much larger than that of load serving entity (LSE), who is a decentralized market agent in the present power system operation [7-9]. In a normal condition of being connected to the main grid, a MGO could get the energy from the main grid and sell the extra power generated by renewable resources to increase the benefit from the market. In the islanded operation mode, however, MGO must supply the demand by itself and maintain some proper level of reliability of its system. For this reason, the role of ESS in microgrid has been emphasized in many researches [10].

This paper focuses on the operation planning of reserve in microgrid considering market participation and ESS operation. The objective is to minimize the total operation cost. In particular, optimal participation ratio between ancillary service market and energy market is derived with the optimal microgrid operation scheme theoretically and evaluated by a simulation. For the definite evaluation of the proposed strategy, the Power Exchange for Frequency Control (PXFC) market, which was devised by Maria Ilic and her coworkers [11] and appropriate for the multi-microgrid circumstances, is postulated as a mandatory market in this paper. This market consists of two sub-markets: a primary energy market for supplying the demand and a frequency control market for ensuring that frequency fluctuation remains within the limits as load and renewable power deviate from its anticipated value.

This paper is structured as follows. Section 2 explains the postulated market scheme, PXFC, and the decision variable of MGO in the PXFC market. Section 3 details the proposed optimal operation strategy of MGO. Its simulation and verification is presented in section 4 with the conclusion drawn in section 5.

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2. Decentralized Operation Circumstances

In several recent references [12-14], it has been suggested that each system participants, like generation owners (GOs) and load serving entities (LSEs), should control their own frequency and only minimal frequency control have to be provided by independent system operator (ISO). The condition would become more serious in the decentralized operation circumstances, in which various types of agents including many MGOs exist. PXFC satisfies the above condition and is appropriate for the decentralized power system operation concept of multi-microgrid [11]. In the following subsections, more details about PXFC and decision variables given to MGO in PXFC are handled.

2.1 Power exchange for frequency control

In the PXFC, all the contracts on the daily market should specify the two quantities; the anticipated demand, $P_{L,i}^{A}$, as a function of time, and an estimation of the maximum deviation from the anticipated value. Fig. 1 shows a representative contract curve in PXFC. Each participant would specify a non-zero band $P_{band,i}$ and ISO or a coordinator of the PXFC estimate the maximum cumulative power mismatch by using this information. By this estimation ISO can decide how much power to purchase for frequency control from the generators participating in frequency control service.

The maximum cumulative imbalance on the system can be estimated by

$$P_{imb} < \sum_{i} P_{band,i} = P_{\max,imb} \tag{1}$$

where P_{imb} is the total cumulative imbalance on the system. A simple and safe strategy for ISO is to purchase $P_{\max,imb}$, which is sufficient even in the worst case scenario, but a smart ISO could decrease the purchase quantity by considering the participants' characteristics. If the unit clearing price for frequency control is given by λ_{FC} and there are m contracts, the reasonable charge to each participant for frequency control will be proportional to the size of $P_{band,i}$ and given by

$$FC_i = (m \cdot \lambda_{FC})\left(P_{band,i} / \sum_{j} P_{band,j} \right) \tag{2}$$

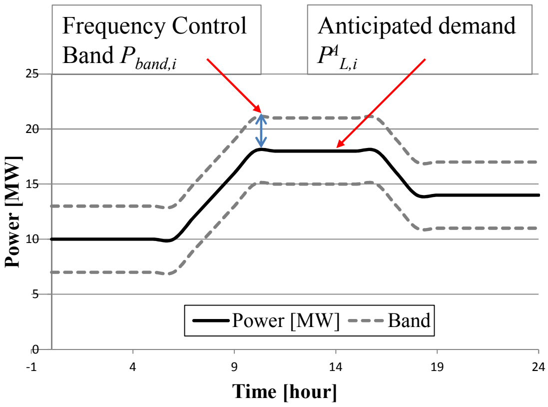

Fig. 1. Proposed structure of a contract in PXFC market

This charge is imposed on each participant, and the total amount of money paid to the coordinator of PXFC is

$$\sum_{i} FC_i = m \cdot \lambda_{FC} \tag{3}$$

This value is equal to the amount paid by the PXFC coordinator to the AGC generator owner.

