

Article

Optimal Operation Method for Distribution Systems Considering Distributed Generators Imparted with Reactive Power Incentive

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Featured Application: The incentive method with flexible contribution functions can be applied to demand response by the reactive power market and distribution company, which has the possibility to reduce the additional installation of distribution control equipment and battery capacity. It also leads to the reduction of total electricity purchase cost of consumers, and the power system can achieve high mixing of renewable energy in the grid with the reactive power incentive demand response and the IoT development. Furthermore, reliability assessment of cooperative control with the participation rate will give an important contribution to the robust design of the system.

Abstract: In order to solve urgent energy and environmental problems, it is essential to carry out high installation of distributed generation using renewable energy sources (RESs) and environmentally-friendly storage technologies. However, a high penetration of RESs usually leads to a conventional power system unreliability, instability and low power quality. Therefore, this paper proposes a reactive power control method based on the demand response (DR) program to achieve a safe, reliable and stable power system. This program does not enforce a change in the active power usage of the customer, but provides a reactive power incentive to customers who participate in the cooperative control of the distribution company (DisCo). Customers can achieve a reduction in their total energy purchase by gaining a reactive power incentive, whilst the DisCo can achieve a reduction of its total procurement of equipment and distribution losses. An optimal control schedule is calculated using the particle swarm optimization (PSO) method, and also in order to avoid over-control, a modified scheduling method that is a dual scheduling method has been adopted in this paper. The effectiveness of the proposed method was verified by numerical simulation. Then, simulation results have been analyzed by case studies.

Keywords: reactive power incentive; BESS; reactive power control; PSO; dual scheduling; renewable energy sources; distributed generator; distribution system

1. Introduction

The world energy demand has been increasing exponentially while conventional energy resources are exhaustible and limited in supply. Therefore, there is an urgent need to conserve the energy resources that are at hand and explore alternative energy resources. Among the various types of renewable energy sources (RESs), solar and wind energies are the most promising sources. Recently, the use of RESs in the form of distributed generators (DGs) and distributed energy systems (DESs) [1] has increased with the aim of an environmentally-friendly society. Moreover, these DGs can supply energy in an isolated situation [2–4]. However, RESs output is influenced by weather uncertainty, causing voltage deviation, fluctuation and reverse power flow under a high penetration of DGs using RESs [5]. The conventional provisional method for voltage fluctuation is often handled by the use of an on-load tap changer (OLTC) transformer such as the load ratio transformer (LRT) and the step voltage regulator (SVR). This method is only effective for slow changes in voltage by switching the primary and secondary winding ratios of the transformer. Thus, this method cannot maintain the voltage well because steep voltage fluctuations are the nature of the DGs. In addition, voltage regulation by OLTC has not reached a fundamental solution for power quality considering the power factor. As a countermeasure to this problem, the use of reactive power controllers, such as additional static VAR compensators (SVCs) [6–11] or the reactive power control system by the inclusion of an inverter with distributed generators [12–18] has been proposed. The literature [19] has discussed rapid and precise tap control online. Another proposed reactive power control improves voltage maintenance and the utilization rate of equipment of the system, which is utilizing the empty area of inverter capacity of an interfaced inverter of an RES generator and battery energy storage system (BESS) [20]. Thus, reactive power compensation methods can be categorized into two types, which are the use of devices at the distribution company (DisCo) side or utilizing the customer side inverter. In particular, using an introduced large capacity BESS at the substation and reactive power output from customer DGs avoids reverse power flow and voltage fluctuation.

An increase in demand and a massive installation of RES with uncertainty frequently causes an imbalance in the power system within hours. It is essential to improve forecasting techniques to solve the imbalance of demand and supply, but prediction accuracy cannot always be raised to 100%. Thus, in order to resolve power imbalance with RESs, the BESS has been installed and operated based on optimal scheduling in several areas. Scheduling of the distribution system has been proposed in much of the literature [21–24]. In addition, power quality such as the power factor has been improved by the reactive power control method using an interfaced inverter of BESS. The BESS can be introduced to the power system to compensate for power quality loss and fluctuations in voltage and frequency [25,26]. With the increase in the expectation of battery utilization to overcome all variations of RES output, the introduction cost becomes large, and the battery has to be introduced into various places according to DG load points. With the increase of batteries, the cost of the interfaced inverter tends to increase. In this trade-off relationship, it is required to optimize the capacity or capacity reduction of the storage battery.

Along with the limitation of control from the upper system, hence, it is proposed to obtain the balance that is controlling and regulating a load demand as the demand response (DR) [27], and the non-cooperative game has been analyzed in the literature [28]. Providing various pricing scheme (e.g., time of use (TOU), real-time pricing (RTP)) means it consciously changes the net load usage and intentionally levels the active power profile of the customers in the DR program. Furthermore, ancillary services of DR secure reserve power, which is effectively supported by battery storage from power security. In order to reach an effective use of BESS and renewable DGs, distributed energy resources management systems (DERMSs) provide the management matching system requirement for a sustainable society associated with the smart meter on the customer side [29]. The DR might be incorporated in the DERMS. The DR mainly brings benefits to the power company such as the generation company (GenCo) and distribution company (DisCo), so it is not for the customers. By optimizing the operation using the smart meter, some users can reduce power purchase cost.

A participative DR program affects electricity consumption; however, this means some options of the program (e.g., interruptible load, load shedding) force one to change the usage of the power schedule. The customer feels dissatisfied with suppressed power consumption by pricing or other DR programs.

Based on the above recent activity regarding the power system, we will summarize the issues considered in this research as follows:

1. Technical issues related to high penetration of RES (voltage deviation and reverse power flow)
2. Cost increase due to increased controllers and storage battery for voltage control and surplus power absorption.
3. Issues for the DR program; increase in dissatisfaction with small demand response due to price change and compulsory DR.

Proposing a balanced system construction is important while securing the benefits of both DisCo and consumers.

Contributions and Structure of This Paper

Recently, the use of customer-side inverter compensation methods has been shown to be more economical in comparison with the installation of additional SVC devices due to the high penetration of DGs and inverters with DGs. However, voltage control of this proposed method [30] depends on an adequate reactive power output from the customer (player in game theory). If customers do not provide the reactive power requested by the distribution company (DisCo) to the grid, the distribution system will be unstable due to large voltage fluctuations. In order to obtain proper reactive power output from the customer, the DisCo should frame the system in such a way as to encourage the customers to follow DisCo requests.

Therefore, this paper proposes a system called the reactive power incentive system. The system is intended to encourage customers to output the appropriate reactive power as requested by the DisCo by allowing them to obtain rewards corresponding to the reactive power requirement of the DisCo. If customers output the proper reactive power, some burden of the DisCo, such as the need for reactive power compensators or LRTs and SVRs, will be mitigated. The compensation that the DisCo pays to its customers is covered by the burden that has been alleviated by coordination with the customers. By using this proposed method, the DisCo can save on costs due to mitigating the burden of some control equipment; customers also get the advantage of incentives by following suitable reactive power output regimes as requested by the DisCo. This reactive power DR program serves to improve the power quality of the power system without requiring a change in normal load consumption, as compared with a conventional DR handling only active power. The effectiveness of the proposed method is confirmed using MATLAB® simulations. Not only does this paper provide a detailed technical assessment, but it also shows the economic benefits of both of the DisCo and customers. In addition, optimal operation is calculated by using the particle swarm optimization (PSO) algorithm, and the solution is provided as optimal one-day scheduling. In order to avoid over-control, a modified scheduling method is proposed in this paper.

The paper is organized as follows: Section 2 explains DR regarding active and reactive power. In Section 3, in order solve the problem of high penetration of DGs using RES causing voltage deviation and reverse power flow, formulations of the distribution model, objective function, optimization method and control device configuration are provided. The method of reactive power incentive is provided in Section 4. The optimization algorithm and modified scheduling method are explained in Section 5. In Section 6, the simulation results are presented as case studies. Section 7 concludes this paper.

2. Demand Response

DR programs are proposed in many countries to solve some of the issues of urgent concern in power generation, especially in developed countries. The details of the DR mechanism on price

have been discussed in [31–33], the research of which revealed the structure between the aggregator and customer relationship, as well as the incentive profit and penalty based on the behavior of changing consumption. DR management of load shedding by directly controlling the turning on/off of device load was proposed as a smart direct load control with the recent Internet of Things (IoT) technology [34].

In the electricity market, a DR configuration consists of some menu (e.g., pricing, market-based DR, physical basis (load), etc.) The DR can be categorized as mandatory, voluntary and based on contract, to name a few, as in Figure 1a [35]. Most cases of DR suppress load demand at a peak time and shift usage time. It is then desirable to level the load profile in the DR program as shown in Figure 1b. Here, in order to show the influence by the pricing-based DR purely, the consumer's willingness to change the demand for the change in the electricity price excluding the operation of the storage battery, etc., will be explained.

