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A Study on the Power Line Operation Strategy by the Energy Storage System to Ensure Hosting Capacity of Distribution Feeder with Electrical Vehicle Charging Infrastructure

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Abstract: The introduction of a complex electrical vehicle charging (EVC) infrastructure consisting of an electrical vehicle (EV) charger and renewable energy source (RES) in the distribution system has been required as an important countermeasure for global environmental issues. However, the problems for hosting capacity and power stability of the distribution feeder can be caused by the penetration of lager scaled RES and EVC infrastructure. Further, it is required for the efficient operation method to prevent congestion and to ensure hosting capacity for the distribution feeder due to the increase of variable RES and EVC infrastructure in the distribution systems. In order to solve these problems, it is necessary to develop a technology which is capable of stably introducing an EVC infrastructure without reinforcing the existing distribution system. Therefore, to maintain the existing hosting capacity of distribution feeder and allowable limits, this paper presents a virtual power line (VPL) operation method using Energy Storage System (ESS) based on the power and voltage stabilization control to ensure hosting capacity of the EVS infrastructure. The proposed operation method is determined by optimal power compensation rate (PCR) and voltage compensation rate (VCR). Specifically, ESS for VPL is controlled according to the charging and discharging mode is operated according to the comparison value of the PCR and VCR. From the test results, it is verified that hosting capacity of the distribution system can be maintained using the proposed control method of ESS for VPL operation.

Keywords: virtual power line; power compensation rate; voltage compensation rate; electrical vehicle charging; renewable energy source

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1. Introduction

1.1. Introduction

As distribution systems have been decentralized along with the technology development of electric vehicle charging (EVC) infrastructure including EV charger, RES have been actively interconnected and operated at the distribution feeder. Especially, introduction of complex electrical vehicle charging (EVC) infrastructure, which is composed of an electrical vehicle (EV) charger and RES in the distribution system, has been demanded as one of the countermeasures against global environmental issues [1–3]. However, a problem with hosting capacity and power stability of the distribution feeder can be caused by introduction of EVC infrastructure. In other words, diverse problems in power quality and hosting capacity at feeder such as voltage variations and acceptable capacity in distribution feeder may occur when EVC infrastructure including RES is interconnected at a secondary feeder in the distribution system. According to several articles dealing with EVC and stabilization of the distribution system, strategies regarding charging cost of the EVC have been presented to mitigate the effect of EV charging to the primary feeder in distribution [4–11]. From

Ref. [4], it is known that EV demand is composed of the route characteristics of users, and the charging cost is determined by considering the voltage deviation in primary feeder in distribution system. On the other hand, the areas where high demand of EV charger is expected as high cost price, and accordingly demand on EV charging has low cost price that regulate the voltage of the feeder, could be kept within stable boundary. And Time-of-Use (TOU) energy metering is introduced to curtail the load demand at peak demand and to eliminate heavy loads at the transformer and feeder [5–11]. In addition, Ref. [12] presented automatic demand response method as a real-time cost price–based method. However, these studies have only proposed to solve the voltage quality in distribution system in terms of concept of EV charger. The increasing introduction of variable RES and EVS infrastructure in distribution systems requires an efficient operation method to prevent congestion and to ensure hosting capacity for distribution feeder. The traditional approach to increasing grid capacity is reinforcing the system with additional network components and the existing feeder or cables to solve power or voltage constraints. However, reinforcement for the existing feeder or cables has a disadvantage of spending a lot of money and time. Recently, to solve these problems and introduce massive scale of RES and EV charger at the distribution feeder, a power line reinforcement method called virtual power line (VPL) method as of non-feeder alternative is being proposed, which is done without reinforcing the power line [13]. Therefore, to maintain the existing hosting capacity of distribution feeder and allowable limit when introducing large scale of EVC infrastructure, this paper presents the Energy Storage System (ESS) control strategy using the VPL method, which makes possible the operation of the distribution feeder interconnected with EVC infrastructure without reinforcing the power line. VPL operation strategy by the ESS is based on the power and voltage stabilization control to ensure hosting capacity of EVC infrastructure. Specifically, the operation method of VPL by the ESS is determined by optimal power compensation rate (PCR) and voltage compensation rate (VCR). Based on the operation strategy to be kept within the hosting capacity of EVC, it is confirmed that power in the distribution system can be maintained within the allowable limit from the actual test results.

1.2. Contributions

To maintain within the existing hosting capacity at distribution feeder when introducing larger scaled EVC infrastructure, this paper proposes a strategy of stabilizing the distribution feeder with EVC infrastructure using the control strategy of ESS for VPL operation. The main contributions are summarized as follows.

- This paper adopts control strategy of ESS for VPL operation to ensure hosting capacity in distribution feeder, which is interconnected with EVC infrastructure. To operate the VPL, power in the distribution feeder with EVC infrastructure is compensated by the ESS as much as the target hosting capacity (ΔP_{ESS} *and* ΔU_{ESS}) of section using the PCR and VCR, considering the bandwidth of ESS. Under these concepts, verification for the proposed operation strategy is performed by the actual test at distribution feeder interconnected with EVC infrastructure.
- In this paper, two cases are analyzed based on ESS control strategy using the VPL method, which is the possible operation of the distribution feeder interconnected EVC infrastructure without reinforcing the power line. The first case is the characteristic test for hosting capacity at DUT (device under test) location of distribution feeder interconnected with EVC infrastructure when ESS for VPL operation is not introduced. The second case is the characteristic test for hosting capacity at DUT location of distribution feeder interconnected with EVC infrastructure when ESS for VPL operation is introduced.

2. Operation Characteristics of ESS for VPL to Stably Introduce of EVC Infrastructure

2.1. VPL Characteristic

The increasing introduction of variable RES and EVS infrastructure in distribution systems requires an efficient operation method to prevent congestion and to ensure hosting capacity for the distribution feeder. The traditional approach to increase grid capacity is achieved by reinforcing the system with additional network components and existing feeder or cables to solve power or voltage constraints. However, reinforcement for existing feeder or cables has the disadvantage of spending a lot of money and time. Recently, to solve these problems and to introduce large scale of RES and EV charger at distribution feeder, a power line reinforcement method, virtual power line (VPL) method, as a non-feeder alternative is being proposed without reinforcing the power line. Therefore, to keep within the existing hosting capacity of the distribution feeder and the allowable limit, this paper presents the ESS operation using the VPL method that makes possible power lines operation without reinforcing the power line, instead of reinforcing or building additional transmission and distribution systems [13]. Specifically, VPLs technology by ESS is based on the concept of virtual power lines innovation landscape brief of IRENA 2020 Page 3, which includes at least two functions as shown in Figure 1 and Table 1. First, the VPL as supply side operation has a charging function for power that cannot be transmitted due to distribution congestion when the RES is generating power. Second, the VPL as demand-side operation has a discharging function for power that ESS uses to meet the demand during periods when there is insufficient hosting capacity of distribution using ESS charged during previous periods of off-peak load and RES generation.

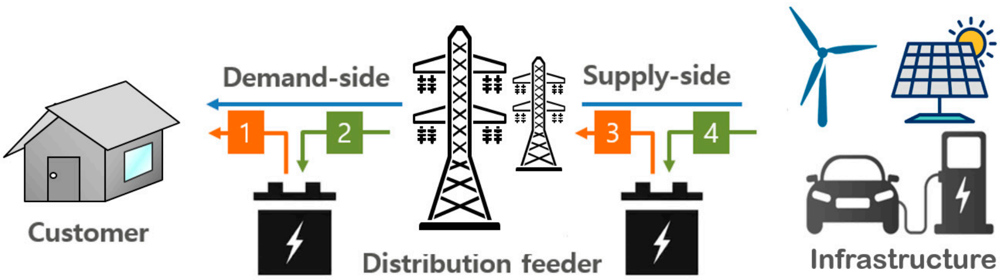


Figure 1. Concept for VPL operation method by ESS.

