IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received September 24, 2020, accepted October 5, 2020, date of publication October 16, 2020, date of current version October 28, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3031591

Practical Power Management of PV/ESS Integrated System

SEOUNG UK JEON, (Member, IEEE), JINAH NOH, (Graduate Student Member, IEEE), SEOKJU KANG, (Graduate Student Member, IEEE), AND JUNG-WOOK PARK, (Senior Member, IEEE)

School of Electrical and Electronic Engineering, Yonsei University, Seoul 03722, South Korea

Corresponding author: Jung-Wook Park (jungpark@yonsei.ac.kr)

This work was supported in part by the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (MIST), Korea Government under Grant 2020R1A3B2079407, and in part by the Human Resources Program in Energy Technology, Korea Institute of Energy Technology Evaluation and Planning (KETEP), Ministry of Trade, Industry and Energy, South Korea, under Grant 20194030202420.

ABSTRACT This study proposes the practical power management of integrated system with photovoltaic (PV) and energy storage system (ESS) to solve the line congestion and voltage problems in a distribution system while considering the electricity price and state of charge (SOC) of ESS. In addition, the proper power management of PV/ESS integrated system (PEIS) enables to increase the hosting capacity of renewable energies in a distribution system and to maximize the profit of independent power producer (IPP). In this study, the real power management of PEIS of 100 kW is implemented in practice and tested with the actual measurements for 3 days. The results show that the proposed method deals with the line congestion problem effectively and efficiently while increasing the profit of IPP by 11%. In particular, the reactive power control based on the international electrotechnical commission (IEC) standard, IEC 61850-90-7 is applied to the PEIS, and it can successfully mitigate the variations of voltage in a distribution system.

INDEX TERMS Distribution system, energy storage system, integrated system, photovoltaic system, power management, reactive power control, renewable energy.

I. INTRODUCTION

To deal with the climate change due to greenhouse gas emission, many countries have been strongly pursuing the green growth policies while focusing on renewable energies such as photovoltaic (PV) and wind, etc. Accordingly, many renewable energy-based generators have been connecting in the transmission and distribution systems of existing power grid. The PV generation has an infinite energy source without making environmental pollution. Its characteristic shows the pattern of general power consumption, and therefore this can make helpful supplying the power. In other words, it mainly generates power during the daytime when the most electricity is consumed. Thus, it can be strategically used for system operator to resolve the power shortage during the peak demand. However, its output power is affected by weather conditions. This results in increasing the variability and uncertainty in its power generation [1]–[3].

The associate editor coordinating the review of this manuscript and approving it for publication was Chandan Kumar.

On the other hand, every distribution line has the power limit, above which is not allowed to flow, due to its thermal capacity. This problem is called as the line congestion in a distribution system [4], [5]. For example, the real power flowing in a general distribution line is limited to 10 MW at maximum in South Korea [6]. As the result, the other PV systems cannot be newly connected to this line because it already has many renewable energy-based generators, of which total output power reaches to 10 MW. Even though the increase of hosting capacity with the installation of new lines and transformers can be a fundamental solution, it requires the high cost. To figure out this problem, the PV and energy storage system (ESS) integrated system (PEIS) can be applied [2], [3]. In other words, even when the PV system can generate its maximum power according to the good weather condition, some amount of power is charged in the ESS depending on its capacity. This can prevent the maximum power from PV system flowing in distribution line. As the result, it enables to solve the line congestion problem, and therefore increase the hosting capacity of renewable energies.

There are several studies on the integrated PV-ESS system [7], [8], which describes the integrated PV-ESS system with the DC bus. It supplies the AC power depending on whether there is a load consumption in DC bus or a generation from PV system. Because the DC bus is separated from AC system, and the associated power management system (PMS) handles the power fluctuation of PV generation and DC load, it can contribute to improving the stability of distribution system. However, because the DC bus voltage mainly depends on the state of charge (SOC) of ESS, it does not change significantly while the power generation from PV system is subject to fluctuate. Therefore, the DC/DC converter is required to adjust the DC voltage and transfer the power. As the result, the additional cost for DC/DC converter and the loss from power conversion reduce the independent power producer (IPP)'s revenue. In contrast, the proposed PEIS does not require the DC bus. Also, its PMS can be easily applied to the conventional PV and ESS system. Moreover, there is no need for additional DC/DC converter or DC bus system. It requires the only line measurement device.

The South Korea government has been carrying out the strong renewable energy promotion program while giving more weight (that is, higher subsidy) to the time schedule operation of ESS. Then, the PEIS gives the chance to sell its stored energy at nighttime at the higher cost determined by this weight. Therefore, it can reduce the investment payback period although it requires the high initial cost [2], [3]. Even though there are several studies to prevent the line congestion by estimating the margin of line capacity and improving the optimal power flow method for microgrid [9]–[11], there are no researches to directly solve the line congestion problem while increasing the IPP's revenue.

This paper proposes the new practical PMS applied to the PEIS with the inverter (INV) for PV system and the power conditioning system (PCS) for ESS, which basically supports the time schedule to consider the economic profit while solving the line congestion problem in a distribution system, and therefore increasing the hosting capacity of renewable energies. This paper is organized as follows. Section II explains the line congestion problem in a distribution line. It also describes the structure of PEIS with its communication process. Section III gives the full details for proposed PMS. Also, it introduces the renewable energy policy of South Korea with the focus on subsidy. In Section IV, the case studies are carried out to verify the performance of PMS applied to the PEIS of 100 kW. Thereafter, the experimental results tested for 3 days are given in Section V. Finally, a conclusion is given in section VI.

II. THE PROPOSED PV/ESS INTEGRATED SYSTEM

A. LINE CONGESTION PROBLEM

As mentioned in above, the PV system can be strategically used because its output pattern is similar to that of load during daytime [1]–[3]. However, it is characterized with the variability and uncertainty depending on weather conditions. In particular, when the PV system is connected to the particular distribution line, and it generates its maximum power output according to the good weather condition, it might excess the power limit (10 MW in South Korea) of line due to its thermal capacity in some sections, as shown in Fig. 1(a), even though the ESS exists in the other separate location [6]. To figure it out, the PEIS is applied as shown in Fig. 1(b). In this case, even if the PV system generates the same maximum power, some amount of power can be charged in the ESS. Then, this results in avoiding line congestion problem. Also, this energy stored in ESS of PEIS can be used when the electricity price is high at peak demand and/or the subsidy supported from government is also high at nighttime [12].