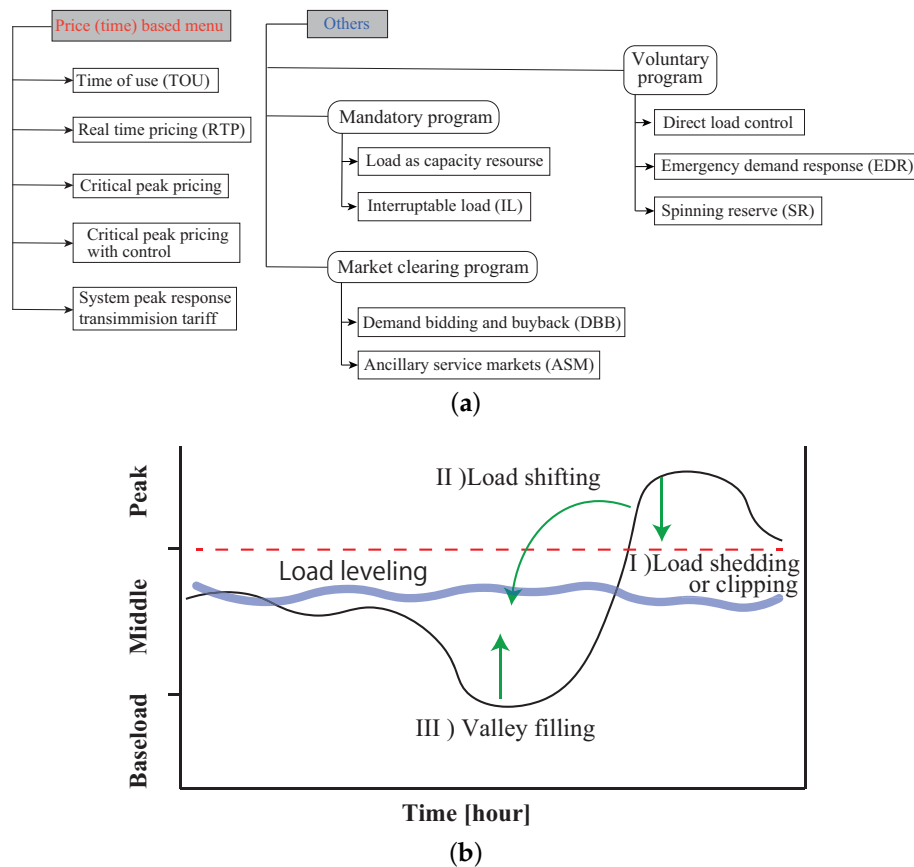


Figure 1. DR menu and its behavior. (a) Several DR menus regarding pricing based and others [35] and (b) an example of net load demand behavior under the DR program.

2.1. Price Elasticity

Under the condition that the DR has been carried out, load flexibility and the ability of responsive capacity are shown by the price elasticity of demand. The price elasticity of load demand is expressed as follows [35,36]:

$$\pi = \frac{p_l}{D} \frac{\partial D}{\partial p_l} \quad (1)$$

According to Equation (1), the price elasticity at term i, j (24 h) can be defined as [35]:

$$\pi(i, j) = \frac{p_l(j)}{D(i)} \frac{\partial D(i)}{\partial p_l(j)} \quad (2)$$

Considering price elasticity at time i corresponding to j , it could the express schedule of load usage regarding shiftable load under the DR event. In the case of reduced load, it is represented by the price elasticity of negative value and vice versa.

Electricity usage has penetrated everywhere, falling into the lifeline of essential goods and services. Therefore, the customer is not sensitive to changing the unit price of electricity, and at present, one can only expect price elasticity of about -0.1 [37]. In other words, DR based on price is not a big adjustment of power in negawatt trading [38], and DR that forces load reduction is a cause of dissatisfaction.

2.2. Reactive Power Market

Reactive power control is an important technique for maintaining the power quality of voltage and power factor improvement. In recent years, due to the improvement of IoT technology, a system capable of giving and receiving reactive power from distributed power sources and household inverters' unused capacity has been proposed. Therefore, a reactive power market has been proposed, which buys and sells with respect to reactive power not normally consumed [39,40]. However, the reactive power market is not opened for end-users of the power system. Y.Han et. al. [41] have discussed reactive power sharing in microgrids with IoT technology. Against this backdrop resulting from IoT development, the mechanism that various customers can participate in for reactive power control is becoming a reality, but there are few papers that have discussed the incentives and benefits that they offer.

3. Modeling and Formulation for the Optimization Problem

In this paper, the distribution system consists of a substation with LRT and 15 customer-side nodes. These nodes can be divided into two types of areas, which are the residential and office areas shown in Figure 2. PV generators and SVCs are installed at all nodes in the distribution system, and parameters related to the distribution system are listed in Table 1, where the nominal capacity and the nominal voltage of the distribution system are 5 MVA and 6.6 kV, respectively. This section describes the decision technique for the tap changing of existing voltage control devices (LRT), the reactive power control method using inverters interfaced with the PV and BESS control at the interconnection point, instead of reactive power supply from SVC and SVR tap ratio control.

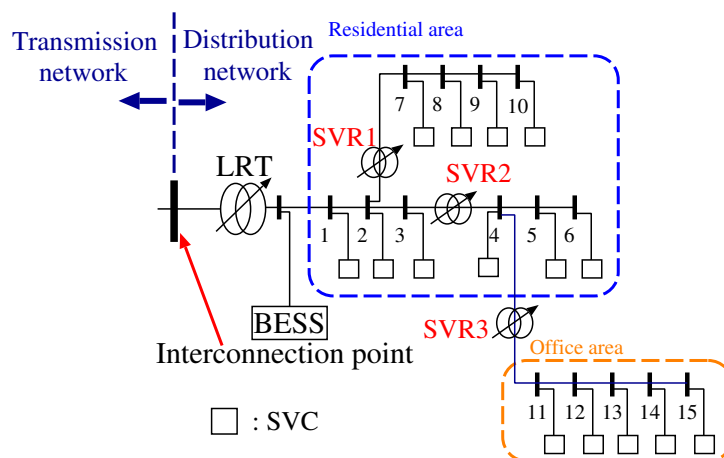


Figure 2. Distribution system model. LRT, load ratio transformer; SVR, step voltage regulator; SVC, static VAR compensator.

Table 1. Parameters of the distribution system.

Line impedance at each section	0.04 + j0.04 pu
Rated capacity of PV node	0.08 pu (400 kW)
Rated capacity of PV-interfaced inverter S_{PV}	0.08 pu (400 kW)
Large BESS capacity C_{LB}	20.0 pu (100 MWh)
Rated capacity of BESS-interfaced inverter S_{LB}	1.0 pu (5 MW)
Rated Capacity of SVC S_{SVC}	0.05 pu (250 kVar)

3.1. Objective Function and Constraints for Optimal Scheduling

In order to adapt the optimization method to the described problem, the objective function and constraints are determined as described in this section. Here, the control devices are the BESS, BESS-interfaced inverter, PV-inverter and tap control transformers.

Objective function:

The objective function for conventional scheduling can be represented as follows:

$$\min : F_{con}(P_{LBinv}, Q_{LBinv}, Q_i, T_k) = \sum_{t=1}^{24} \sum_{i=1}^{N_{node}} P_{Loss,i}(t) \quad (3)$$

The objective function F_{con} is used to minimize the distribution losses for a period of one day. P_{LBinv} , Q_{LBinv} , Q_{PVinv} , T_k are determined as control variables. N_{node} means the number of distribution nodes. This function is used to find the optimal reference value of cooperative operation. In the proposed incentive approach, the objective function is updated as follows:

$$\min : F_{inc}(P_{LBinv}, Q_{LBinv}, Q_{PVinv}, T_k) = \sum_{t=1}^{24} \sum_{i=1}^{N_{node}} (P_{Loss,i}(t) - v_i(t)) \quad (4)$$

3.2. Constraints

Robust voltage range for PV installation:

Generally, all nodes' voltage constraint is expressed as Equation (5):

$$V_{min} \leq V_m(t) \leq V_{max}. \quad (5)$$

A stipulated voltage range of a low voltage distribution area under a pole transformer is set to be within 101 ± 6 V in the Electricity Act of Japan. According to [20], the distribution voltage will fluctuate up to 6.5 V in a low voltage area under the high penetration of RES. In order to preserve robustness, thus a restriction has been put on the general voltage limit (95–107 V) as 101.5 V–105 V in this work. By configuring all pole transformers at a transformation ratio of 6600 V:105 V, the V_{min} and V_{max} are assigned 6380/101.5 V (0.967 pu) and 6600/105 V (1.0 pu), respectively.