Table 1. Classification for two functions of VPL.

Concept	Number	Content for Function
Demand side	1	Discharges to address peak-to-peak load
	2	Charges when load is lower than RES and hosting capacity is available
Supply side	3	Discharges to demand-side ESS when hosing capacity is available
	4	Charges using RES to avoid curtailment due to grid congestion

2.2. Operation Characteristic of ESS to Stably Introduce of EVC Infrastructure

When the larger scaled EVC infrastructure is introduced at the distribution system, the hosting capacity of feeder increases over the existing hosting capacity by the EV charging capacity and the output of the RES. For example, when the output of renewable energy is higher than the customer power, the capacity and voltage of feeder is increased by the reverse power flows. Moreover, when the EV capacity and the end user power are increased, the capacity of the feeder is raised and the voltage of the feeder is dropped by the forward power flows. Therefore, this paper presents VPL control strategy by ESS to ensure and to stably operate the hosting capacity of distribution feeder interconnected with EVC infrastructure. Specifically, ESS for VPL operation is operated as the charging mode when RES output should violate the capacity of feeder. Further, it controls the discharge mode when customer power and EV power should be higher than the hosting capacity of the feeder. Because the power system has the characteristics of changing voltage and frequency, this paper adopts a voltage and power value as a control variable for maintaining rated power of distribution considering EVC infrastructure. Under these concepts, limited upper and lower limit set points for voltage and power are assumed as the limit range for reverse hosting capacity and limit range for forward hosting capacity. Figure 2 shows the principle of discharging the ESS when the voltage or power (forward power flow) is less than lower limit during a heavy load. In addition, Figure 3 shows the principle of charging the ESS when the voltage or power (reverse power flow) is higher than the upper limit during the off-peak load and reverse power flow.

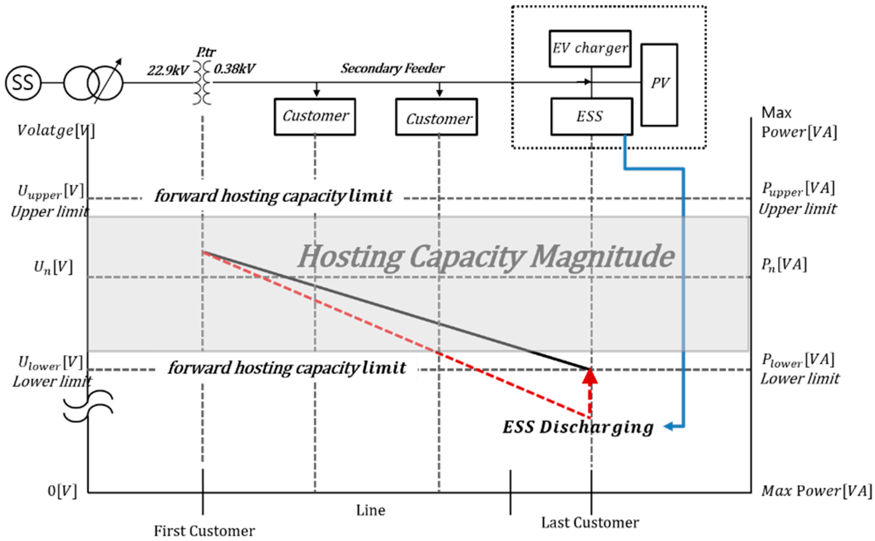


Figure 2. Operation strategy of VPL ESS in case of lower limit.

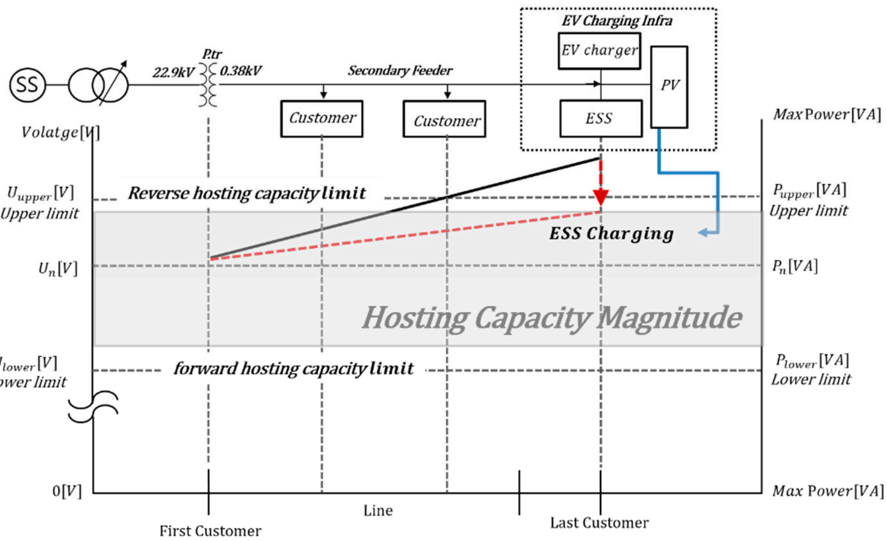


Figure 3. Operation strategy of VPL ESS in case of upper limit.

On the other hand, if ESS based on the VPL control strategy suppresses peak demand, it can reduce investment in the distribution system infrastructure such as transformers and distribution lines through peak shaving in certain areas at times of peak demand. It can postpone the investment needed by mitigating network congestion through peak shift. However, it is not economical to apply large-capacity ESS as a VPL function at the price per kWh of ESS. Therefore, in order to minimize the introduction capacity of the ESS, this paper proposes a strategy of VPL operation by ESS that operates only when it exceeds the allowable value (upper and lower limit of hosting capacity).

3. Operation Strategy of the ESS for VPL

3.1. Control Concept of ESS for VPL Operation

When the EVC infrastructure including the RES is introduced in the distribution feeder, the magnitude of voltage and power have a possibility to be not kept within allowable limit (voltage and hosting capacity) by the EV charging capacity and the output of the RES. For example, when the output of renewable energy is greater than the customer power, the feeder voltage and power is increased by the reverse power flow. Moreover, when the EV charging load and the customer load are increased, as feeder voltage is dropped, power is raised by heavy load and forward power flow. Therefore, to maintain within the existing hosting capacity at distribution feeder when introducing the larger scaled EVC infrastructure, this paper proposes a strategy of stabilizing the distribution feeder with EVC infrastructure using the control strategy of ESS for VPL operation, which is operated according to the charge operation when RES output violates the hosting capacity. Moreover, it is controlled by the discharge operation when EV output is higher than the hosting capacity of the feeder.

To briefly explain the proposed VPL operation strategy by ESS, the power at the feeder with EV infrastructure is controlled within hosting capacity (upper limit capacity, lower limit capacity) by charging and discharging of ESS as much as the determined power and voltage (ΔP_{ESS} *and* ΔU_{ESS}) range as expressed in Figure 4.