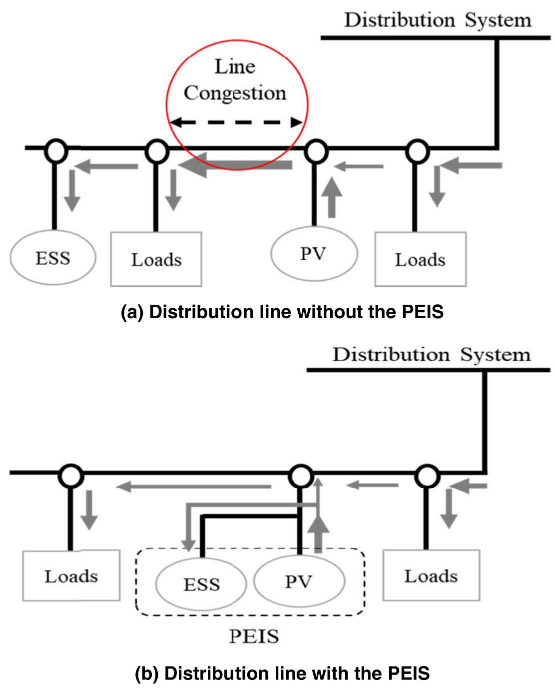


FIGURE 1. Line congestion in a distribution line.

B. PRACTICAL PV/ESS INTEGRATED SYSTEM OF 100 KW

The structure of practical PEIS of 100 kW is shown in the Fig. 2. It consists of the INV for PV system and the PCS for ESS in hardware. The measurements from the INV is firstly transmitted to the PMS. Also, the PCS measures the input DC voltage, output AC voltage/current, and SOC of battery. Then, they are sent to the PMS in every second based on the recommended standard (RS) 485 communication. The power flow from the PEIS to line is measured by the power protection & monitoring equipment (PPME), and this is transmitted to the PMS. Note that the PPME, which is added to the conventional PEIS, can also perform block function of reverse power flow [6]. The power flow monitoring equipment (PFME) measures the power flowing through the line, and send it to the PMS.

The communication method used to implement the proposed PEIS is the RS485 communication, which is more resistant to noise than the other serial communications such

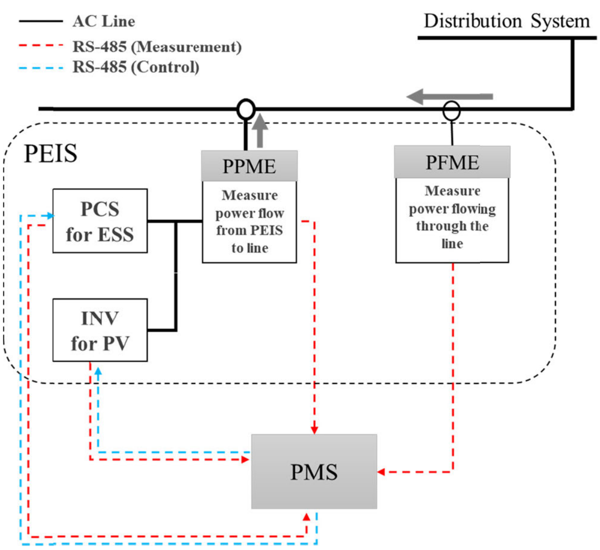


FIGURE 2. Structure of PEIS with its communication process.

as RS232, RS442. Also, it is more preferably used for the long-distance communication. In particular, the PFME (which acquires the information of line) is inevitably far from the PMS. For this case, it can transmit the information more stably. For these reasons, the RS485 communication has been used in many industry applications. The important components of proposed PEIS, which are INV for PV, PCS for ESS, PPME, and PFME, are using the RS485 communication. In addition, in order to prevent the accident by communication error, the acknowledge signal is periodically transmitted and received to check whether the communication is stable. If a communication error occurs, the proposed PEIS is stopped. It is set to 19200 bps, which is the communication speed, which can transmit the most data while being able to perform the stable communication. There is no interference between the AC system of 60 Hz and the PWM frequency of 7.2 kHz. Moreover, the device equipped with a terminating resistor is used in the RS485 communication module to prevent the signal reflection. Also, the proposed PMS can be easily applied to the conventional PV and ESS system because there is no need for additional DC/DC converters or DC bus systems, which are required in [7] and [8].

On the other hand, the reactive power must be effectively compensated to keep the voltage stability in distribution system. In practice, the only INV performs this function. This study proposes the new reactive power compensation method with the smart inverter functions based on the international electrotechnical commission (IEC) standard, IEC 61850-90-7 [14]. Then, its effectiveness is verified by the practical hardware experimental test.

III. THE PROPOSED POWER MANAGEMENT SYSTEM

A. POWER FLOW CONTROL

Each renewable energy-based generator must be connected in practice after considering the allowable hosting capacity of distribution system based on the grid code including the line congestion problem.

The existing PMS does not consider the real-time various conditions of distribution line, and therefore it does not actively manage the output powers from PV and ESS systems to solve the line congestion and voltage stability problems, etc [15]–[18]. In other words, it has simply made the only charging and discharging operations of ESS in their time schedule modes. In particular, when the line capacity is still insufficient, this line congestion problem will be more aggravated if the ESS discharges its energy at the same time [13]. Then, the proposed PMS can actively handle this with the real-time information of distribution system while solving the line congestion problem.

B. VOLTAGE CONTROL

By the IEC 61850-90-7, the PCS of renewable energy-based generator must be able to carry out the smart inverter functions, which can deal with the frequency-real power, frequency-reactive power, voltage-real power, and voltage-reactive power relationships, etc. In addition, they support the operation for giving the economic profit to the IPP. Among the above functions, which can be implemented by the virtual droop control, this study focuses on the voltage control by reactive power compensation, as shown in Fig. 3. That is, the PEIS provides or absorbs the reactive power to control the voltage by the INV for PV system and/or PCS for ESS while regulating the power factor within ±0.9 in South Korea [6].

The values from V1 to V4 in Fig. 3 might be different depending on the system condition and grid code in each country. When the value of voltage is lower than that of V2 (which is 372.4 V), the INV supplies the positive (over-excited) reactive power to increase the voltage. In contrast, if it is higher than that of V3 (which is 372.4 V), the negative (under-excited) reactive power is compensated to decrease voltage. For this study, this compensation starts right after the voltage is above ±2% of the rated voltage. When it reaches to ±5% of the rated voltage (which are corresponding to V4 and V1, respectively), the PEIS makes the maximum reactive power compensation up to 48.4% of rated power so that the power factor becomes ±0.9.

For the reactive power compensation, when the line voltage exceeds its limit, the proposed PMS calculates the amount of reactive power required to restore the voltage. Then, it adjusts the power factor of PEIS until it supplies the required reactive power. In this case, the power factor is limited not to drop below 0.9 according to the grid-code regulation in [6]. In some cases, when the reactive power compensation cannot be fully made due to the lack of PV generation or SOC of ESS, this control can be accomplished inside of the dark triangle in Fig. 3.