Power flow constraints regarding reverse power flow and the power factor:

The active and reactive power flow constraints at an interconnected point are written as follows:

$$P_f^{min}(t) \leq P_f(t) \leq P_f^{max}(t) \quad (6)$$

$$Q_f^{min} \leq Q_f(t) \leq Q_f^{max} \quad (7)$$

To compensate for reverse power flow in the static simulation, a flexible boundary is set as the active power flow. In order to avoid unnecessary use of control devices, the active power flow limit is shaped in such a way that a lower amount of control is necessary. Distribution losses also depend on

power flow fluctuation; hence, the bandwidth of active power flow is set to ± 0.25 pu. It is essential to note that the bandwidth and shape should be set by considering the installation rate of PV amount and the load curve profile. On the other hand, the acceptable range of reactive power flow considers the power factor (PF) value, which depends on active power flow [42].

The PF of the interconnection point is maintained from 0.85–1.0. Reactive power flow limits are determined from the active power flow value. Thus, the upper and lower reactive power limit are rewritten as follows:

$$Q_f^{min}(t) = -P_f(t) * \tan(\cos^{-1}(0.85))$$

$$Q_f^{max}(t) = P_f(t) * \tan(\cos^{-1}(0.85)).$$

BESS configuration and operation:

To suppress large fluctuations of power flow at the interconnection point, the power flow constraint is supported by using the BESS at the substation. The power controller of BESS is shown in Figure 3b. The optimized control reference signal is generated based on the forecasted information. In this paper, the BESS is assumed to have NASbatteries; the charge/discharge efficiency of the BESS is 80%; whilst the self-discharging of the BESS is not considered. These constraints are described as follows:

$$\sqrt{P_{LBinv}^2(t) + Q_{LBinv}^2(t)} \leq S_{LBinv} \quad (8)$$

$$\zeta_{LB}(t+1) = \begin{cases} \zeta_{LB}(t) - \frac{P_{LB}(t)/\eta}{C_{LB}} & (P_{LB}(t) \geq 0) \\ \zeta_{LB}(t) - \frac{P_{LB}(t) \cdot \eta}{C_{LB}} & (P_{LB}(t) < 0) \end{cases} \quad (9)$$

$$20 \leq \zeta_{LB}(t) \leq 80 \quad [\%] \quad (10)$$

These equations are constraints regarding the large capacity BESS, considering battery SOC and the efficiency of charging and discharging.

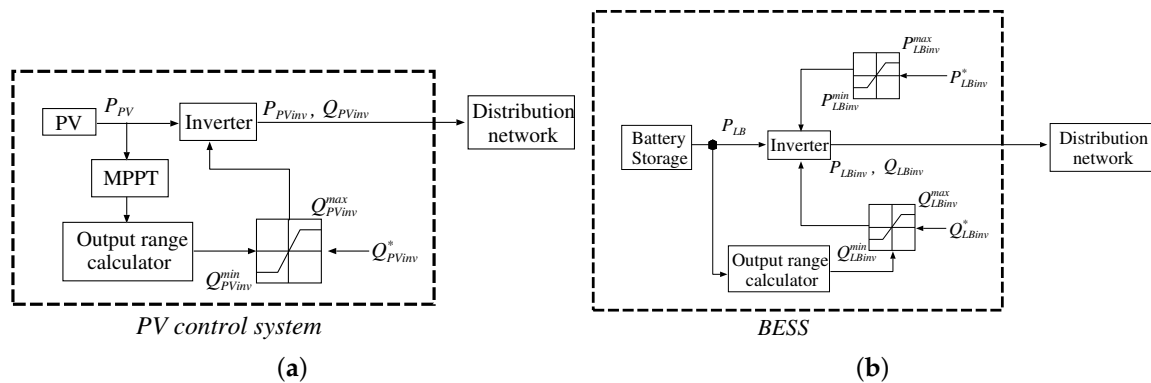


Figure 3. Active and reactive power control system. (a) Interfaced inverter of the PV system and (b) inverter of BESS at the interconnection point.

PV system:

DGs using PV have a simple configuration and maintenance-free characteristics. Details of the PV cell and its inner structure are described in [43]. For utilization improvement of the PV system in an ever-changing climate, it is assumed that the PV system has the maximum power point tracking (MPPT) algorithm. The reactive power control scheme utilizes capacity margins of the installed PV inverter shown in Figure 3a. The inverter constraint is defined as Equation (11):

$$\sqrt{P_{PVinv}^2(t) + Q_{PVinv}^2(t)} \leq S_{PVinv} \quad (11)$$

The feedable reactive power from the PV inverter is rewritten as follows:

$$|Q_{PVinv}(t)| \leq \sqrt{S_{PVinv}^2 - P_{PVinv}^2(t)} \quad (12)$$

Here, the amount of $Q_{PVinv}(t)$ is the main factor for cooperative operation, which is discussed in Section 4.

OLTC tap constraints:

The OLTC concludes the LRT and SVR, the tap positions' constraint of which is given by:

$$T_k^{min} \leq T_k(t) \leq T_k^{max}. \quad (13)$$

In LRT operation, short-term operation is undesirable. Thus, LRT can control at a rate of one tap-step ratio in one hour. The tap position variable is discrete. Therefore, the optimization problem is known as a mixed integer non-linear problem (MINLP).

4. Reactive Power Incentive Method

DR methods can be roughly classified into two categories, such as TOU type and incentive type. DR using the TOU method depends on the electricity price [27,44], which encourages the customer to change the usage of electric power. On the other hand, incentive-based DR is independent of electricity price, in which a customer can earn a profit from DisCo by the cooperative operation process. The customer side does not need to change the usage of power. Generally, DisCo has to invest in maintaining the power system, and the investment costs include equipment, maintenance and operation, which becomes a burden to the DisCo. However, these costs can be reduced through the cooperative operation of the customer side. A cooperative operation system is possible with HEMS smart grid technology [45–48]. The reactive power incentive concept provides an amount of profit to the customer to contribute to the sustainable power system of DisCo. If all customers follow the DisCo's request for the specified reactive power output Q_{PV}^* , the DisCo can remove the unnecessary burdens of equipment costs. Therefore, the DisCo can provide incentives from saved money to customers participating in the cooperative operation program.

4.1. Calculation of Reactive Power Incentive Unit Price

Reducing the cost of voltage control devices through the cooperative operation of the customer can be described by Equation (14). This equation includes SVR and SVC costs. N_{SVC} and N_{SVR} are set to 15 and three, respectively. These numbers of devices are required when this case is considered without cooperative operation. Figure 2 shows SVR1, SVR2 and SVR3, which are located between Nodes 2 and 7, between Nodes 2 and 3 and between Nodes 4 and 11, respectively.

$$C_Q = C_{SVC} \times N_{SVC} + C_{SVR} \times N_{SVR} \quad (14)$$

By considering the depreciation term and total costs, v_q can be obtained from the following equation:

$$v_q = \frac{C_Q}{Y_{D,SVC}(\text{year}) \times 365(\text{days}) \times 24(\text{hours}) \times S_{SVC} \times N_{node}} \quad [\text{JPY/kVarh}] \quad (15)$$

The depreciation term $Y_{D,SVC}$ is determined for 20 years. SVC and SVR costs are displayed in Table 2, and also, SVC capacity and reactive power unit price are listed in Table 2. Because the S_{SVC} should distribute to all customers, the value is derived by the number of branching nodes in the distribution system.

Table 2. Parameters for the comparison case.

Variable	Cost (JPY) & Capacity (kVar)
C_{SVC}	1.5×10^8 (JPY)
C_{SVR}	3.0×10^8 (JPY)
C_Q	3.15×10^9 (JPY)
S_{SVC}	250 (kVar)
v_q	4.8 or 3.4 (JPY/kVarh)

4.2. Contribution Factor

DisCo pays incentives for requesting reactive power cooperation. Due to the decision of the incentive amount, DisCo has two processes to assess the contribution; (1) decide and notify $Q_i^*(t)$ based on the day-ahead scheduling, (2) the contribution factor is calculated based on the difference between $Q_i^*(t)$ and the provided reactive power $Q_i(t)$.

The proper value $Q_i^*(t)$ is generated by solving Equation (16):

$$Q_i^*(t) = \arg \min F_{con}(t). \quad (16)$$

Then, consumers are requested to use the optimal reactive power amount allocated as the reference value $Q_i^*(t)$ for the proposed DR event. Consumers can then make a contribution to reactive power if they can provide a value close to this reference value for the cooperative control. DisCo calculates the contribution rate according to the consumer's reactive power supply amount. In this work, linear and sigmoid functions have been developed to calculate the contribution factor.