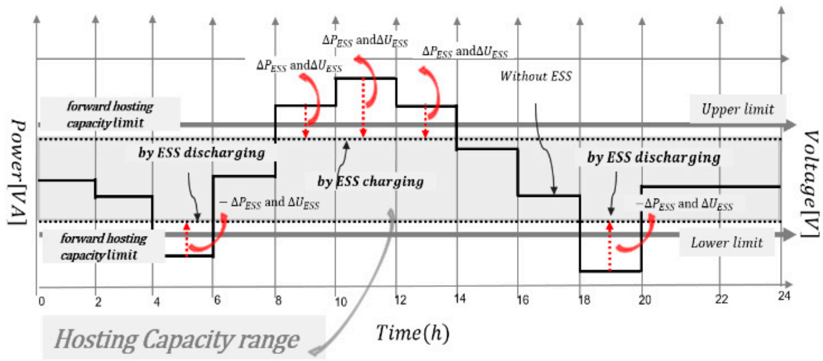


Figure 4. Operational concept of proposed method.

On the other hand, the power is compensated by the ESS for VPL as much as the target hosting capacity (ΔP_{ESS} *and* ΔU_{ESS}) of the feeder that is defined as the power compensation rate (PCR) and power compensation rate (VCR). However, in order to prevent frequent operation when ESS is activated, a non-operational boundary must be a set point. Therefore, this paper presents a setting method with margin, as shown in Figure 5. Specifically, the margin (Bandwidth) is applied to the under area of reverse hosting capacity limit (upper limit) and over area of forward hosting capacity limit (lower limit), and ESS is operated by considering PCR and bandwidth coefficient. Power compensation rate means target hosting capacity (ΔP_{ESS} *and* ΔU_{ESS}).

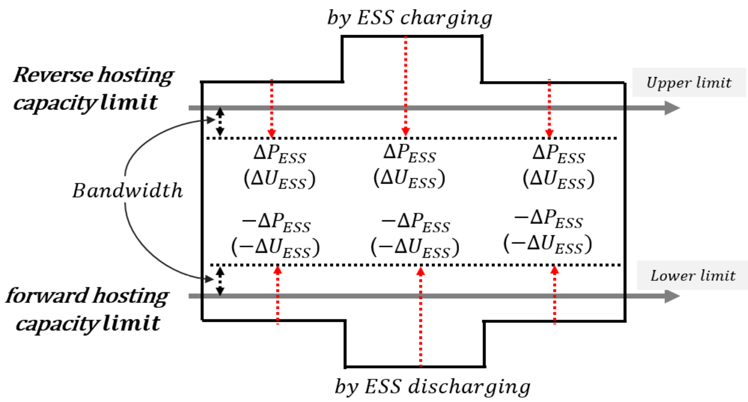


Figure 5. Margin (Bandwidth) considering PCR.

3.2. Control Strategy of ESS for VPL Operation

As mentioned above, the control strategy of ESS for VPL operation based on the power and voltage to ensure the hosting capacity of feeder when introduced with the EVC infrastructure is categorized as follows.

To determine bi-directional capacity magnitude ($U_{pacatiy}$) from rated voltage to the upper and lower limit set point at distribution feeder with EVC infrastructure, it is calculated by multiplication of the maximum allowable current in feeder, line impedance and load factor as shown in Equation (1). Here, load factor is assumed as available maximum hosting capacity for VPL operation and is applied as the peak load boundary from 0.7 to 0.8. Maximum passing current means largest passing current in the whole time period in Equation (2). In addition, voltage range in each section has the same value because of the linear characteristic of voltage based on the current variation.

$$U_{capacity} = I_{max.i} \times feeder\ Z_i \times LF^{hosting} \tag{1}$$

$$I_{max.i} = Max\left(ABS\left(I_{feeder}(k \cdot T_s)\right)\right)\ \forall\ m = 1 \cdots N,\ 0 \leq k \cdot T_s \leq 24\ \text{h} \tag{2}$$

where, $U_{capacity}$ is voltage value at distribution feeder of EVC infrastructure, I_{max} is maximum passing current, $LF^{hosting}$ is load factor at heavy load, $Z\ i$ is section number of EVC infrastructure, ΔT_s *is* sample time and I_{feeder} is passing current at distribution feeder.

The upper limit and lower allowable limit are determined by rated voltage and voltage range calculated by considering the hosting capacity of the feeder, as expressed in Equations (3) and (4).

$$U_U = U_n + U_{capacity} \tag{3}$$

$$U_L = U_n - U_{capacity} \tag{4}$$

where, U_u is upper limit (voltage), U_L is under limit (voltage) and U_n is rated voltage.

From the Equations (3) and (4), the hosting capacity value at the distribution feeder introduced with the EVS infrastructure is defined by the relationship between average value of upper limit (U_U) and lower limit (U_L) and maximum passing current, as shown in Equation (5), where upper and lower limit are considered as absolute values.

$$P_{capacity} = I_{max.i} \times \frac{ABS(U_U) + ABS(U_L)}{2} \tag{5}$$

where, $P_{capacity}$ is voltage value at distribution feeder with EVC infrastructure, $ABS(U_U)$ is absolute value for upper limit and $ABS(U_L)$ is absolute value for lower limit.

Then, settings of reverse hosting capacity limit (upper limit) and forward hosting capacity limit (lower limit) are expressed as follows.

$$P_u = I_{max.i} \times U_U \tag{6}$$

$$P_L = I_{max.i} \times U_L \tag{7}$$

where, P_u is upper limit (Power), P_L is under limit (Power) and U_n is rated voltage.

ESS has a possible difficulty in frequent control within 1 s because of response time of the converter for ESS. Under these concepts, this paper proposes the operation method of ESS through the time interval as applying average real-time power value at the feeder during the set time (t_x) and real-time voltage value in Equations (8) and (9). However, operation time of ESS is only defined by pre-set time to calculate average real-time power value.

$$P_{real}(t_x) = \left[\int_{t=0}^{t=tx} P_{ci}(t)\right]/t_x \tag{8}$$

$$U_{real}(t_x) = \left[\int_{t=0}^{t=tx} U_{ci}(t)\right]/t_x \tag{9}$$

where, $P_{real}(t_x)$ is average power at section of EVC during t_x time, $V_{real}(t_x)$ is average voltage at section of EVC infrastructure during t_x time, t_x is continuous operation time before next operation time of ESS, and $P_{ci}(t)$ and $U_{ci}(t)$ are real-time power and voltage at section of EVC infrastructure.

In addition, to curb increment for introduction capacity of ESS, PCR (power compensation rate, $\Delta P_{ESS}(t_x)$) and VCR (voltage compensation rate, $\Delta U_{ESS}\ (t_x)$) in Equations (10) and (11) are obtained by relationship with average real-time power value, bandwidth coefficient and hosting capacity value (power) of feeder from the from the Equation (1) to Equation (9). To prevent frequent operation and ensure stable control of ESS for hosting capacity, the bandwidth coefficient is considered to VCR and PCR.

$$\Delta P_{ESS}(t_x) = (P_{capacity} - P_{real}(t_x)) \pm BW \tag{10}$$

$$\Delta U_{ESS}(t_x) = (U_{capacity} - U_{real}(t_x)) \pm BW \tag{11}$$

where, $\Delta P_{ESS}(t_x)$ is PCR (power compensation rate), $\Delta U_{ESS}(t_x)$ is VCR (voltage compensation rate) and BW is bandwidth of ESS.