C. RENEWABLE ENERGY PRICE POLICY

The South Korea government is operating the renewable energy certificate (REC) program to support and expand the renewable energy business. The system operator sets the

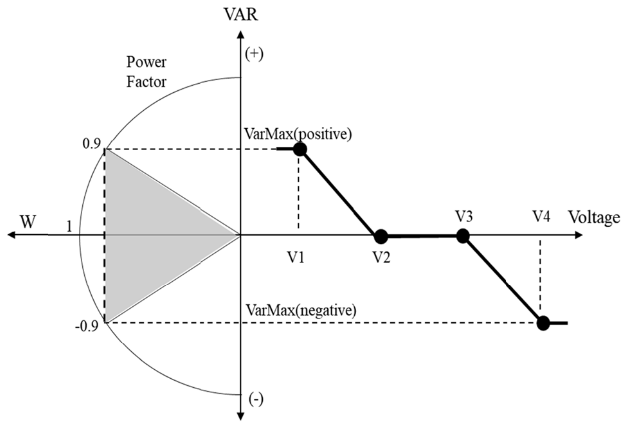


FIGURE 3. Voltage control by reactive power compensation by PEIS.

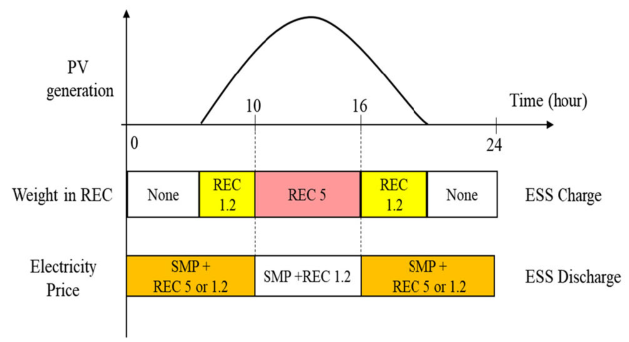


FIGURE 4. REC program and its corresponding electricity price obtained by the PEIS.

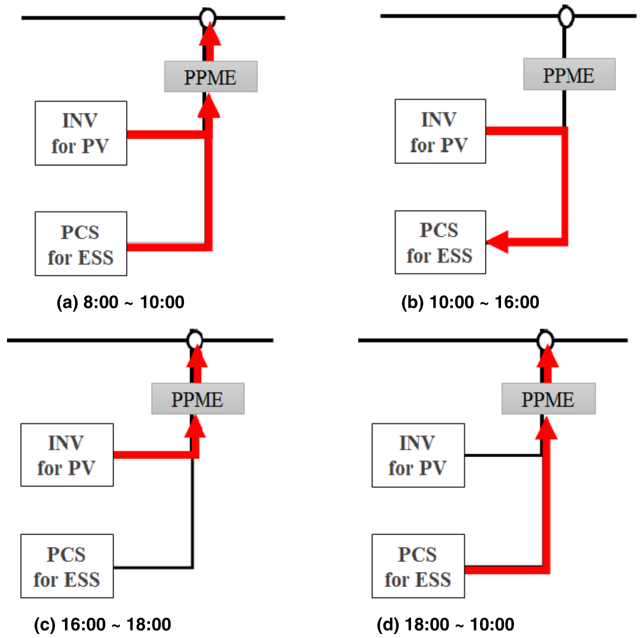


FIGURE 5. Power flows by the proposed PEIS to get the REC price in different time periods.

electricity price by the annual bidding. This fixed bidding price consists of the system marginal price (SMP) and REC prices. The SMP is the price of electrical energy (kWh) produced by power plants, and it varies depending on the energy sources such as fossil fuels, nuclear, and liquefied natural gas (LNG), etc. Then, REC price is determined by subtracting the SMP from the fixed bidding price. The details of REC program are shown in Fig. 4. The weight of REC is different depending on the type of renewable energy source. For example, when compared to other renewable energy sources such as wind and geothermal power, the PV system is easy to install, and its generation time is more predictable. Therefore, the weight of 1.2 (which is the REC 1.2) is applied to the electricity from PV system. In summary, the IPPs with the PV system can get both SMP and 1.2 · REC when they sell the power to the grid. On the other hand, the PV system with the ESS can store the energy, and they can sell the power any time they want while contributing to the grid management. Thus, the weight of 5 (which is REC 5.0) is applied to this system when the ESS charges the energy from PV system from 10:00 to 16:00, and it sells the power to the grid by discharging the energy between 16:00 and 10:00 in the next day. In conclusion, the proposed PEIS monitors the power flow of the PCS for ESS to reflect the REC price as follows. Firstly, the amount of energy charged from 10:00 to 16:00 is measured. Thereafter, this accumulated energy is sold to the grid from16:00 to 10:00 in the next day. If the IPP follows this time schedule, he can get the REC 5.0. If it charges in the other times, the IPP receives the REC 1.2, which is the same as the case by the only PV system. In particular, when the ESS receives the power from the grid (not the power generated by the PV system), all RECs are impounded. Moreover, if this happens repeatedly, the system is forcibly cut off. Thus, the IPP is recommended to strictly follow the above suggested time schedule while preventing the reverse power flow.

The power flows by the proposed PEIS to get the REC price in different time periods is shown in Fig. 5. When the power from PV of proposed PEIS flows to the grid before 10:00 as shown in Fig. 5(a), it gets the REC 1.2, not the REC 5.0 (see the yellow period about 8:00∼10:00 in Fig. 4). In contrast, the power flow from the PCS for ESS is monitored and the ESS discharges the energy before 10:00 with the REC 5.0. As shown in Figs.5 (b) and (c), all powers generated from the PV is charged in the ESS from 10:00 to 16:00. If the proposed PEIS sells the power to the grid in this period, it still gets the REC 1.2. After 16:00, the proposed PEIS stops charging the ESS, and it still sells the power from the PV with the REC 1.2 until the PV stops generating power (see the yellow period about 16:00∼18:00 in Fig. 4). Thereafter, the ESS discharges the energy until 10:00 in the next day with REC 5.0, as shown in Fig. 5 (d). Note that the REC price is paid as a subside in every 1,000 kWh.

In the first half of 2020, the fixed bidding price of South Korea is 160 Korean won/kWh. Then, the values of SMP and REC price for 3 days in March are shown in Fig. 6, where the time intervals between 10:00 and 16:00 to get the REC 5.0 in each day are indicated in the grey area [18]. In this

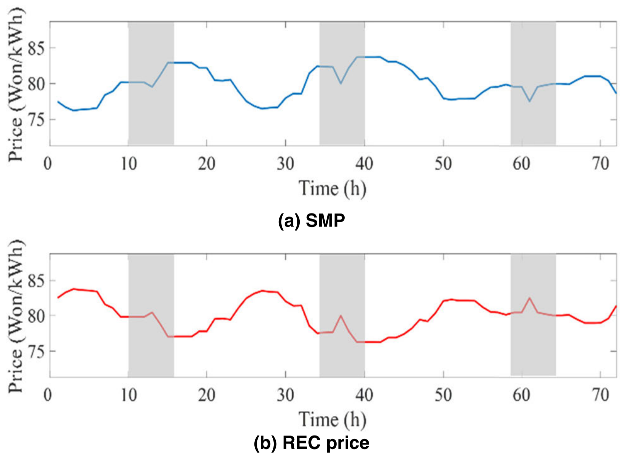


FIGURE 6. Values of SMP and REC price for 3 days in March.

period, the SMP is generally high. In contrast, the REC price is relatively low. In particular, the sudden drop in the SMP (and the sudden increase in the REC price) occurs because the power consumption is temporarily decreased between 12:00 and 13:00 during lunch time. If the PEIS discharges (and sells the power) on around 3:00 at night, when the REC price is the highest among the day, the IPP can earn the much bigger economic profit.