Linear contribution function:

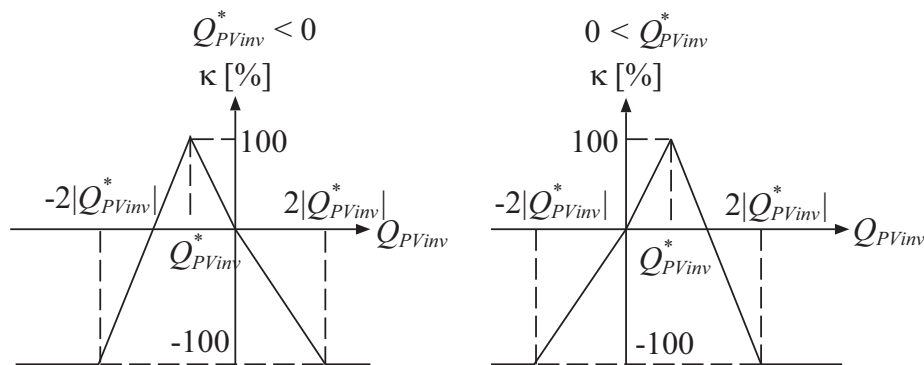
The contribution rate defined as a linear function is shown in Figure 4, in which the slope of the linear contribution function is generalized as follows:

$$A_{lin,i}(t) = \begin{cases} \frac{1}{Q_i^*(t)}, & \text{if } 0 \leq |Q_i(t)| \leq |Q_i^*(t)| \\ \frac{-1}{Q_i^*(t)} + 2, & \text{if } |Q_i^*(t)| \leq |Q_i(t)| \\ 2 \times \frac{1}{Q_i^*(t)}, & \text{others.} \end{cases} \quad (17)$$

Then, the contribution factor is determined as follows:

$$\kappa_{lin,i}(t) = A_{lin,i}(t) \times Q_i(t) \quad (18)$$

When the $\kappa_{lin,i}(t)$ indicates a negative value, the participating customer will have a penalty applied.

**Figure 4.** Contribution factor of the reactive power incentive.

Sigmoid function:

The contribution factor is written by applying the sigmoid function as:

$$\kappa_{sig} = 2 \times \left\{ \frac{1}{1 + \exp(-A_{sig} * Q_i(t))} - 0.5 \right\}. \quad (19)$$

where coefficient A_{sig} determines the shape of sigmoid function, whenever Equation (19) $-1 < \kappa_{sig} < 1$. $A_{sig,i}(t)$ is given by solving Equation (19) for each time step t :

$$A_{sig,i}(t) = \ln \left\{ 1 - \frac{2}{1 + \kappa_{ref}} \right\} \times \frac{1}{Q_i^*(t)} \quad (20)$$

Here, κ_{ref} is the contribution reference value when DisCo obtained $Q_i(t) = Q_i^*(t)$. Furthermore, in order to determine the proper reactive power contribution, $\kappa_{ref} = 0.9$ is assigned in the work, since $\kappa_{ref} = 1 (\because Q_i(t) = \infty)$. The sigmoid contribution factor is given by substituting $A_{sig,i}(t)$ into Equation (20), yielding:

$$\kappa_{sig,i}(t) = 2 \times \left\{ \frac{1}{1 + \exp(-A_{sig,i}(t) * Q_i(t))} - 0.5 \right\} \times 100[\%] \quad (21)$$

The $\kappa_{sig,i}(t)$ is plotted against several reference values $Q_i^*(t)$ in Figure 5a. A feasible region comparison for linear and sigmoid contribution functions is illustrated in Figure 5b.

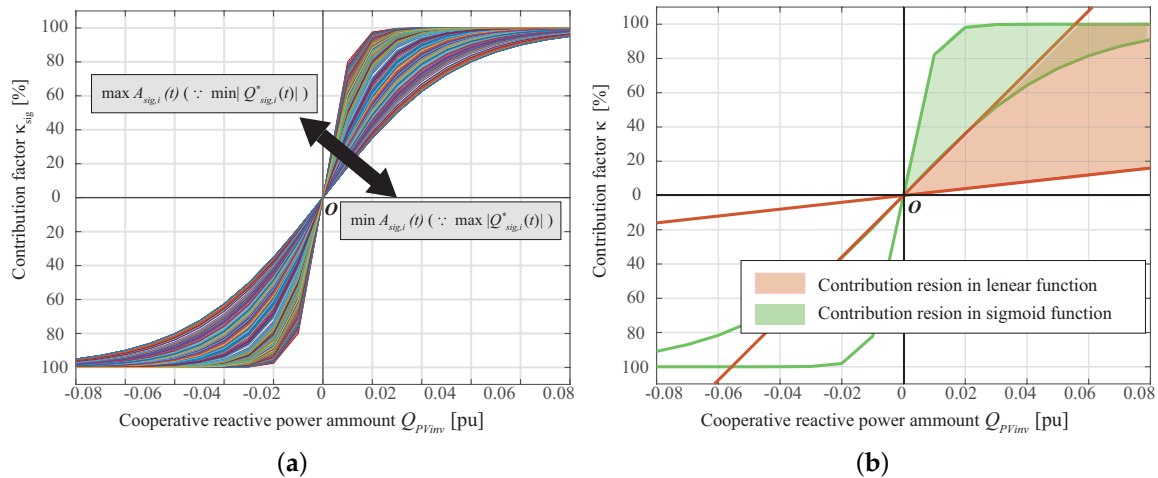


Figure 5. Sigmoid contribution factor of reactive power incentive. (a) Sigmoid contribution function for hourly power and each node and (b) contribution region of the sigmoid and linear function.

4.3. Profit Obtained by Customers

Once v_q is determined, customers can calculate their own obtained profit v following the order from DisCo. The κ is disclosed in Figure 4, and the profits obtained by the customers can be derived using Equation (22).

$$v_i(t) = Q'_{PVinv,i}(t) \times v_q \times P_{base} \text{ [JPY]} \quad (22)$$

In this paper, P_{base} is 5000 kW. $Q'_{PVinv,i}(t)$ is the reactive power incentive considering the contribution factor κ , and it is described by the following equation:

$$Q'_{PVing,i}(t) = |Q_{PVinv,i}(t)| \times \kappa_{f,i}(t), \quad f \in \{lin, sig\}. \quad (23)$$

Therefore, customers can obtain a maximum profit by supplying reactive power output close to Q_{PV}^* . Since all customers should carry out the command for maximizing the profit, DisCo can maintain the voltage using this incentive.

5. Optimization Algorithm

5.1. Particle Swarm Optimization

In order to solve optimization problems of the distribution network, the PSO algorithm has been used in this research. PSO is an optimization method that uses the general idea of a flock of birds that can find the path to food by coordination. This is modeled by the particle swarm, which has a search position and velocity information in multidimensional space. Each step of the PSO algorithm is as follows:

- Step 1:** Generate an initial searching point for each swarm.
- Step 2:** Evaluate the objective function using each swarm's searching point.
- Step 3:** Finish searching if stopping conditions are satisfied. If not, go to Step 4.
- Step 4:** Search the next point considering the best of the current swarm's searching point and every swarm's best searching point. Go to Step 2.

The searching algorithm communicates the best positions' information to all swarms, and each continues updating its own positions and velocities until searching is finished. The updating of velocity and search position is shown by following equation:

$$V_{k+1}(i) = w \cdot V_k(i) + c_1 \cdot rand_1 \cdot (pbest(i) - S_k(i)) + c_2 \cdot rand_1 \cdot (gbest - S_k(i)) \quad (24)$$

$$S_{k+1}(i) = S_k(i) + V_{k+1}(i) \quad (25)$$

where,

- $V_{k+1}(i)$: i -th particle velocity in the $(k + 1)$ -th search
- $rand_1$: uniform random numbers from 0–1
- S_{k+1} : search position of the i -th particle in the k -th search
- w : weighting of inertia
- c_1 : weighting for the best position of the self-particle
- c_2 : weighting for the best position of the particle swarm
- $pbest$: best position of the self-particle
- $gbest$: best position of the particle swarm.

The OLTC integer variables are rounded in order to apply the PSO algorithm to MINLP.

5.2. Modified Particle Swarm Optimization for Scheduling

In order to perform optimal scheduling for a power system, the one-day scheduling method has been introduced in previous literature [49,50]. Many researchers have developed algorithms for one-hour scheduling. This algorithm performs step-wise optimal scheduling. However, this algorithm cannot perform optimal scheduling through one day. The scheduling method depends on the previous step in the target time. If it has two candidate solutions, the best solution is chosen whilst compromising the other solution by few differences in the time of convergence and loss reduction in the next step. Usually, conventional scheduling methods choose a global best solution; however, in this scenario, it is

proven that a compromised solution leads to a better solution. Since the conventional methodology has the drawback of over control and unnecessary operations, it is necessary to perform optimal scheduling through 24 h; although, one-day scheduling through the 24-h method has difficulty in convergence and the explosion of variables. Therefore, in order to avoid these drawbacks, a dual scheduling method has been proposed in this research. This method uses the conventional one-hour scheduling method (SC 1) and every two-hour scheduling method (SC 2) simultaneously. In this two-scheme approach, the most efficient combination of schedules will be chosen. The schematic diagram is shown in Figure 6.