By considering the equations from Equation (1) to Equation (11), the operation signal to ensure hosting capacity of the distribution feeder interconnected with EVC infrastructure is determined by the relationship between voltage and power compensation rate with EV infrastructure. Meanwhile, when the increment ratio of power like PCR (ΔP_{ESS}) during the (t_x) in Equation (10) is not kept within the determined upper limit of power, ESS for VPL is introduced to ensure that hosting capacity is controlled as charging mode wherein 'A' signal is "1" and 'B' signal is "0". Furthermore, ESS is controlled as discharging mode in which A value is "0" and B value is "1" when increment ratio of power like PCR(ΔP_{ESS}) during the (t_x) in Equation (11) is lower than the P_L value. However, because ΔP_{ESS} only considers the feeder capacity, ΔV_{ESS} is applied to determine the non-operational state of the ESS. Therefore, the above-mentioned strategy is expressed as shown in Equation (12) and expression for the operation signal of ESS is illustrated in Table 2.

$$A(t_x), B(t_x) = \begin{bmatrix} \Delta P_{ESS}(t_x) > P_U & A = 1,\ B = 0 \\ \Delta P_{ESS}(t_x) < P_L & A = 0,\ B = 1 \\ U_L \le U_{real}(t_x) + \Delta U_{ESS}(t_x) \le U_U & A = 0,\ B = 0 \end{bmatrix} \tag{12}$$

where, $A(t_x)$ is the charging signal (+) and $B(t_x)$ is the discharging signal (−).

Table 2. Operation signal classification of ESS.

Classification	$\boldsymbol{A(t_x)}$	$\boldsymbol{B(t_x)}$
Charging operation (+)	1	0
Discharging operation (−)	0	1
Not in operation	0	0

From the determined control characteristics of Equation (13), when the ESS is operated, the output is determined by the PCR value.

$$\mathrm{P}_{\mathrm{ESS}}^{\mathrm{cmd}}(k) = \Delta P_{ESS}, A(\mathrm{K}), B(\mathrm{K}) \tag{13}$$

where, $\mathrm{P}_{\mathrm{ESS}}^{\mathrm{cmd}}(k)$ is the output value of ESS $A(\mathrm{K})$ is the charging signal (+), $B(\mathrm{K})$ is the discharging signal (−) and K is control function.

As mentioned earlier, the control strategy of ESS for VPL operation considering hosting capacity ($LF^{hosting}$) is expressed by Figure 6.

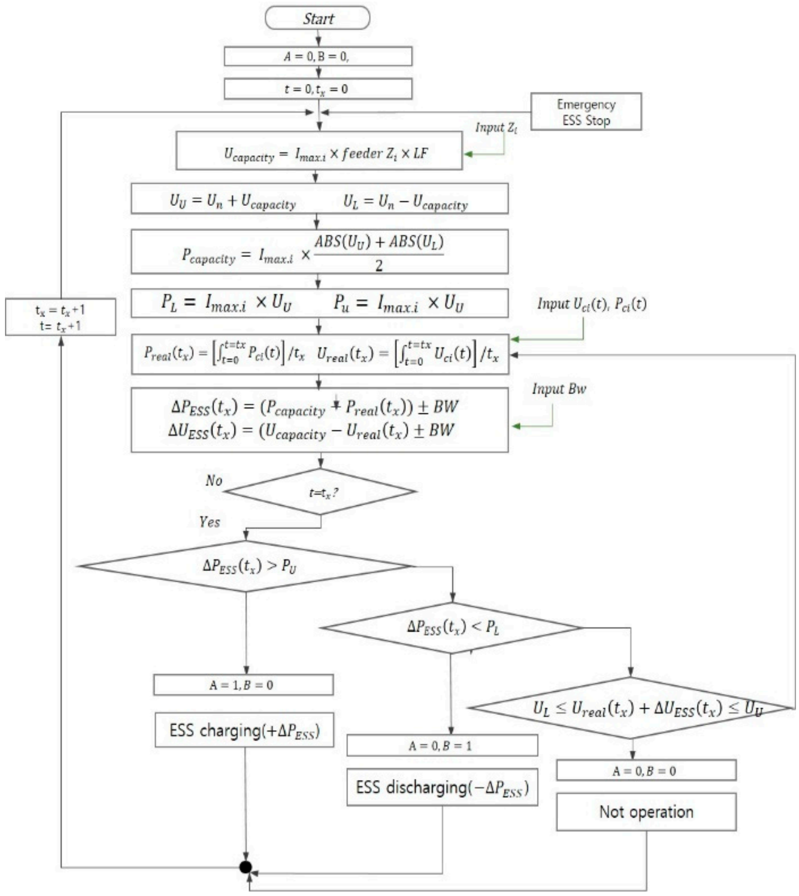


Figure 6. Stabilization strategy of hosting capacity by the ESS control.

4. Implementation of EVS Infrastructure

Figure 7 shows the EVS infrastructure site, which is composed of an artificial distribution system (15 kW load, line impedance), test device (PHILS: Load HILS and line impedance HILS), standard charger (7.7 kW), ESS (40 kWh) and PV system (20 kWp). Under these concepts, verification for proposed operation strategy is performed by the actual test at distribution feeder interconnected with EVC infrastructure based on the control strategy using the ESS for VPL operation. Meanwhile, this paper presents a method to keep the allowable limit for power and voltage of distribution feeder through the ESS introduction with electric vehicle and RES. Here, PHILS means power-hardware-in-loop-system and Load HILS means artificial controllable load device.

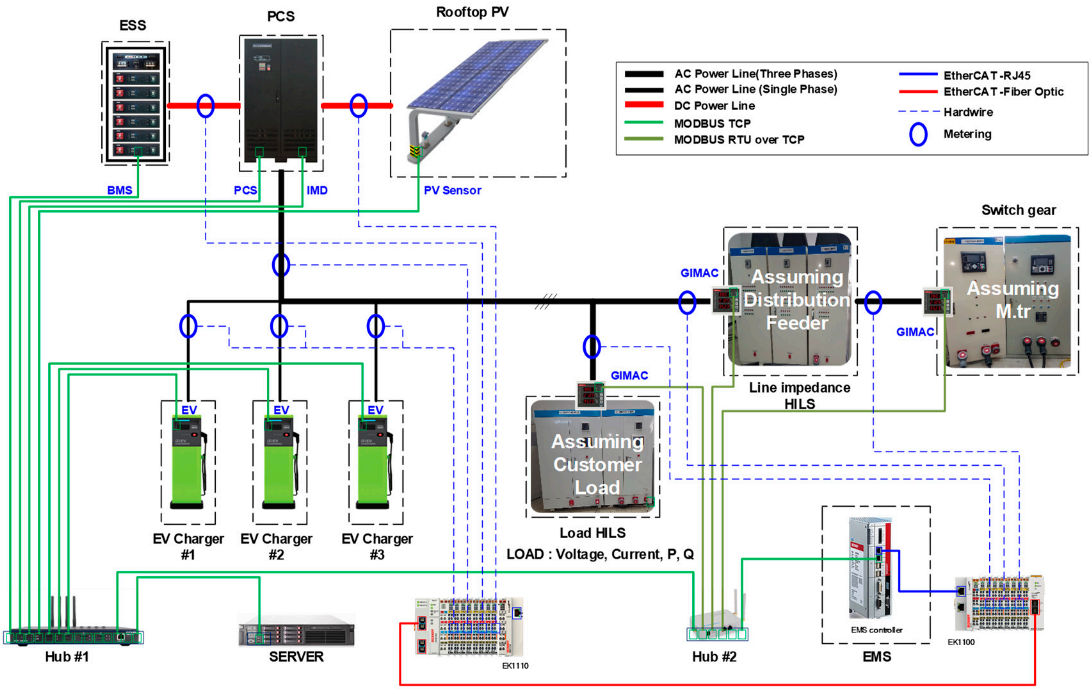


Figure 7. Electric vehicle charging infra linked with PHILS.