D. PROCEDURE TO IMPLEMNT THE PROPOSED PMS

The most important feature of proposed PMS is the use of line and SMP information so that it avoids the line congestion and voltage stability problems while maximizing the economic profit. The procedure to implement the proposed PMS is given in Fig. 7. Firstly, the PMS acquires the data from the PEIS and external route. That is, the output powers, P_{pv} and P_{ess} and power factors, pf_{pv} and pf_{ess} from the INV and ESS, respectively, are measured. Also, the SOC of ESS is obtained, and it is transmitted to the PMS. In addition, the line capacity, $P_{l.cap}$ and the line voltage, v_l are measured by the PFME. Then, with the SMP and time information from the external source, the PMS determines the REC price and its weight information (ω_{REC}), as shown in Fig. 4. By using the above information, the reference power flow, P_{ref} for ESS and reference power factor, pf_{ref} for PEIS are calculated. In particular, the P_{ref} is used as a variable of optimization problem. The measured P_{ess} can be expressed with the difference between the charging, P_c and discharging, P_d powers as

$$P_{ess} = P_c - P_d \tag{1}$$

Depending on the charging time in Fig. 4, the ω_{REC} is selected to 1.2 or 5. Then, it is important that the ESS must be charged when the ω_{REC} is 5.0 to maximize the profit of IPP. Therefore, during the period from 10:00 to 16:00, the PMS controls to charge the ESS fully such that the reference charging power, $P_{ref.c}$ becomes 100 kW as (2). On the contrary, when the ω_{REC} is 1.2 for the time intervals from 16:00 to

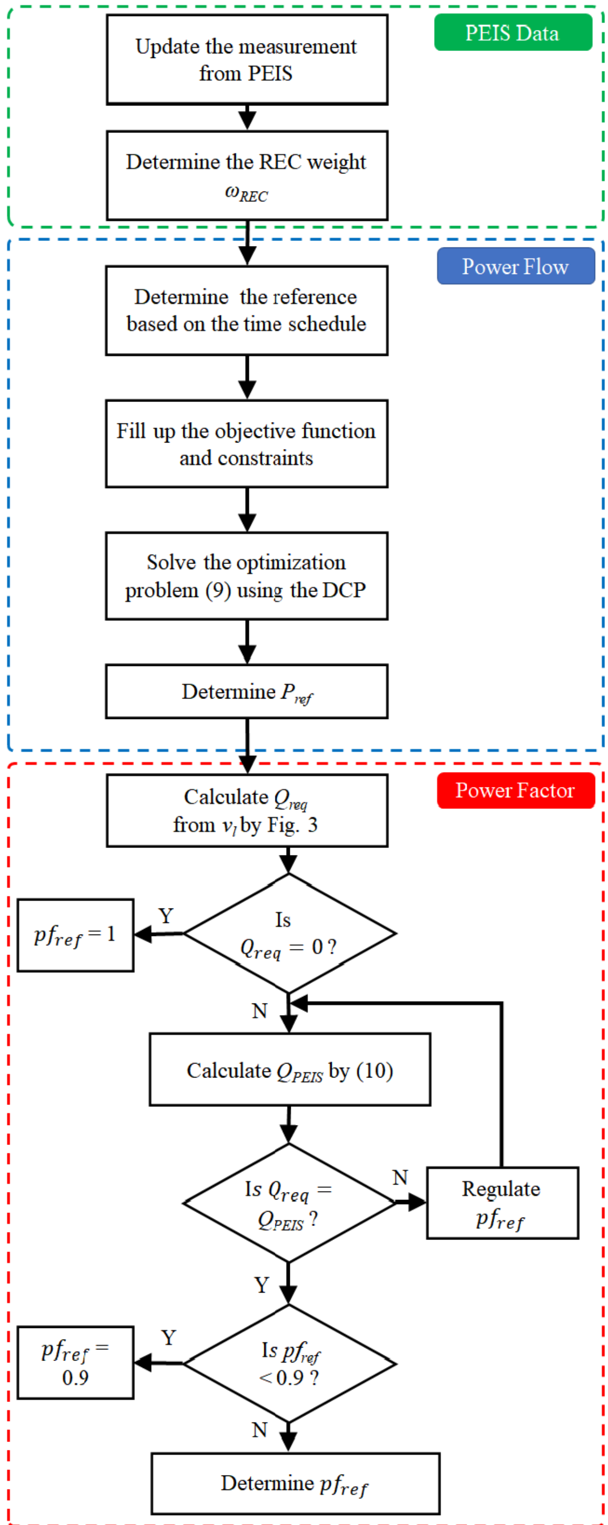


FIGURE 7. Procedure to implement the proposed PMS.

10:00 in the next day, the reference discharging power, $P_{ref.d}$ is computed as (3). The PMS receives the SOC information in real-time, and it determines the reference discharging power.

In other words, it can be calculated by multiplying the rated capacity of PCS (which is 100 kW) and the ratio of ΔSOC and Δ*Time*.

$$P_{ref.c} = 100 \tag{2}$$

$$P_{ref.d} = 100 \cdot \frac{\Delta SOC}{\Delta Time} \tag{3}$$

where ΔSOC is the difference between the present SOC and the constant SOC of 10%, which is the recommended as the minimum limit of ESS. And, Δ*Time* is the remaining time until 10:00 in the next day from the present time. After calculating the $P_{ref.c}$ by (2) and $P_{ref.d}$ by (3), the objective function, J_p, for the power flow of ESS is defined as

$$J_p = \left[P_{ref} - \left(P_{ref.c} or P_{ref.d}\right)\right]^2 \tag{4}$$

Firstly, the PMS determines the value of P_{ref} to minimize the objective function, J_p in (4), which makes the reference charging and discharging powers, $P_{ref.c}$ or $P_{ref.d}$ to operate as (2) and (3), respectively, while reflecting the renewable energy policy. That is, if the value of P_{ref} is different from that of $P_{ref.c}$ or $P_{ref.d}$, the value of J_p increases. In contrast, if they are same, the value of J_p becomes zero. To prevent diverging its value to the negative infinity, the J_p is set as a quadratic equation. Thereafter, with the ω_{REC}, the total selling price (*SP*) can be obtained as