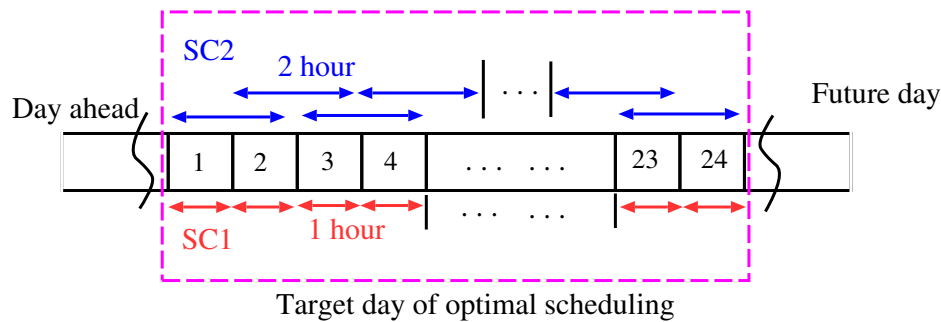


Figure 6. Scheduling (SC) method for optimal scheduling.

6. Simulation Results

The PV output profile used for the scheduling is the hourly average of the actual PV output shown in Figure 7a. Similarly, the load demand profile is shown in Figure 7b, and it is assumed that Nodes 1–10 have residential loads, while Nodes 11–15 are designated as an office area in Figure 2. For the sake of simplicity, the forecasting error of PV output and load demands is ignored in this research. The discussion in this section is divided into two parts: the guaranteed power quality of the grid and reliable profit of the customers (incentive DR participants), respectively. For all of the simulations, the optimal schedule was determined by solving the MINLP problem optimization by PSO algorithm, whilst the conventional scheduling and proposed dual scheduling methods were evaluated based on distribution power losses and convergence performance.

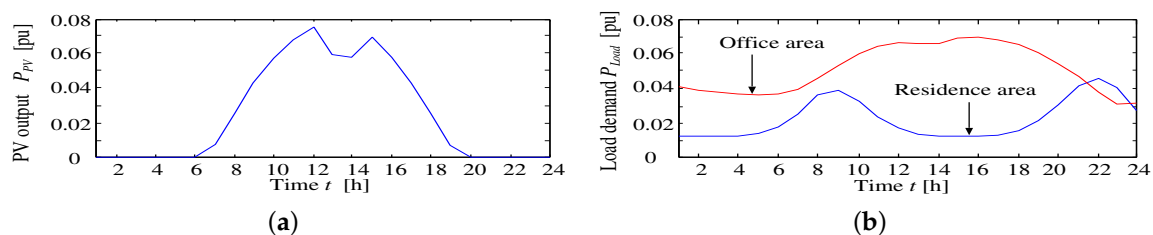


Figure 7. PV output and load demand curve. (a) PV output and (b) load demand profile for each area.

6.1. Optimal Scheduling for Voltage Control

The simulations have been conducted in four-case scenarios as follows:

- Case 1: Without optimization impact evaluation for massive penetration of RESs.
- Case 2: Conventional control method by DisCo; the distribution system consists of BESS, OLTCs (LRT, three SVRs), SVCs at each node, DGs (PV and its interfaced inverters) and loads.
- Case 3: Coordinated operation under the DR program; DisCo verifies the maximum amount of control equipment reduction.
- Case 4: Although this case concludes the coordinated operation of the DR program, unlike Case 3, distribution loss reduction is the main point of view.

The system configurations of each case are indicated in Table 3, and the equipment location is shown in Figure 2. The third and final cases are proposed scenarios, which adopt the reactive power incentive program. Case 2-4 employ the dual scheduling algorithm.

Figure 8a–c illustrates the influence of the massive installation of RESs. The dashed line in each figure denotes the acceptable range of the system constraints. Figure 8a shows the voltage deviation from the proper range, and the reverse power flow is confirmed by the negative value, as shown in Figure 8b. The bandwidth of Figure 8c expresses PFlimitations ($PF = 0.85$); thus, the power quality has not been satisfied under the high penetration without reactive power control. In order to verify the conventional system and control, Case 2 provides the optimal operation schedule of control devices (BESS, SVCs, SVR, OLTCs), and this result is shown in Figure 9. Figure 9a–c shows node voltages, active and reactive power for Case 2. From these plots, it is seen that voltage deviations and reverse power flow are resolved. Furthermore, the proper PF is confirmed by the reactive power flow within the stipulated range from Figure 9c. Control devices' operation is shown in Figure 9d–h. Figure 9d,e illustrates BESS operation of the active, reactive power output and SOC, then, each SVC and OLTC operation is illustrated in Figure 9g,h, respectively. This result indicated the necessary equipment configuration for maintaining system safety and satisfied power quality with optimal operation. The distribution losses are shown in Figure 9i. High distribution losses in the day-time (11–16 h) and night-time (19–24 h) are caused by heavy power flow amounts.

Table 3. Control device cases and reduction state for each case.

Comparison Method	Proposed Method		Reduction Status	
case2	case 3	case 4	case 3	case 4
LRT	LRT	LRT	-	-
(Substation)	(Substation)	(Substation)	-	-
Three SVRs	-	Three SVRs	✓ (three SVRs)	-
(nodes 2–7,3–4,4–11)	-	(nodes 2–7,3–4,4–11)	✓ (fifteen SVCs)	✓ (fifteen SVCs)
Fifteen SVCs	-	-	✓ (fifteen SVCs)	✓ (fifteen SVCs)
(all nodes installed)	-	-	-	-
PV output	PV output	PV output	-	-
(P_{PVinv})	(P_{PVinv} , Q_{PVinv})	(P_{PVinv} , Q_{PVinv})	-	-
BESS	BESS	BESS	✓ (capacity 7 pu)	✓ (capacity 7 pu)
(P_{LBinv} , Q_{LBinv})	(P_{LBinv} , Q_{LBinv})	(P_{LBinv} , Q_{LBinv})	✓ (capacity 0.2 pu)	✓ (capacity 0.2 pu)
BESS inverter	BESS inverter	BESS inverter	✓ (capacity 0.2 pu)	✓ (capacity 0.2 pu)
(S_{LB} 1.0 pu)	(S_{LB} 0.8 pu)	(S_{LB} 0.8 pu)	✓ (capacity 0.2 pu)	✓ (capacity 0.2 pu)

In Case 3, DisCo attempted to reduce the investment of control devices by cooperation control from the customer instead of using SVR and SVC controllers. The results in Figure 10 accomplished the effort to reduce the introduction of control devices by supplying the reactive power incentive method for customers. In a similar order as shown in the figures of Case 2, Figure 10a–i shows comparable variables. As opposed to Figure 9g of Case 2, Figure 10g illustrates the coordinated reactive power from the customers with SVCs' output replaced with the output of the PV inverter. The reactive power supply limitation illustrates a curved dashed line because this cooperation was provided by the unused capacity of the PV inverter, which differs from Figure 9g for Case 2. In Figure 10h, the tap operation of LRT is illustrated. It is shown in Figure 10 that the voltage control by cooperative control can reach the proper value of the distribution system (voltages, active and reactive power flow); as shown from Table 3, cooperative achievement has been confirmed, despite the reduction in capacity of the control equipment on the DisCo side and the storage battery. The hourly distribution losses shown in Figure 10i are described after the description of Case 4.

Figure 11, which is the result of Case 4, confirms the control contents based on the same configuration as Case 3, except for Figure 10h, which shows three SVRs' support voltage control. Therefore, a noticeable difference in the hourly power distribution losses is observed in Figure 12, and the differences of the total distribution losses of each case are listed in Table 4. From the viewpoint

of distribution losses, conventional (Case 2) and cooperative (Case 4) controls have been carried out and obtained a similar percentage of loss reduction. The loss reduction rate of Case 3 was comparatively smaller than others, although it can prevent the procurement of additional control devices.

Table 4. Results of distribution losses for each case.

	Distribution Loss
Without optimization (Case 1)	7513 kWh
Comparison method (Case 2)	3743 kWh (−50.2%)
Proposed method (Case 3)	4258 kWh (−43.3%)
Proposed method (Case 4)	3718 kWh (−50.5%)

The computation result with the scheduling method and computational load are summarized in Table 5. It is confirmed from Table 5 that the proposed method used more computation time compared to the conventional method due to the increase of the scheduling variable and the synchronization of the time step. The proposed scheduling method achieved the required percentage loss reduction, and the determination of the flexible time width of the operation plan brought high accuracy to the conventional scheduling algorithm. However, it is necessary to design the scheduling method by paying attention to the fact that the calculation load due to the variable increase caused an increase in the convergence time.

Table 5. Comparison of the scheduling scheme.