The EVC infrastructure is an integrated system in which PV, ESS, and artificial controllable loads device are linked to secondary feeder and must be kept in stable operation under various conditions by external environment. Depending on the unpredictable generation of renewable energy and consumption of the loads like EV, the voltage could reach an unstable state occasionally, and an emergency stop may be necessary in case of malfunction of the components. Therefore, the proposed control algorithm is implemented based on the state machine to operate the whole system, as shown in Figure 8.

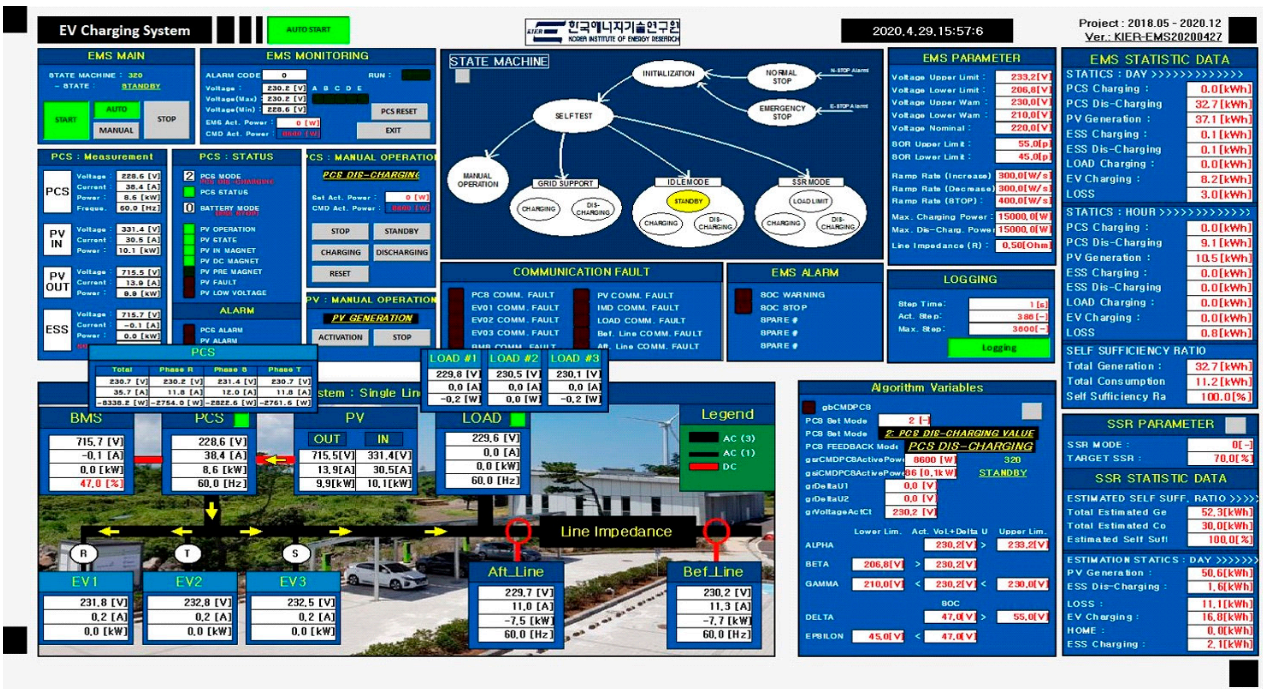


Figure 8. EMS for EV Charging Infrastructure.

The EVC infrastructure is an integrated system in which PV, ESS, and loads are linked to secondary feeder and must be kept in stable operation under various conditions by external environment. Therefore, combining low voltage (LV) distribution system, PV, ESS, load, EV, and EMS with the proposed strategy, the entire EVS infrastructure is implemented in the test site of the Korea Institute of Energy Research, as shown in Figure 9.

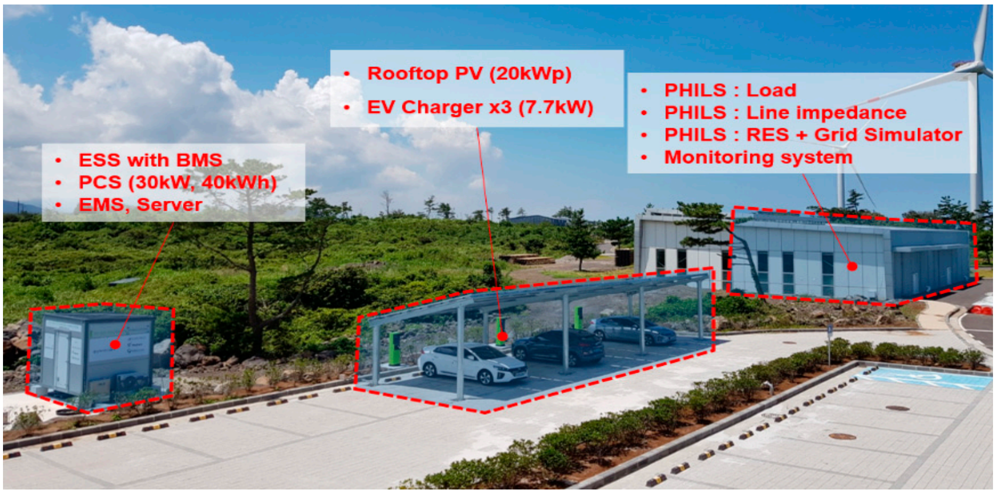
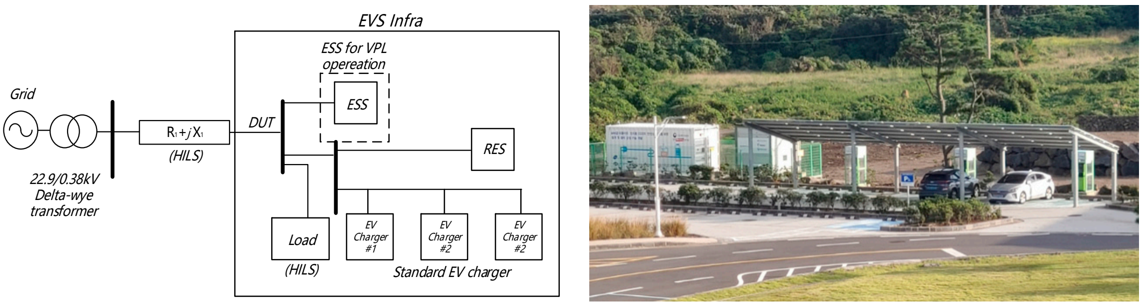


Figure 9. EV Charging infrastructure test site.

5. Case Studies

5.1. Test Condition

To verify the proposed strategy, the configuration of EVC infrastructure is composed of an artificial distribution system (15 kW Load, Line impedance) test device (PHILS), standard charger (7.7 kW), ESS (40 kWh) and PV system (20 kWp), as shown in Figure 10. Moreover, the feeder voltage and capacity were analyzed as average value per 10 min from 00:00 to 24:00 (all time) and real test conditions for ESS control are expressed in Table 3.



(**a**) (**b**)

Figure 10. Configuration of EVC infrastructure. (**a**) Single diagram. (**b**) Test Bed.

Table 3. Real test Data.