$$SP = SMP + \omega_{REC} \cdot RECprice(\omega_{REC} = 1.2, 5) \tag{5}$$

Next, the second objective function, J_s reflecting the price information is defined as the product of *SP* in (5) and P_{ref} as

$$J_s = SP \cdot P_{ref} \tag{6}$$

Because the value of J_s becomes negative only when the ESS discharges, it is recommended that the PEIS controls to discharge the ESS more than the $P_{ref.d}$ when the *SP* is high. As shown in the Fig. 6, the REC price becomes different depending on the time. For example, even though the SMP is the lowest at around 3:00, the corresponding REC price is the highest among the day. The J_s reflects this price information to the PMS. There are some constraints to solve the optimization problems in (4) and (6). Firstly, if the PEIS receives the power from the grid, the profit supported by the REC is reduced [6]. Thus, the PEIS must charge the power less than the P_{pv}. The associated constraint is formulated as

$$P_{ref} \le P_{pv} \tag{7}$$

Also, because the power flowing to the grid, $P_{pv} - P_{ref}$, cannot exceed the $P_{l.cap}$ to avoid the line congestion problem, the following constraint is required to consider.

$$P_{pv} - P_{ref} \le P_{l.cap} \tag{8}$$

Finally, the optimization problem to find the proper value of P_{ref} is solved by the disciplined convex program (DCP) [19] such that the objective function of $J_p + J_s$ is minimized as

$$\begin{aligned} &min\left(J_s + J_p\right). \\ &\text{s.t } P_{pv} - P_{ref} \le P_{l.cap} \\ &\quad P_{ref} \le P_{pv}. \end{aligned} \tag{9}$$

The minimization of combination of J_p in (4) and J_s in (6) becomes a convex optimization problem and it consists of a quadratic objective function and two linear constraints. Then, it can be solved by the DCP while finding the proper value of P_{ref}. For solving this quadratic equation with upper and lower bounds, the DCP is transformed into a quadratic program (QP) which can be solved with a standard QP solver [20].

The DCP is implemented in MATLAB and solves the optimization problem with least-squares gradient estimation as follows. Firstly, the proposed PMS updates the measurement, and it assigns the variables to the optimization problem. Thereafter, the gradient method starts to find the optimal value within the available range. If the value of objective function of $J_p + J_s$ is decreased after the P_{ref} is decreased in a present iteration, then the P_{ref} will be decreased in the next iteration with the update in search of finding its minimum value. In the opposite direction, if the value of objective function of $J_p + J_s$ is decreased after the P_{ref} is increased in a present iteration, then the P_{ref} will be increased in the next iteration with the update in search of finding its minimum value. This iteration performs the gradient method to find the proper value until the change in the objective function $\Delta(J_p + J_s)$ is less than one. As mentioned above, the PMS is implemented in the DCP under electricity price, measurement information and grid-code regulation.

Next, as shown in Fig. 3, the required reactive power, Q_{req} depending on the variation of v_l, is compensated. In other words, if the v_l is within ±2% of the rated voltage, there is no need to compensate. Therefore, the Q_{req} is zero, and the pf_{ref} becomes 1. Otherwise, the Q_{req} has non-zero value. Thereafter, it is compared with the actual reactive power from the PEIS, Q_{PEIS}, which is defined as the sum of the reactive powers from INV for PV and PCS for ESS as

$$Q_{PEIS} = P_{pv} \cdot \frac{\sqrt{1 - pf_{pv}^2}}{pf_{pv}} + P_{ess} \cdot \frac{\sqrt{1 - pf_{ess}^2}}{pf_{ess}} \tag{10}$$

The PMS keeps decreasing the pf_{ref} by 0.001 in step from 1 to 0.9 until the values of Q_{PEIS} and Q_{req} become same. According to [6], if the pf_{ref} is lower than 0.9, its value is set to 0.9. Note that when the value of Q_{req} is positive and negative, the PEIS performs the lagging and leading pf_{ref} controls, respectively.

IV. SIMULATION RESULTS

To evaluate the performance of PMS applied to the PEIS of 100 kW, the case study is carried out by using the real measurements for 3 days, as shown in Fig. 8.

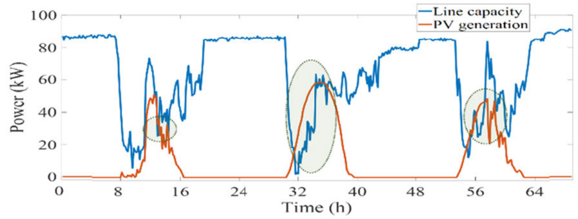


FIGURE 8. Line capacity and output power from PV system for 3 days.

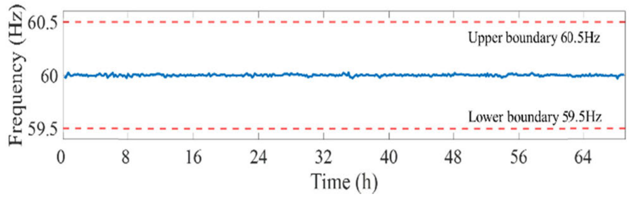
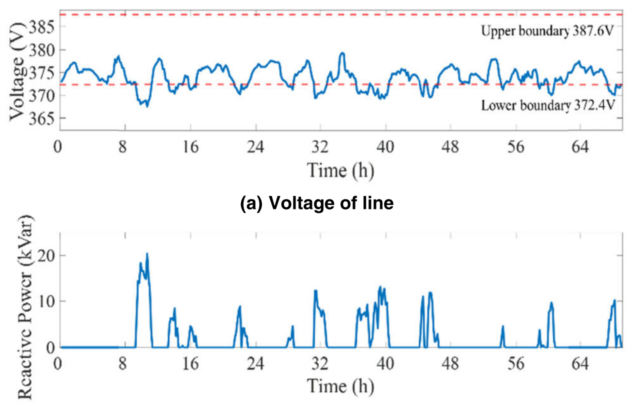


FIGURE 9. Frequency measurement of line.



(a) Voltage of line

(b) Required reactive power for compensation

FIGURE 10. Voltage measurement of line and required reactive power compensation.

In this case study, the $P_{l.cap}$, which is indicated by the blue line, is assumed to be the difference between the power of 100 kW and load consumption in the range from few kW to 100 kW at maximum. The P_{pv} is represented by the red line. Then, the line congestion problem might occur when the P_{pv} is greater than the $P_{l.cap}$, as shown in the light green circles in each day. Also, the practical measurement of frequency in the line is shown in Fig. 9. It is observed that the frequency of system is kept stable within the proper range from 59.5 Hz to 60.5 Hz required by the grid code. In contrast, it is known from the measurement shown in Fig. 10(a) that the v_l drops below the lower limit of 372.4 V required by the grid code whenever the load varies seriously (for example, at around 9:00 in every morning). Then, the corresponding Q_{req} can be calculated, as shown in Fig. 10(b).