2.2 Decision variable of MGO in PXFC

The incurred cost in PXFC market consists of three parts: the energy cost in the primary market, the band cost in frequency control market, and the penalty cost related with band contract. Each MGO will make a decision to minimize its operation cost from these three parts. However, there is no clear answer in [9] and it just mentions the necessity of penalty in the case of violation that actual deviation exceeds the contracted band capacity. For evaluating the operation cost of participant, the penalty cost $\lambda_p \cdot E_p$ is imposed to each violator in this paper. λ_p may be the unit penalty price, which should be included in the contraction of PXFC market. E_p is the statistical data related with the accumulation of exceeded capacity and duration. A detailed method of calculating the penalty cost will be discussed in section 3.

Therefore MGO could determine the optimal band capacity to minimize the operation cost, which include the band purchase cost and expected penalty cost. And if MGO have ESSs in its grid, then they can participate in both the primary electricity market and the frequency control market. In each case ESS can change the value of P_L^c or P_{band} , and affect the total operation cost. So MGO could determine the optimal participation ratio of ESS between these two markets considering with the optimal band capacity.

3. Optimal Operation Strategy by MGO

3.1 Determination of optimal band capacity

As mentioned in the subsection 2.2, a MGO should calculate the expected value of penalty cost first to determine the optimal band capacity of minimizing its operation cost. And variability model of the microgrid have to be built to formulate and analyze the penalty cost. Therefore, MGO not only forecasts the quantity of load and renewable generation to bid optimally in the primary energy market, but also analyzes the uncertainty of them to bid optimally in the frequency control market. For example, the MGO could predict the quantity and variability of wind generation using well-known Weibull distribution in Fig. 2 [15]. Variability model could be formulated as follows

$$\Delta P(t) = \Delta P_{Load}(t) + \Delta P_{WT}(t) + \Delta P_{PV}(t) \tag{4}$$

where $\Delta P_{Load}(t), \Delta P_{WT}(t), \Delta P_{PV}(t)$ are uncertainties from load, wind and PV generators. $\Delta P(t)$ is the total uncertainty, which denotes the difference between actual value and anticipated value. Therefore the expected value of penalty cost can be calculated as follows

$$C_p = 2 \cdot \int_{P_{band}}^{\infty} \left\{ P_{DF}(\Delta P) \cdot \lambda_p (\Delta P - P_{band}) \right\} d\Delta P \tag{5}$$

where C_p is the expected penalty cost, P_{DF} is the probability density function (PDF) of ΔP, P_{band} is the purchased band capacity, and λ_P is the penalty cost per unit [\$/MW]. Multiplying 2 by the integration means that violation could happen in both up and down direction. Fig. 3 shows probabilistic meaning of Eq. (5).

To analyze the optimal band capacity, total cost can be calculated by adding the penalty cost and the band cost FC as below

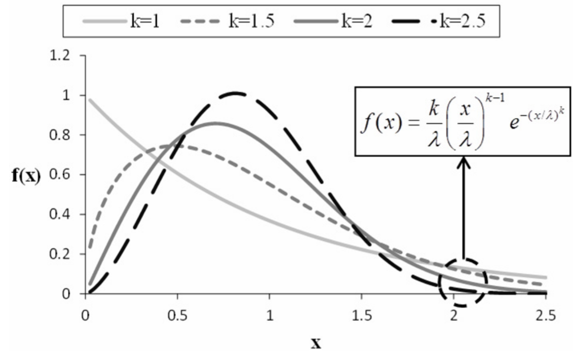

Fig. 2. Weibull distribution utilized in weather forecasting

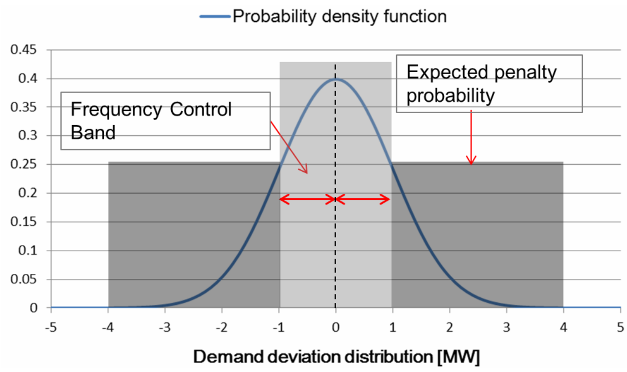

Fig. 3. Variability distribution curve with frequency control band and expected penalty probability

$$\begin{aligned} C_{tot,i} &= C_{p,i}(P_{band,i}) + FC_i(P_{band,i}) \\ &= \left[2 \cdot \int_{P_{band,i}}^{\infty} \left\{ P_{DF}(\Delta P_i) \cdot \lambda_p (\Delta P_i - P_{band,i}) \right\} d\Delta P_i \right. \\ &\qquad \left. + m\lambda_{FC} \cdot \left(P_{band,i} / \sum_j P_{band,j} \right) \right] \end{aligned} \tag{6}$$