EVC Infrastructure Configuration at Test Site			
Grid	3phase 380VL-L	Load capacity	Max. 30 kW Variable
PV Capacity	20 kWp	Load pattern by load HILS	Residential Area
EV Charger	7.7 kW	Line impedance per km	0.2 + j0.4 step Variable
Wire type	Thr-cv 15 mm^2	$R_1 + jx_1$ feeder	2 km 0.4 + j0.8
ESS	40 kWh (PCS 30 kW)	Transformer capacity	50 kVA

To verify proposed control strategy, test conditions for the load pattern, output of RES with the PV system and demand pattern of EV charger are adopted as actual output pattern, as shown in Figure 11. The above patterns show results by the operation characteristics under the 30 kW scale based on the EVC infrastructure capacity. Here, PV output exceeds 120% of the rated power generation considering the weather characteristics. Furthermore, demand loads are composed of the EV charger and artificial controllable loads device.

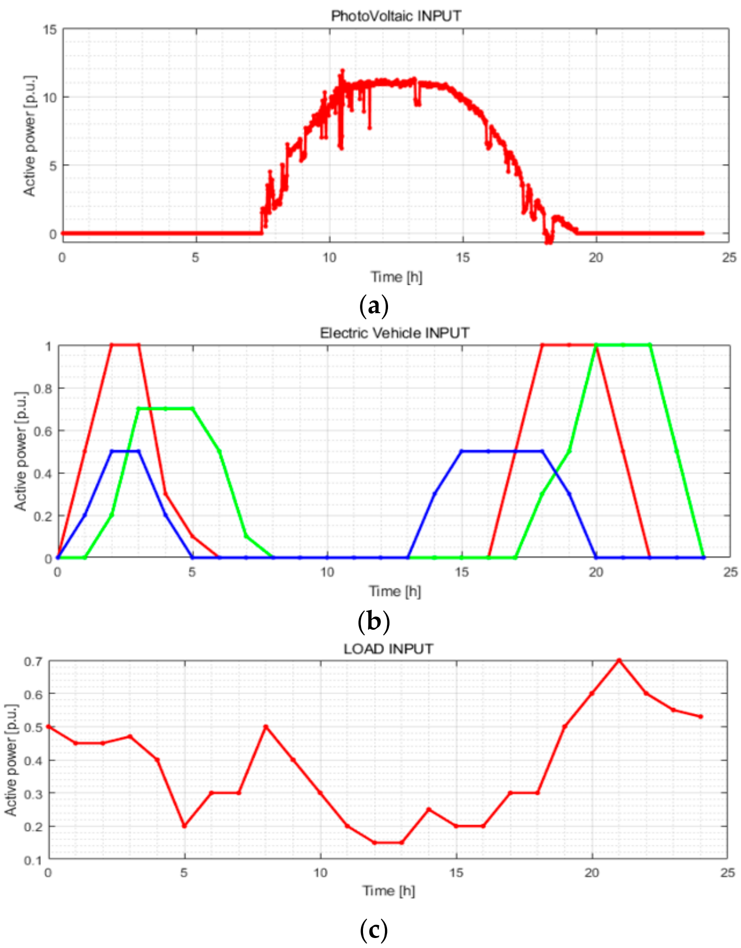


Figure 11. Output pattern of the EV charger, PV system and Load. (**a**) PV data (24 h). (**b**) EV charging data (24 h). (**c**) Load data using the PHILS (24 h).

In addition, hosting capacity ($LF^{hosting}$) of VPL is adopted to 70% (21 kW) of rated power (30 kW) considering load HILS and EV capacity. It is expressed in Table 4.

Table 4. Hosting capacity ($LF^{hosting}$) of VPL.

Hosting Capacity Characteristic				
$LF^{hosting}$	70%	Hosting capacity	Existing	30 kW
			VPL	21 kW

5.2. Results and Discussion

In this paper, two cases are analyzed based on ESS control strategy using the VPL method, which is the possible operation of distribution feeder interconnected with EVC infrastructure without reinforcing the power line. The first case refers to the characteristic test for hosting capacity at DUT (device under test) location of the distribution feeder interconnected with EVC infrastructure when ESS for VPL operation is not introduced. The second case refers to the characteristic test for hosting capacity at DUT location of the distribution feeder interconnected with EVC infrastructure when ESS for VPL operation is introduced. The grid power availability time for test for two cases is considered 24 hours' time horizon.

5.3. Hosting Capacity Characteristic by Proposed Strategy

5.3.1. Analysis of Hosting Capacity Characteristic without ESS

Figures 12 and 13 show the voltage and power characteristics at DUT location in EVC Infrastructure site when ESS is not operated with proposed control strategy. From the violated power with reverse power flow (from 10:00 to 14:10) and violated power with forward power flow (from 01:40 to 04:00 and from 18:00 to 22:10) phenomena, it is clear that the hosting capacity cannot be kept within allowable power conditions (over power phenomena) at 10:00–15:10 when the PV system generated the maximum output. Furthermore, at heavy load time (from 01:40 to 04:00 and from 18:00 to 22:10), the power at the section of EVC infrastructure was also less than the lower limit due to energy demands for the charging of EV. Therefore, the power cannot be exactly maintained within the hosting capacity at distribution feeder interconnected with EVS infrastructure because the power is not able to be compensated by the ESS for VPL operation.

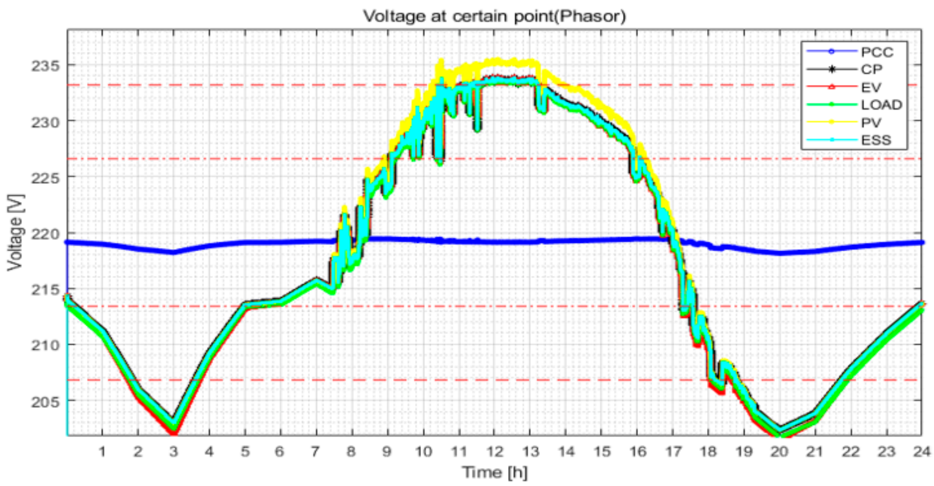


Figure 12. Analysis (voltage) of hosting capacity characteristic at EVC infrastructure without ESS.