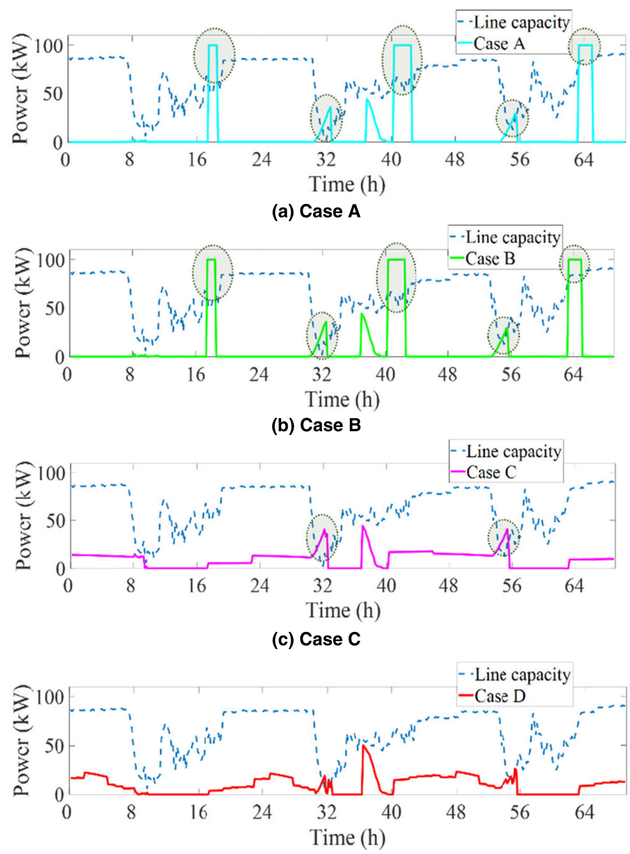
A. CASE A: CONVENTIONAL PMS METHOD

In this case, the PV system and the ESS operate in the scheduled mode by the conventional PMS method [15]–[18]. The ESS is charged in the recommended time period between 10:00 and 16:00. At the other times, it sells the power by discharging. Most IPPs have to sell the stored power from 16:00 to 10:00 in the next day. In other words, they discharge the ESS in a short time (about 2 hours) among this long-time duration, and they stop the PCS for ESS in the rest time, when it cannot participate in the compensation. Therefore, it does not contribute to solve the line congestion problem.

B. CASE B: PROPOSED PMS METHOD WITH VOLTAGE CONTROL ONLY

In this case, the proposed PMS method performs the charging and discharging operation of ESS based on the scheduled mode by the conventional PMS method (like the case A) with the only voltage control.

As shown in Figs. 11(a) and 11(b), the ESS charges the power from PV system in the period of time with the REC 5.0. After that, the PCS discharges the stored energy with the rated capacity of 100 kW for about 2 hours, and it stops until the next charging time. Also, it receives the voltage information of line, and it makes the reactive power compensation. It is possible to perform the reactive compensation by its voltage control when the PV system is generating, or the ESS is discharging. However, even if the voltage drops below the lower limit of 372.4 V, the PEIS often cannot participate in the compensation when there is no generation from the PV system, and the ESS does not discharge, as shown in Fig. 12(a).



(a) Case A

(b) Case B

(c) Case C

(d) Case D

FIGURE 11. Results of line congestion for each case.

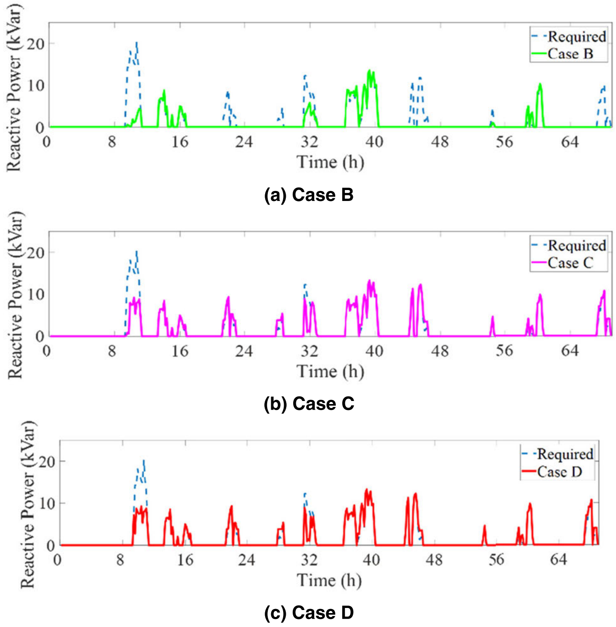


FIGURE 12. Required reactive power and PEIS voltage compensation output for each case.

C. CASE C: PROPOSED PMS METHOD WITH VOLTAGE AND POWER MANAGEMENT CONTROLS

In this case, in order not to discharge the ESS too quickly, the power from ESS is uniformly produced by (3) during the discharge time. By the consideration of SOC and time, the PMS makes the ESS discharging with the small amount of power from 16:00 to 10:00 in the next day, as shown in Fig. 11(c). Even if there is no PV generation, the PEIS enables to participate in all compensations for the entire time, as shown in Fig. 12(b). However, the PMS does not consider the line capacity and the electricity price information for this case. Therefore, the line congestion problem might occur, and the discharging power will not change significantly.

D. CASE D: PROPOSED PMS METHOD BY OPTIMIZATION WITH CONSIDEREATION OF ELECTRICITY PRICE

In this case, the power reference of ESS is optimized, and it applied to the PMS with the consideration of economic profit for the IPP as well as line congestion problem and the reactive power compensation. Firstly, the PMS adjust the output power from the PEIS to avoid the line congestion problem in all operations, as shown in Fig. 11(d). That is, if the PEIS operates without considering the power flow information of line as in the cases A–C, its output can exceed the line capacity, as shown in the light green circles of Figs. 11(a)–(c).

When compared to the discharging operation in the cases C and D, it is observed that amount of selling power for the IPP is adjusted to maximize the profit. In other words, it is increased at around 3:00, when the REC price is the most expensive, as shown in Fig. 11(d) because the SMP and REC price are reflected to the PMS. In particular, at around 32:00 and 56:00 in the morning, when the line congestion becomes rapidly serious, the ESS is charged despite it is not the time period of REC 5.0. It is shown in Fig. 12 that the reactive power is supplied for the voltage control in all cases except for the case A. The compensation result for case B is shown in Fig. 12(a). The PEIS cannot participate in the compensation at around 22:00, 46:00, and 70:00, when there is no generation from the PV system, and the PCS does not discharge the ESS. By considering the SOC and time to use the discharging power properly as the cases C and D, the PEIS can participate in the reactive power compensation for the entire time, as shown in Figs. 12(b) and 12(c). At around 10:00 and 32:00 for both cases, the amount of compensation is less than the required reactive power because the real power is insufficient, and the power factor is limited by 0.9.