Then, optimal band capacity can be calculated by differentiating the $C_{tot,i}$ by $P_{band,i}$. If the MGO would have forecasted the quantity of demand and renewable generation well, then it is reasonable to assume that the P_{DF} have the mean value of zero. Actually differentiating $C_{tot,i}$ by $P_{band,i}$ is a laborious task, since P_{DF} follows the probability distribution with complicated form. For the sake of calculation simplicity, optimal band capacity condition using the normal Gaussian distribution function is given in Eq. (7). However, this equation will also derive a very complex solution form of Gaussian error function even in the case of simple normal Gaussian distribution function.

$$2 \cdot \int_{P_{band,i}}^{\infty} \left\{ P_{DF}(\Delta P_i) \cdot \lambda_p \right\} d\Delta P_i = m\lambda_{FC} / \sum_j P_{band,j} \tag{7}$$

3.2 Optimal operation of ESS in energy market

Mathematical models for ESS operation are selected from [16] to analyze the operation cost and the sequential quadratic programming (SQP) method is applied to achieve the maximum benefit. Used model and assumptions are described in the following.

3.2.1 ESS model and assumption

If the output power of ESS is selected as a state variable, then the stored energy could be calculated from the sum of that output power. Since it is generally assumed that hourly spot price is given, time step used in the operation of ESS is one hour. The stored energy can be expressed as

$$\begin{cases} E_{t+1} = E_t + \eta P_t, \ when\, charging \\ E_{t+1} = E_t + \eta P_t, \ when\, discharging \end{cases} \tag{8}$$

where P_t is the output power of ESS at hour t, η is the efficiency of charging/discharging, and E_t is the stored energy in ESS at hour t. Some assumptions related with the ESS are below.

There are maximum charging/discharging power and maximum energy capacity of ESS.

$$\begin{gathered} -P_{\max} < P_t < P_{\max} \\ 0 < E_t < E_{\max} \end{gathered} \tag{9}$$

The stored energy in the ESS at 00:00 hour is the same with the stored energy at 24:00 hour.

$$E_0 = E_{24} \tag{10}$$

The hourly system price is not changed by the operation of the ESS.

3.2.2 Problem formulation

Since the hourly day-ahead system price is given, MGO can decide the charging schedule in order to maximize the profit. The profit in a day can be calculated as follows

$$PF(P_{\max}) = \sum_{t=1}^{24} P_t \cdot \lambda_{DA_t} \tag{11}$$

where PF is the profit of the ESS, and λ_{DA_t} is the given hourly day-ahead price. Therefore, the objective function for the maximum profit scheduling of ESS can be written as

$$\max\left\{PF(P_{\max})\right\} = \max_{P_t}\left(\sum_{t=1}^{24} P_t \cdot \lambda_{DA_t}\right) \tag{12}$$

3.3 Optimal operation strategy considering both band capacity and ESS capacity

In subsection 3.2 MGO could get the profit by ESS scheduling, as considering the hourly system price. However, ESS also could have a role of P_{band} in subsection 3.1 and this could decrease the band cost and expected penalty cost. Therefore, MGO should determine the optimal participating ratio of ESS between energy market and frequency control market as below

$$\begin{cases} P_{bid} = \alpha \cdot P_{\max} \\ P_{bd,ESS} = (1-\alpha) \cdot P_{\max} \end{cases} \tag{13}$$

where P_{bid} is the ESS capacity of participating in energy market and α is the ratio of it, and $P_{bd,ESS}$ is the ESS capacity of participating in frequency control market. In this case, final objective function can be expressed by adding Eq. (6) by Eq. (11) as follows

$$C_{tot,i}(P_{band,i}, \alpha) = C_{p,i}(P_{band,i} + \frac{P_{bd,ESS}}{2}) + FC_i(P_{band,i}) + PF_i(P_{bid}) \tag{14}.$$

Final optimal solution of P_{band} and α, or P_{bid} and $P_{bd,ESS}$, can be calculated by differentiate the Eq. (13). However, the solution will have more complex form than Eq. (7), and formulation of this equation is very hard to find any meaning on it. Therefore, iteration between the optimizing method in subsection 3.1 and 3.2 is utilized to get the optimal solution of P_{band} and P_{bid}. Flow chart of the utilized iteration method, which is based on the bisection method, is represented in Fig. 4.