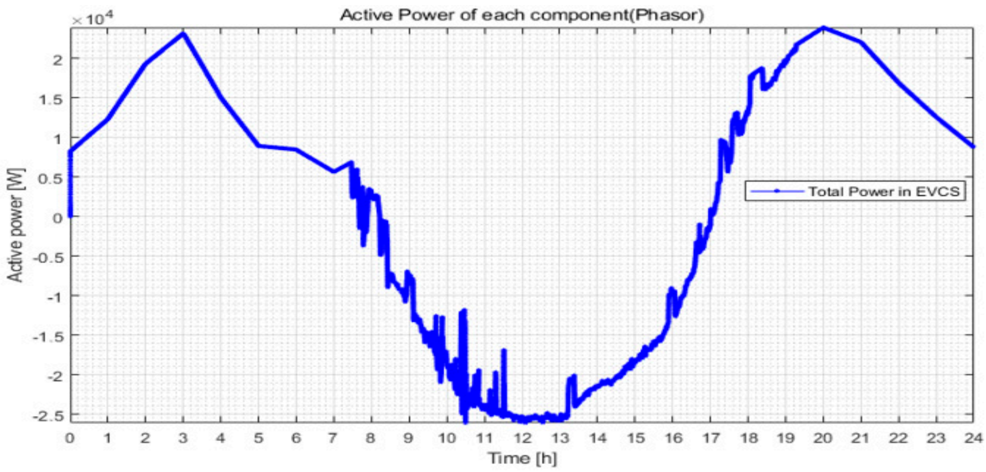


Figure 13. Analysis (power) of hosting capacity characteristic at EVC infrastructure without ESS.

On the other hand, Figure 14 shows the characteristics that only RES, EV, and load are outputted when the ESS is not operation.

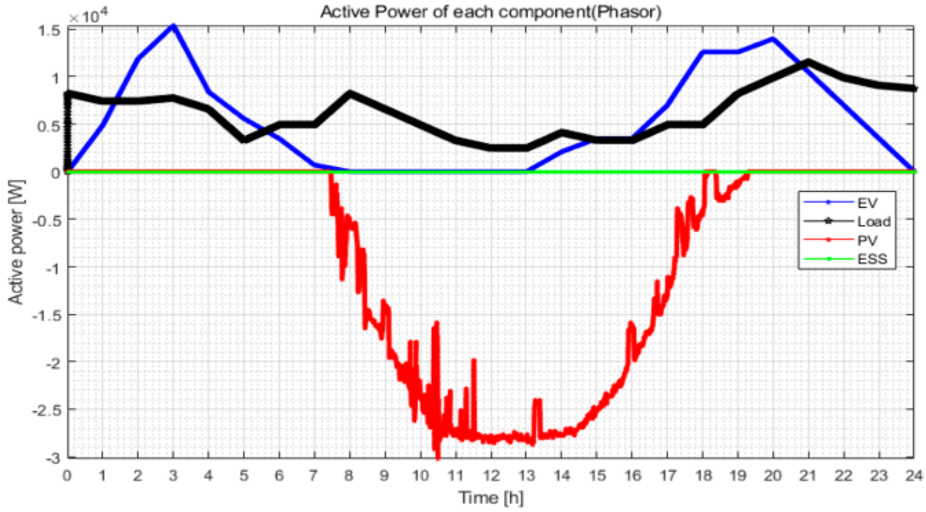


Figure 14. Analysis (power) of active power characteristic without ESS.

5.3.2. Analysis of the Hosting Capacity Characteristic by ESS Operation

Figures 15 and 16 show the voltage and power characteristics at DUT location in EVC Infrastructure site when ESS is operated by proposed control strategy as VPL function. Based on the test result using the 30 kW scaled EVC infrastructure, the value of power (20.8 kW) at all-time could be perfectly kept within the hosting capacity by operation strategy at feeder with EVS infrastructure. Specifically, from the violated power with reverse power flow (from 10:00 to 14:10) and violated power with forward power flow (from 01:40 to 04:00 and from 18:00 to 22:10) phenomena, it is clear that it is possible to be kept within hosting capacity by ESS control strategy for VPL operation at EVS infrastructure in Figure 15. Therefore, it is confirmed that better power conditions can be maintained through the control method of ESS for VPL operation to keep hosting capacity.

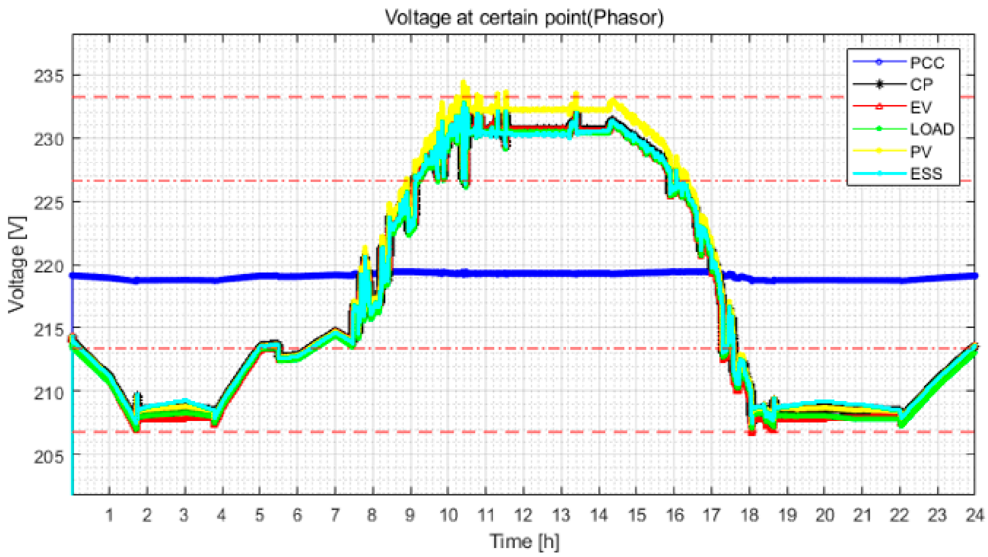


Figure 15. Analysis (voltage) of hosting capacity characteristic at EVC infrastructure with ESS.

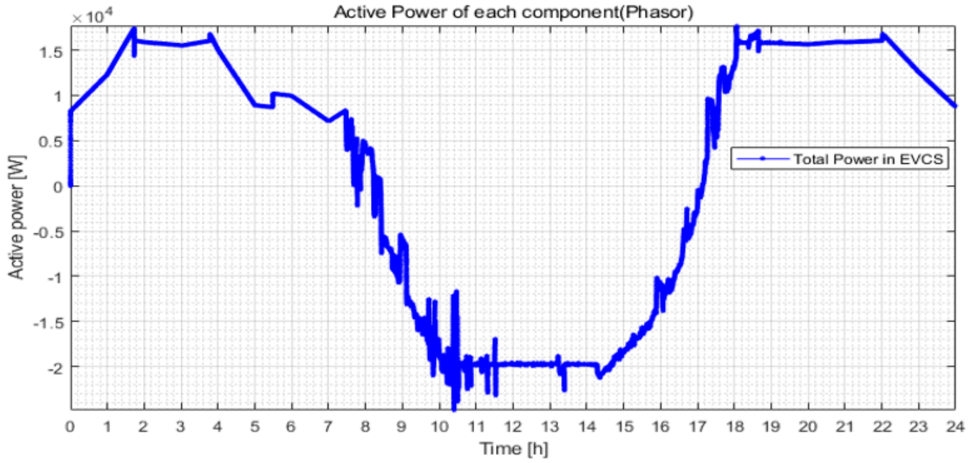


Figure 16. Analysis (power) of hosting capacity characteristic at EVC infrastructure with ESS.