Table I summarizes the comparison results of all case studies. The line congestion time represents the time, when the line congestion problem might occur, if there is no specific constraint reflecting the power flow information of line. It is observed that the PEIS might not participate in reactive power compensation if the PMS discharges the ESS in a short time, and it do not distribute the discharging power appropriately. The charging and discharging operations for the case B are the same as those for the case A. However, the profit in the case B is slightly reduced than that in the case A because the active power decreases as much as the PMS participates in the reactive power compensation for voltage control in the case B. Also, it is proved from profits in the cases C and D that the proper distribution of discharging powers can increase the profit of IPP because the PMS discharges the ESS in the time period, when the REC price is expensive.

TABLE 1. Comparison of PMS performance in all cases.

Cases	Line congestion time [min]	Compensation time [min]	Profit for 3 days [Korean won]
Case A	422	0	253,280
Case B	422	720	253,230
Case C	110	1,061	272,340
Case D	0	1,061	281,130

In particular, the profit in the case D becomes the highest because it has some adjustment reflecting the price information.

V. EXPERIMENTAL RESULTS

A. IMPLEMENTATION WITH HARDWARE PROTOTYPE

To verify the relation between the reactive power and the line voltage, the power factor of PEIS is regulated [21]. The power capacity of implemented PEIS is 100 kW, and it is too small when compared to the practical distribution line of 10 MW. Therefore, the line voltage will not change noticeably by the reactive power compensation of 100 kW PEIS. To overcome this problem, the experimental test in Fig. 13 is carried out. In other words, the power factor of PEIS is changed to

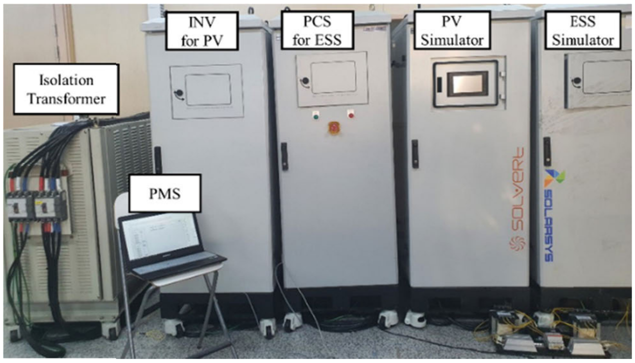
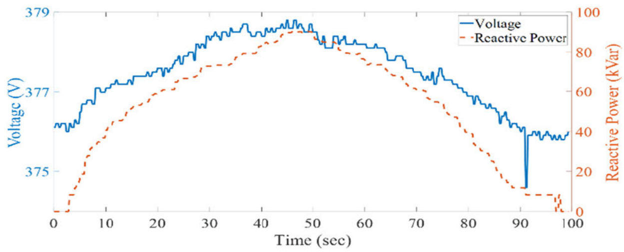
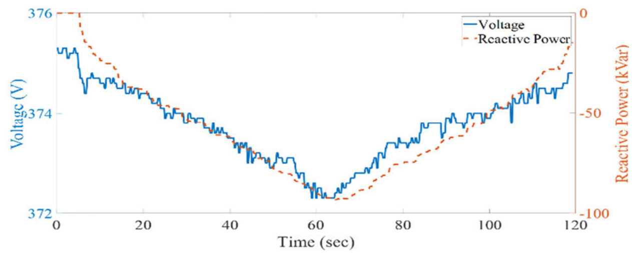


FIGURE 13. Experimental set for voltage compensation function.



(a) Lagging power factor control



(b) Leading power factor control

FIGURE 14. Voltage compensation due to reactive power supply.

confirm the change of voltage by the reactive power compensation, while the output power from PEIS is fixed. The P_{pv} and P_{ess} are supplied from the PV and ESS simulator, and they are fixed with the rated power of 100 kW. Also, the INV for PV and the PCS for ESS are connected to the same line. However, they are isolated by transformer to prevent switching interference and circulating current. Then, they are supplying the reactive power up to their rated capacity of 48.4% by adjusting the power factor of 0.9.

The real-time results are shown in Fig. 14. It is observed from Fig. 14(a) that the PMS regulates the lagging power factor, and the INV for PV and the PCS for ESS provide the positive reactive power. As the result, the voltage is increased. In contrast, it is known from Fig. 14(b) that the PMS adjusts the leading power factor, and the INV for PV and the PCS for ESS generate the negative reactive power. Correspondingly, the voltage is decreased.

B. VERIFICATION ON REAL TEST-BED

To verify the practical effectiveness of proposed PEIS of 100 kW, it is constructed on real test-bed, as shown in Fig. 15,

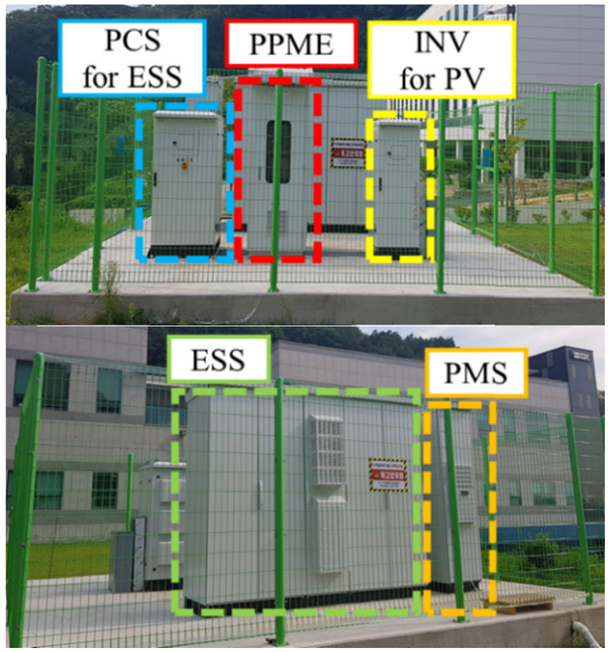


FIGURE 15. PEIS of 100 kW on the real test-bed.