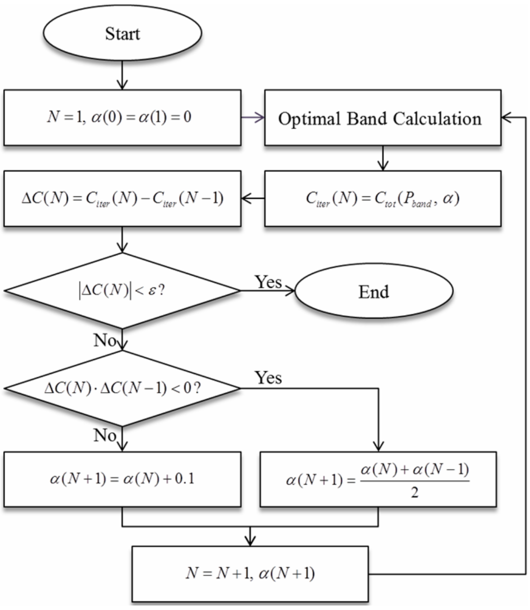

Fig. 4. Flow chart of the iteration method

4. Simulation and Verification

4.1 Simulation settings

The proposed optimal strategies by MGO are simulated and verified by Matlab/Simulink. Elspot system prices of Nordic Pool on 01-04-2013 and 26-04-2013 are selected for the hourly day-ahead system price, which is necessary for the optimal scheduling of ESS. Furthermore several assumptions are added to support yet non-existent PXFC Market and simplify the problem. The coefficients or unit prices of band purchase cost, FC_i, are assumed to have the average value of the Elspot system prices and there is no price difference between up band and down band. And unit price of penalty cost is assumed to be a constant, which is about 5 to 10 times of Elspot prices. Because AGC prices have positive correlation with the system marginal price and penalty price would happen only when there is some faults in the system, these two assumptions

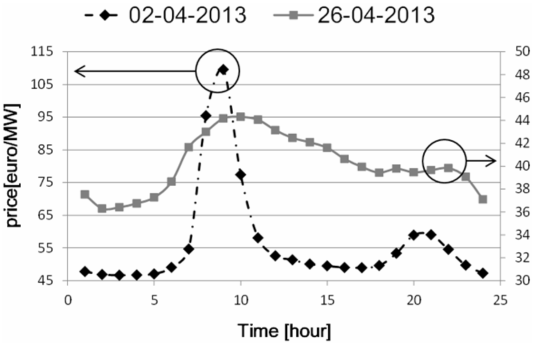

Fig. 5. Hourly system prices of Elspot on 02-04-2013 and 26-04-2013

are reasonable to some extent. In addition to this, P_{DF}, the probability density function (PDF) of ΔP, is assumed to follows the Gaussian distribution with the mean value of zero and the standard deviation of it is to be 10 MW. Elspot system price data is in Fig. 5 and used setting values including load deviation model and ESS characteristics are in Table 1.

Table 1. Simulation setting data

	Category	Value
Common Data	Standard deviation of load deviation (σ)	10 MW
	Unit price of penalty cost(λ_P)	500 euro/MW
	Maximum power capacity of ESS	2 MW
	Maximum energy capacity of ESS	5 MWh
03-04-2013	Unit price of band ($m\lambda_{FC} / \sum P_{band,j}$)	56.4 euro/MW
26-04-2013		40.2 euro/MW

4.2 Optimal band capacity without ESS

The simulation results of optimal band capacity without ESS are shown in Table 2. The optimal band capacity is calculated from Eq. (7). Since case 1 has larger average price, the unit price of band on 02-04-2013 is higher than that on 26-04-2013. As a result, MGO can purchase larger band at cheaper price and have less expected penalty cost on 26-04-2013. To check the optimality of the results in case 2, two more cases are simulated. Results of case 3 have lower band cost, but have higher expected penalty cost. This is because band capacity is not enough and means that MGO would have more probability to pay large penalty cost than case 2. On the contrary to this, results of case 4 have higher band cost and lower expected penalty cost. This means that MGO will overpay the band cost.