	Comparison Method (Case 2)	Proposed Method (Case 3)	Proposed Method (Case 4)
SC1	1,2,5–24 (h)	1,6–24 (h)	1,8–21,24 (h)
SC2	3–4 (h),	2–3,4–5 (h)	2–3,4–5,6–7,22–23 (h)
Simulation time	+20 %	+18 %	+21 %
Loss reduction	3.2 %	5.1%	6.5 %

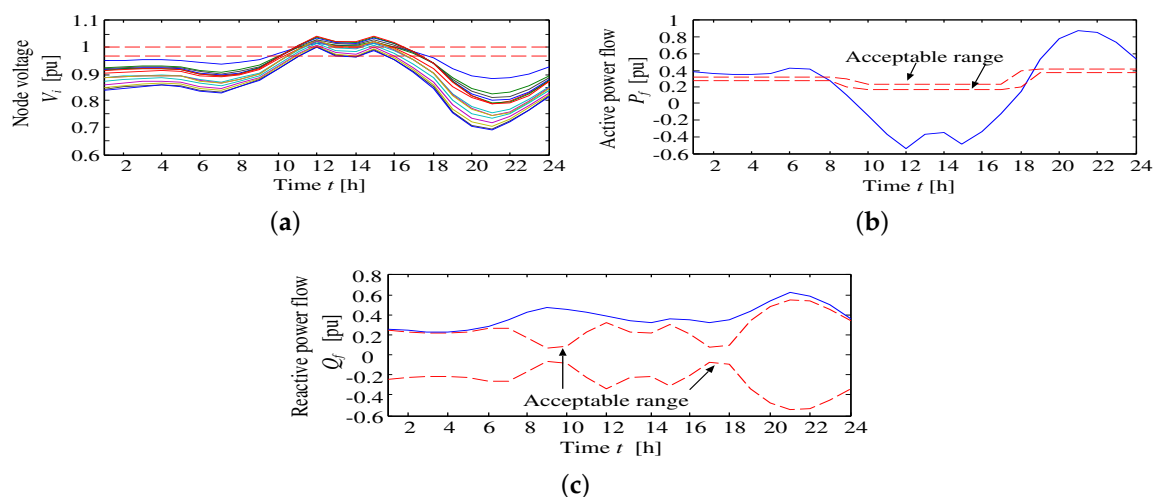


Figure 8. Simulation results without optimization (Case 1). (a) Voltage profile without control, (b) active power flow at the interconnection point and (c) reactive power flow at the interconnection point.

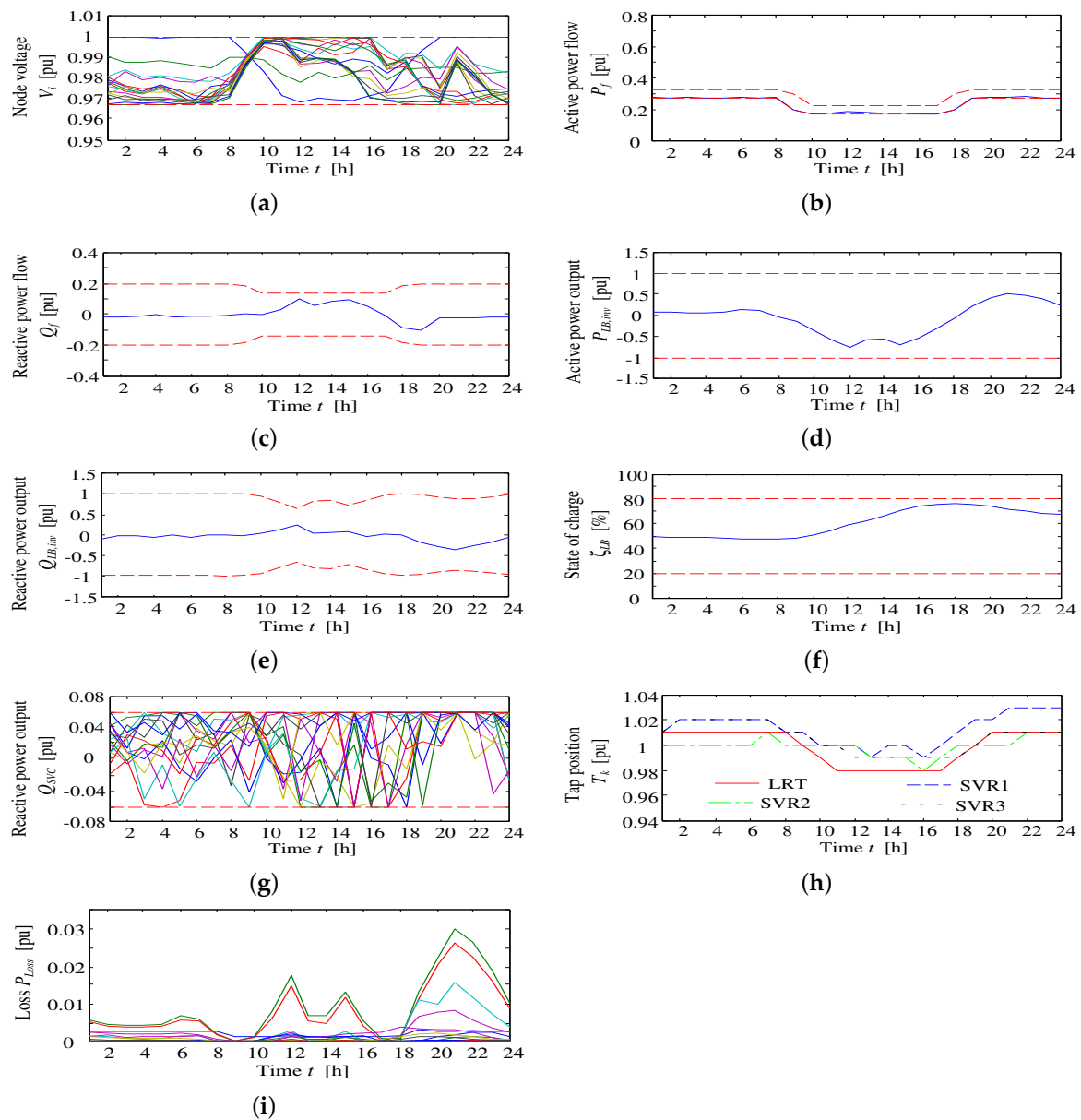


Figure 9. Simulation results of the comparison method (Case 2). (a) Voltage profile without control, (b) active power flow at the interconnection point and (c) reactive power flow at the interconnection point. (d) Active power output of large BESS. (e) Reactive power output of large BESS. (f) SOC of large BESS. (g) SVC output. (h) Tap position of on-load tap changers (OLTCs) (LRT and SVRs). (i) Distribution losses of each node over time.