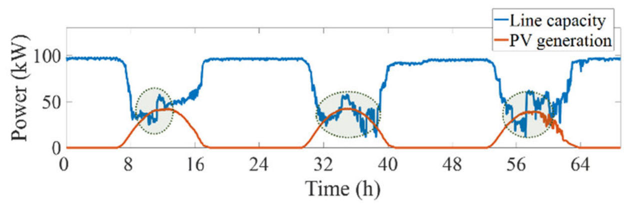


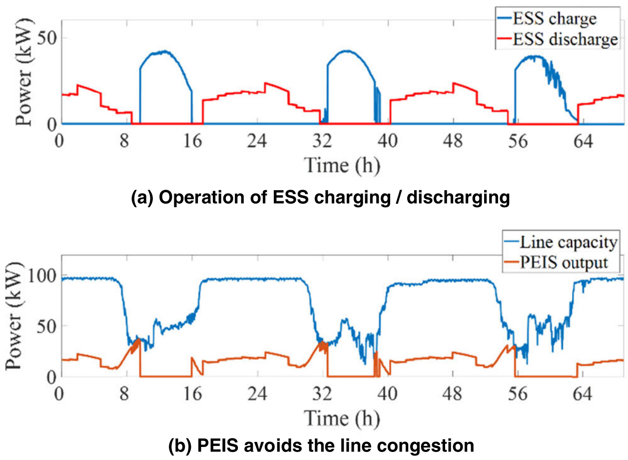
FIGURE 16. Line capacity and PV generation of demonstration test-bed in 3 days.

while implementing the proposed PMS. Because the amount of PV generation must be charged to the ESS, both the rated capacity of the INV for PV and the PCS for ESS are implemented to be equal as 100 kW. Also, the rated capacity of ESS is designed such that it is 2.5 to 3 times bigger than that of maximum PV generation [22], [23]. Therefore, the ESS of 274 kWh is connected to the PEIS.

After carrying out the test for 3 days, the experimental results are shown in Fig. 16. It is observed that the line congestion problem might occur when the P_{pv} is greater than the $P_{l.cap}$ (see the light green circles of Fig. 16). As confirmed in the case studies of Section IV, all functions such as voltage compensation and SOC management to solve this problem are performed in the experiment.

Also, it is known from the results of Fig. 17(a) that the PEIS discharges more power because its PMS reflects the price information at around 3:00, 27:00, and 50:00 when the REC price is the most expensive. In contrast, the output power of PEIS is adjusted not to exceed the line capacity even though it is the time to sell the PV generation at around 9:00, 32:00, and 56:00, as shown in Fig. 17(b).

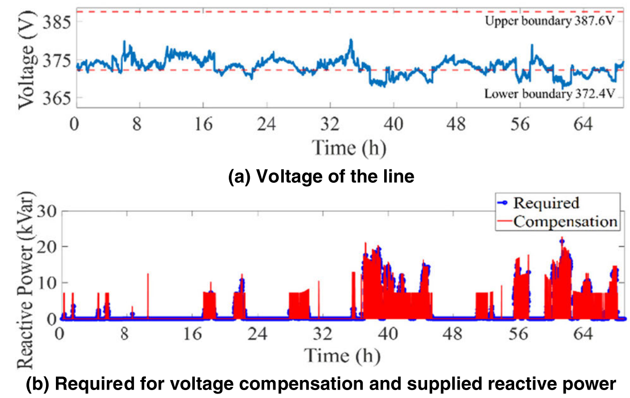
As mentioned in above, the effect of reactive power compensation is not high because the PEIS of 100 kW is not



(a) Operation of ESS charging / discharging

(b) PEIS avoids the line congestion

FIGURE 17. Results of active power control by the PEIS on the real test-bed.



(a) Voltage of the line

(b) Required for voltage compensation and supplied reactive power

FIGURE 18. Voltage measurements and corresponding reactive power compensation by the PMS on the real test-bed.

large enough to actually affect the line voltage. Nevertheless, the proposed PMS effectively supplies the reactive power by the power factor control according to the variations of line voltage in all times while solving the line congestion problem, as shown in Fig. 18.

VI. CONCLUSION

This paper proposed the new practical power management system (PMS) applied to the photovoltaic (PV) and energy storage system (ESS) integrated system (PEIS) to solve the line congestion and voltage problems in a distribution system. Also, it utilized the electricity price and state of charge (SOC) of ESS information for its optimal operation. To evaluate the performance of proposed PMS, the simulations case studies were carried out with the actual data. Moreover, the hardware prototype of PEIS with the rated power of 100 kW was implemented and tested on the real test-bed. Both simulation and experimental results verified that the proposed PEIS with new PMS can successfully solve the line congestion problem, mitigate the variations of voltage, and increase the economic profit of producer at the same time.

In this study, the South Korea electricity price and renewable energy supply policy were applied to the practical test on demonstration test-bed. In other words, the proposed PEIS and PMS is developed by considering the real price information and grid-code policy, etc. Also, many real-time field tests were carried out with actual data to verify the practical effectiveness of proposed PEIS and PMS. Therefore, it would be expected that the proposed PEIS and PMS over 1 MW (with the enhanced scalability) can be expanded for the field test on a practical distribution system of 22.9 kV without much difficulty.

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SEOUNG UK JEON (Member, IEEE) received the B.S. degree from Yonsei University, Seoul, South Korea, in 2011, where he is currently pursuing the Ph.D. degree through the combined M.S. and Ph.D. Program with the School of Electrical and Electronic Engineering. His research interests include power conversion system control, optimal management using converter-based renewable energy, and energy storage systems.

JINAH NOH (Graduate Student Member, IEEE) received the B.S. degree from Gyeongsang National University, Jinju, South Korea, in 2011. She is currently pursuing the Ph.D. degree through the combined M.S. and Ph.D. Program with the School of Electrical and Electronic Engineering, Yonsei University, Seoul, South Korea. She was an Assistant Researcher with KD Power Company Ltd., Chuncheon, South Korea, from 2012 to 2015. Her research interests include control and operation of power systems, energy management systems, and renewable energies-based distributed generation systems.

SEOKJU KANG (Graduate Student Member, IEEE) received the B.S. degree from Yonsei University, Seoul, South Korea, in 2016, where he is currently pursuing the Ph.D. degree through the combined M.S. and Ph.D. Program with the School of Electrical and Electronic Engineering. His research interests include operation of distribution networks, renewable energies-based distributed generation systems, and voltage stability of power systems.

JUNG-WOOK PARK (Senior Member, IEEE) was born in Seoul, South Korea. He received the B.S. degree *(summa cum laude)* from the Department of Electrical Engineering, Yonsei University, Seoul, South Korea, in 1999, and the M.S.E.C.E. and Ph.D. degrees from the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA, in 2000 and 2003, respectively. He was a Postdoctoral Research Associate with the Department of Electrical and Computer Engineering, University of Wisconsin-Madison, USA, from 2003 to 2004. He was also a Senior Research Engineer with LG Electronics Inc., South Korea, from 2004 to 2005. Since 2005, he has been with the School of Electrical and Electronic Engineering, Yonsei University, where he is currently a Professor. He is also the Director of the Yonsei-Power System Research Center for Great Energy Transition (Yonsei-PREFER) supported by the Leading Research Program (7.2*M* USD Grant for nine years), National Research Foundation (NRL), South Korea. His current research interests include power system dynamics, energy management systems, renewable energies-based distributed generation systems, operation and planning of microgrid, hardware implementation of power-electronic-based inverters, and so on. He was a recipient of the Young Scientist Presidential Award from the Korean Academy of Science and Technology (KAST), South Korea, in 2013.