Table 2. Optimal band capacity without ESS

	Category	Value
Case 1 (02-04) Optimal band	Band capacity	0.9 MW
	Band cost	50.7 euro
	Expected penalty cost	136.6 euro
	Total cost	187.3 euro
Case 2 (26-04) Optimal band	Band capacity	2.0 MW
	Band cost	80.4 euro
	Expected penalty cost	80.9 euro
	Total cost	161.3 euro
Case 3 (26-04) Insufficient Band	Band capacity	1.0 MW
	Band cost	40.2 euro
	Expected penalty cost	130.6 euro
	Total cost	170.8 euro
Case 4 (26-04) Excessive band	Band capacity	3.0 MW
	Band cost	120.5 euro
	Expected penalty cost	47.5 euro
	Total cost	168.0 euro

4.3 Optimal band capacity with considering the operation strategy of ESS

Applying the iteration method in subsection 3.3, final optimal solution of P_{band} and P_{bid} can be calculated. Table 3 shows the optimal solutions of case 1 and 2. All of the ESS capacity in case 1 participate in the primary energy market and the MGO has negative total cost, or produces a profit by ESS. This is because the peak price on that day is very severe. For this case, frequency control is conducted by only P_{band}. Fig. 6 shows the hourly system price and state of charge of ESS in case 1.

In case 2, only 15% of ESS capacity participate in the primary energy market and the remaining 85% play a role like frequency control band. As a result band cost in frequency control market is smaller than that of case 1. It is the difference of system price pattern that makes totally different bidding strategy. In other words, as system price of case 2 has flatter shape and larger average value or unit price of band, arbitrage trading of ESS in case 2 shows lower profit margin. And the reduction in expenditure is much more effective than the increase in income in minimizing the total operation cost.

Results above show that the optimal operation of MGO should be changed to maximize its benefit if the system

Table 3. Optimal band capacity and operation strategy of ESS minimizing total operation cost

	Category	Value
Case 1 (02-04-2013)	Optimal band capacity	1.1 MW
	ESS bidding	2.0 MW (100%)
	Benefit by ESS	298.7 euro
	Band cost	62.0 euro
	Expected penalty cost	124.8 euro
	Total cost	-111.9 euro
Case 2 (26-04-2013)	Optimal band capacity	0.3 MW
	ESS bidding	0.3 MW (15%)
	Benefit by ESS	11.8 euro
	Band cost	12.0 euro
	Expected penalty cost	80.9 euro
	Total cost	81.1 euro

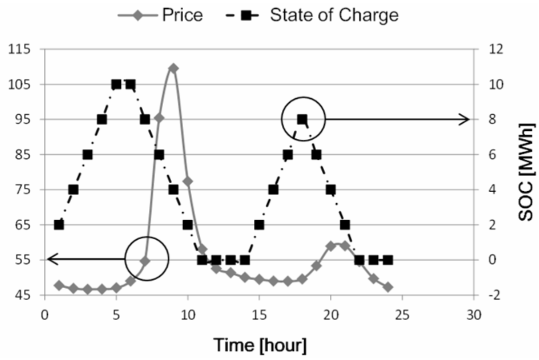

Fig. 6. Hourly system price and SOC of ESS on 02-04-2013

or market condition varies. Therefore proposed operation strategy could be applied to numerous MGOs in decentralized and deregulated market condition and give some flexibility to them.

5. Conclusion

Deregulation and decentralization in the power system inevitably require new operation scheme, and microgrid concept would be a proper solution. Innumerable microgrid operators would share their roles, rights and respobsibilities with ISO in many parts of system operation. And ESS, which can play many important roles in the grid, would demonstrate its ability increasingly in this circumstance.

This paper focuses on the method for minimizing the operation cost of MGO in decentralized operation scheme of PXFC market. For this purpose, optimal band capacity is acquired by calculating the expected penalty cost and band purchase cost, and optimal market participation of ESS is attained by using the SQP method. By the proposed method, MGO could develop an optimal operation strategy considering daily system condition such as system marginal price and load deviation and renewable uncertainty characteristics. And this is demonstrated by using the Elspot system price data of Nordic Pool in section 4. Different operation strategies are compared on two days in which system price shows totally different pattern.

Further researches are necessary to handle more realistic market circumstances, in which unit band price and penalty price have time varying characteristics.

Acknowledgements

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