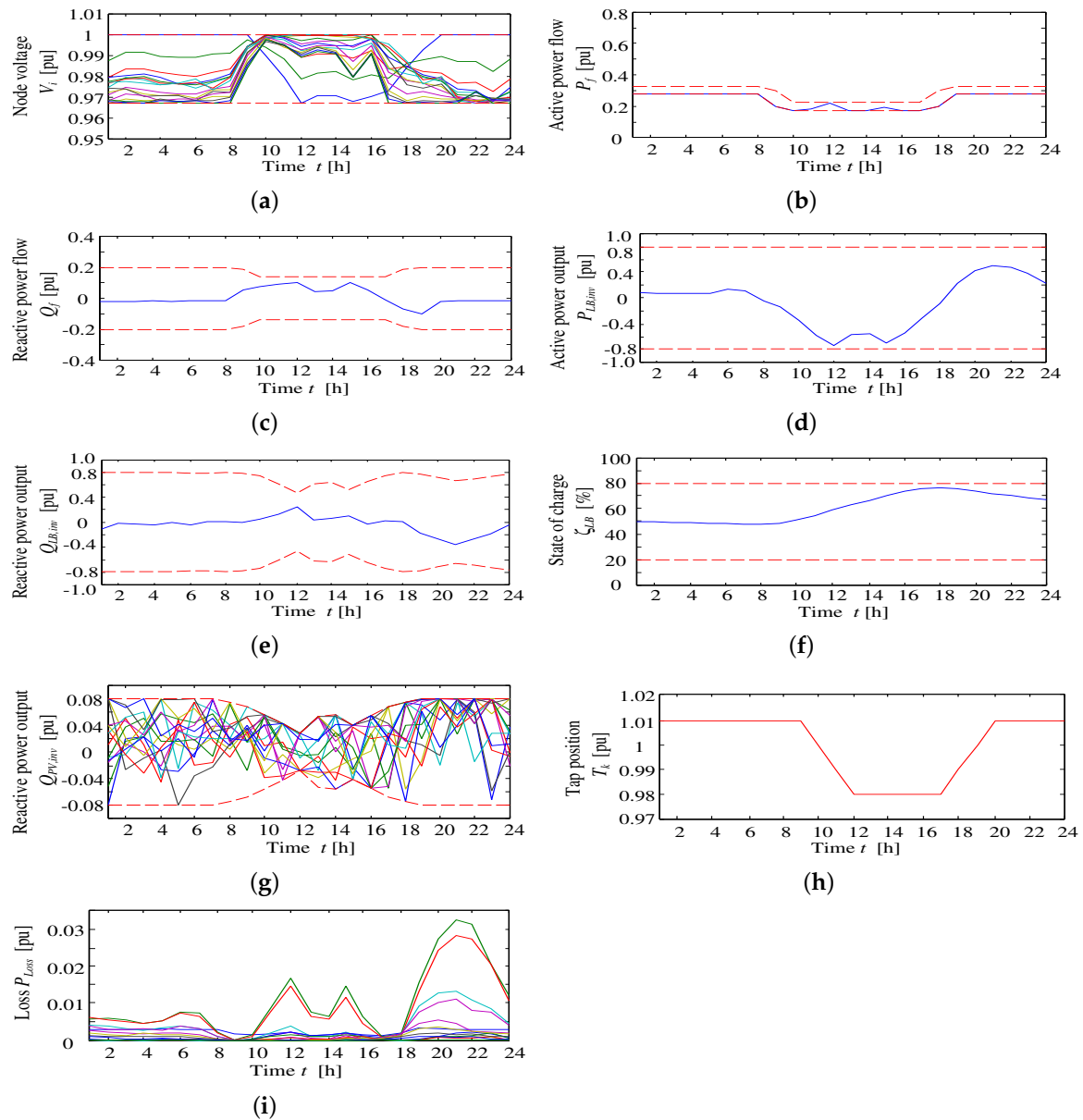


Figure 10. Simulation results of the comparison method (Case 3). (a) Voltage profile without control, (b) active power flow at the interconnection point and (c) reactive power flow at the interconnection point. (d) Active power output of large BESS. (e) Reactive power output of large BESS, (f) SOC of large BESS. (g) Reactive power compensation from the interfaced inverter of end-users. (h) Tap position of OLTC (LRT). (i) Distribution losses of each node over time.

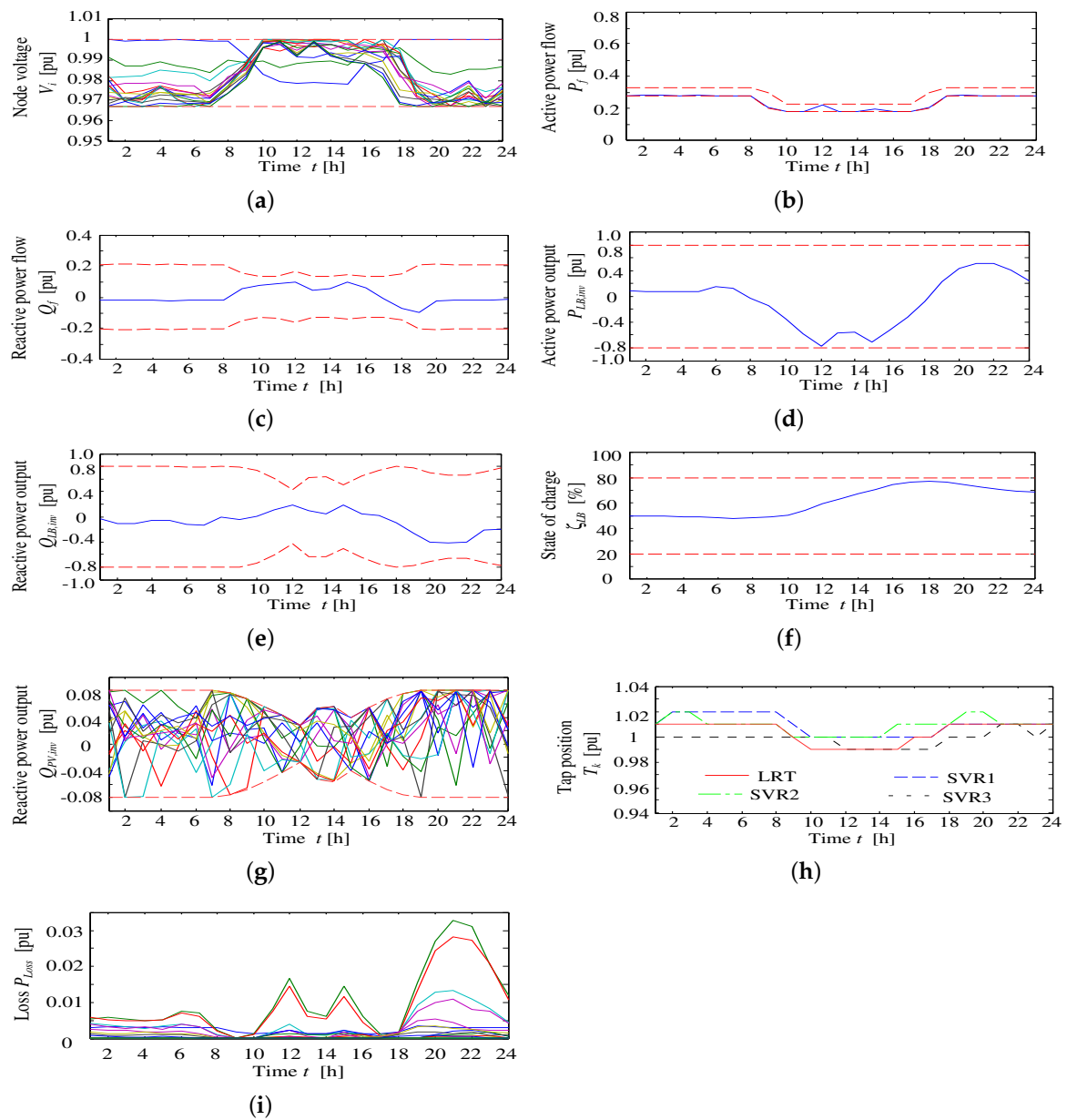


Figure 11. Simulation results of proposed method (Case 4). (a) Voltage profile without control, (b) active power flow at the interconnection point and (c) reactive power flow at the interconnection point. (d) Active power output of large BESS. (e) Reactive power output of large BESS. (f) SOC of large BESS. (g) Reactive power compensation from the interfaced inverter of the end users. (h) Tap position of OLTCs (LRT and SVRs). (i) Distribution losses of each node over time.

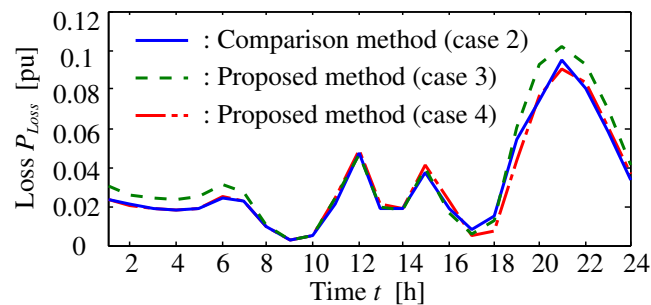


Figure 12. Comparison of distribution losses for each case.

6.2. Economic Assessment with the DR Program

Section 6.1 outlined the optimal scheduling and operation for system security for the proposed study, whilst this section outlines the assessment of the effectiveness of the proposed incentive method alongside the customer's profit. Profits gained by customers from the incentive program of operation Cases 3 and 4 are shown in Figures 13 and 14, respectively. All customers who are providing coordination by participating in the incentive market can gain a profit throughout without changing their electrical energy consumption pattern. In Figures 13a and 14a, it can be confirmed that the obtained profit is small in the day-time when the inverter margin is small, but on the other hand, it gains higher profit at night when compensating for voltage deviation due to heavy load. It is different from the end-of-day profit for customers at each node from Figure 13b, due to the absence of voltage compensation from SVR in Case 3. Therefore, the contribution by cooperative control from customers is necessary, as it helps the customer to gain high profit for the end-of-nodes (Nodes 12–15). Otherwise, in order to levelize the distribution of incentives shown in Figure 13b, it is advisable to introduce SVRs.

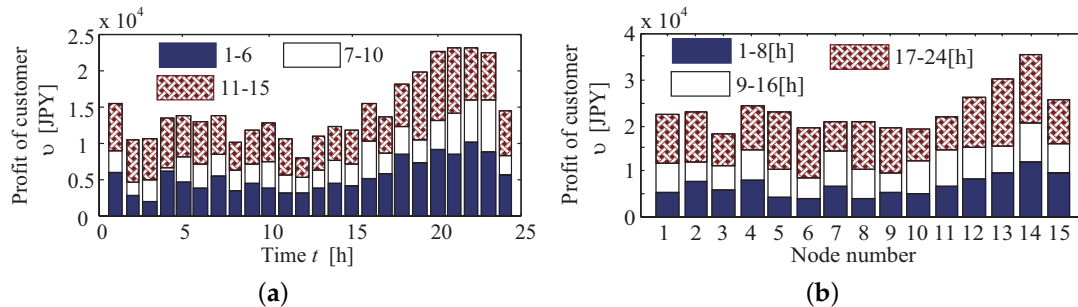


Figure 13. Profit of the customer from reactive power incentive (Case 3). (a) Hourly profits of each node and (b) end-of-day profit for customers at each node.

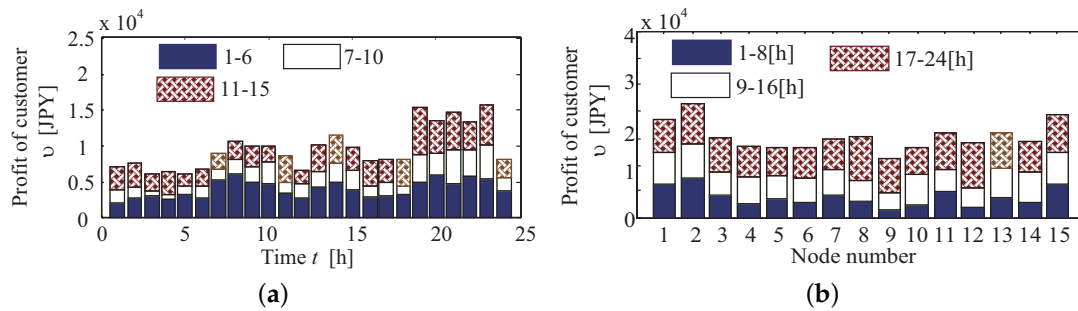


Figure 14. Profit of the customer from reactive power incentive (Case 4). (a) Hourly profits of each node and (b) end-of-day profit for customers at each node.

Next, an analysis that changes the participation rate of the incentive market is shown in Figure 15. This figure provides three comparisons; (1) comparison of profits with the participation rate, (2) comparison of profits obtained by the contribution functions and (3) the participation rate for appropriate control. The participation rate of customer changes in Cases 3 and 4. The profit obtained by linear and sigmoid contribution functions is plotted for each case. First, as the participation rate increased, it can be confirmed that the profits of all the participants increased. Secondly, linear and sigmoid profits intersected about the 84% point. It is clear that the linear contribution function gave higher profit than the sigmoid contribution at a participation rate beyond 84%. In contrast, the sigmoid function showed a benefit for a lower participation rate. The vertical dotted lines indicate boundaries that satisfy all constraints. In other words, the area to the left of this boundary line indicates the impossibility to maintain a safe system. Therefore, on the operation points, the participation rate exceeded 82% in Case 3 and 73% or more in Case 4, which is necessary for maintaining the grid stability.

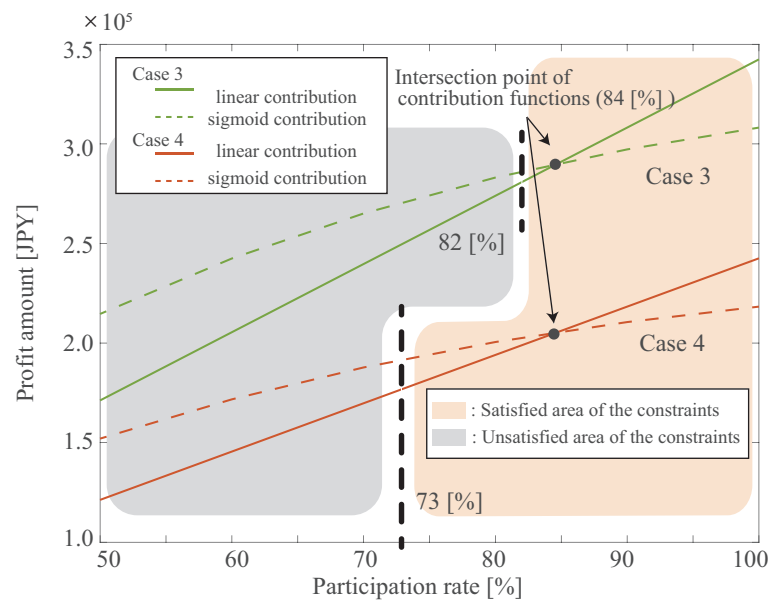


Figure 15. Profit comparison for the case study (Case 3 and 4) with the participation rate of customers.

Assuming that all consumers participated in the DR event in Case 3, the average profit of the sigmoid function decreased over the linear function, and the result is shown in Figure 16. However, in actual systems, it is difficult to meet an expectation of 100% participation from consumers in the market. In addition, several control devices have already been introduced, so in such a case, the sigmoid function is more likely to distribute profits to consumers. Since the sigmoid function has high flexibility, versatility is high even in real systems.

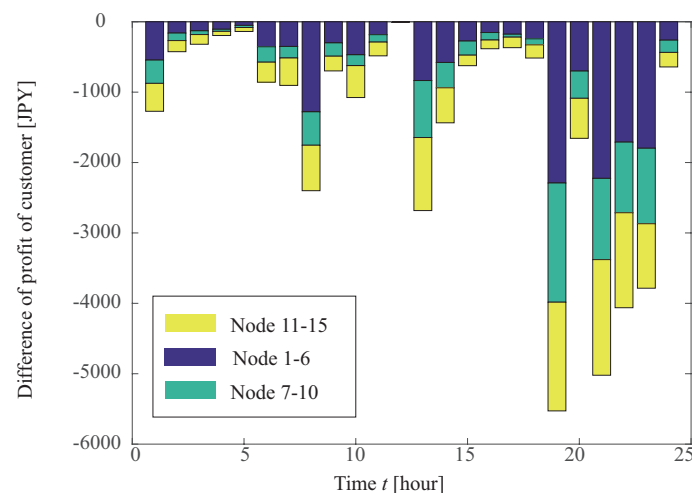


Figure 16. A comparison of hourly profit with contribution functions ($=\kappa_{sig} - \kappa_{lin}$) in the cooperative condition (participation rate is 100%).

7. Conclusions

This paper proposed a program that encourages customers to follow orders from their DisCo in order to maintain distribution system reliability by establishing a reactive power incentive. This incentive can be awarded only to customers who follow orders given by the DisCo. The DisCo does not need to procure new equipment for voltage regulation. Hence, the DisCo and the customer can coordinate for each others' mutual profit. To demonstrate the effectiveness this method, a proof of

concept was given by simulations, which used numerical optimization and the dual scheduling method. The effectiveness was confirmed by numerical simulation and case studies.

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Abbreviations

The following notations are used in this manuscript:

Objective function and constraints:

F_{com}	Objective function for the conventional problem
F_{inc}	Objective function for the proposed incentive method
N_{node}	Node number of the distribution system
P_f	Active power flow at the interconnection point
P_f^{min}, P_f^{max}	Lower and upper limit of active power flow at the interconnection point
$P_{Loss,i}$	Active power loss of node i
Q_f	Reactive power flow at the interconnection point
Q_f^{min}, Q_f^{max}	Lower and upper limit of reactive power flow at the interconnection point
t	Time step at optimization
T_k	Tap positions of LRT and SVR
T_k^{min}, T_k^{max}	Lower and upper tap limit of LRT and SVRs
V_{min}, V_{max}	Minimum and maximum voltage constraints
V_m	Node voltage at node m
BESS	: BESS
η	Charging and discharging efficiency of large BESS
ζ_{LB}	State of charge of large BESS
C_{LB}	Capacity of large BESS
P_{LBinv}	Active power output of BESS from DisCo
P_{LBinv}	Active power output of large BESS
$P_{LBinv}^{min}, P_{LBinv}^{max}$	Lower and upper limit of active power of a large BESS inverter
Q_{LBinv}	Reactive power output of large BESS
$Q_{LBinv}^{min}, Q_{LBinv}^{max}$	Lower and upper limit of reactive power output of a large BESS inverter
S_{LBinv}	Inverter capacity of large BESS
Photovoltaic system:	
P_{PVinv}	Active power output from the PV generator system
P_{PV}	Active power output from the PV panel
Q_{PVinv}	Reactive power output of inverters interfaced with PV
Q_{PVinv}^*	Order value of reactive power
$Q_{PVinv}^{min}, Q_{PVinv}^{max}$	Lower and upper limit of the PV inverter regarding reactive power output
S_{PVinv}	Inverter capacity of the PV inverter
Reactive power incentive	
κ	Contribution factor of reactive power
κ_{lin}	Linear contribution function
κ_{sig}	Sigmoid contribution function
A_{lin}	Slope of the linear contribution function
A_{sig}	Coefficient value for the sigmoid contribution function
C_Q	Total cost regarding voltage regulation devices
C_{SVC}	Introduction cost of SVC
C_{SVR}	Introduction cost of SVR

N_{SVR}	Total number of SVR
P_{base}	Rated power in the distribution system
Q'_{PV}	Contribution of the customer for DisCo with reactive power output
v	Customer profit of the reactive power incentive
v_q	Reactive power incentive unit price
$Y_{D,SVC}$	Depreciation term of SVC
π	Price elasticity of demand
$\pi(i, j)$	Price elasticity at time i corresponding to j
D	Load demand
p_l	Price of goods

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