Meanwhile, Figure 17 shows the characteristics of the ESS being controlled by the proposed strategy when the RES, EV, and load are in operation. From the test result in Table 5, the value of power (maximum 20.8 kW) at all-time could be perfectly kept within the hosting capacity by operation strategy, and acceptance rate was improved by more than 30% compared to the existing method (without VPL function) Therefore, it was confirmed that the ESS operates stably according to the proposed strategy, and also the power flow of distribution feeder is kept within the hosting capacity. Moreover, it is clear that the introduction of ESS as VPL function can also expect an indirect benefit such as reduction of the investment cost by the effective utilization of distribution feeder facilities.

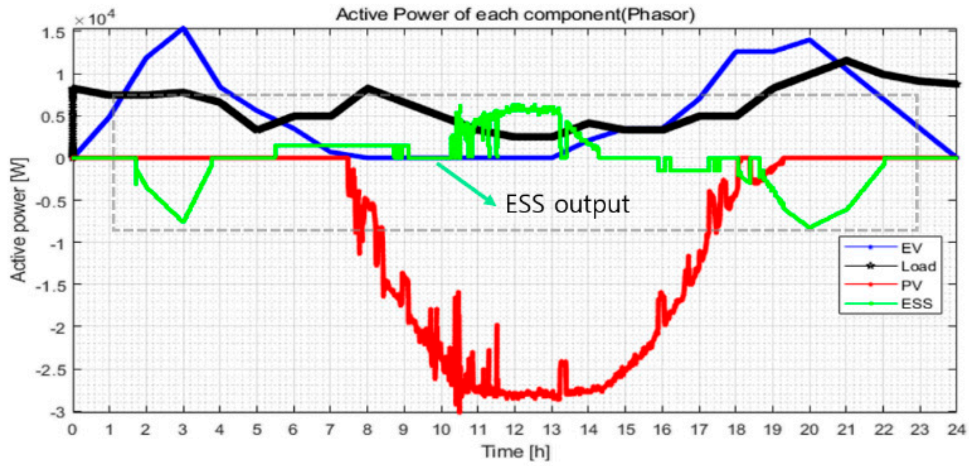


Figure 17. Analysis of active power characteristic with ESS.

Table 5. Results of hosting capacity ($LF^{hosting}$) of VPL.

Hosting Capacity Test Results					
$LF^{hosting}$	69.8%	Hosting capacity	Existing (Feeder)	condition	Max. 30.0 kW
				result	Max. 29.7 kW
Additional available capacity	7 kW (30.2%)		Pro posed (VPL)	condition	Max. 21.0 kW
				result	Max.20.8 kW

5.4. ESS Control Characteristic by Proposed Strategy

Based on the proposed strategy of ESS for VPL operation, control characteristics of ESS were analyzed for the stable operation of VPL when the hosting capacity of distribution feeder was not kept within an allowable limit. In this case, it is confirmed that ESS was exactly controlled by the operation determination signal which is ($\alpha(t_x)$: *charging*) and ($\beta(t_x)$: *discharging*) in Figure 18.

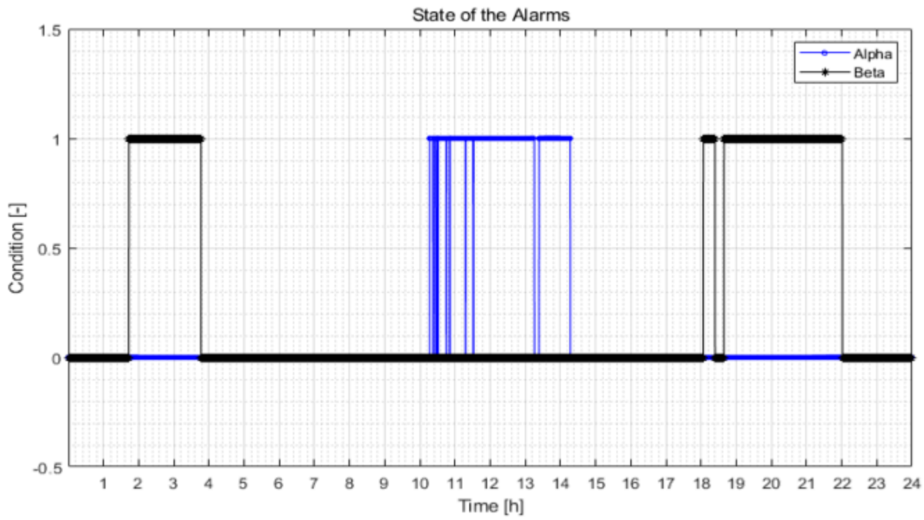


Figure 18. Operation signal of EVS for VPL operation.

On the other hand, output characteristics of ESS to keep the hosting capacity of distribution feeder interconnected with EVC infrastructure during the 24 h is shown in Figure 19. Meanwhile, when real-time power magnitude cannot be maintained within the hosting capacity, it is confirmed that the ESS properly compensates power within hosting capacity by charging and discharging according to the reverse power flow and the forward power flow. From the control characteristics in Figures 18 and 19, it is clear that the proposed control strategy of ESS for VPL operation is a useful tool.

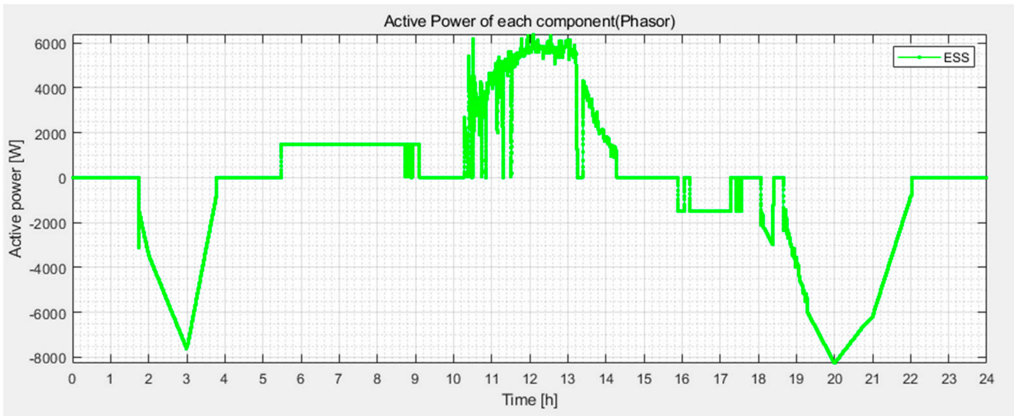


Figure 19. Control capacity by the ESS operation.

6. Conclusions

In order to ensure the hosting capacity in the distribution feeder interconnected with EVS infrastructure, the paper proposes a control strategy of ESS for VPL operation which is operated according to the charging mode when RES output exceeds hosting capacity, or the discharge mode when customer power and charging output of EV violates the hosting capacity. The main results are summarized as follows:

(1) To keep within the existing hosting capacity of distribution feeder and allowable limit, this paper presents the ESS operation using the VPL method, which makes possible the operation of distribution feeder interconnected EVC infrastructure without rein-

forcing the power line, instead of reinforcing or building additional transmission and distribution systems.

(2) In order to overcome the problem of violating the hosting capacity at the feeder with EVC infrastructure, an operation method for stabilization of the hosting capacity by the ESS control strategy was proposed. Based on the test result using the 30 kW scaled EVC infrastructure, power value at all-time can be perfectly kept within the hosting capacity by control strategy of ESS for VPL operation at the EVS infrastructure.

(3) From the verification result for the control characteristic, it is clear that ESS was accurately controlled by the operation determination signal. Moreover, when real-time power magnitude cannot be maintained within the hosting capacity, it is confirmed that the ESS properly compensates power within the hosting capacity by charging and discharging according to the reverse power flow and the forward power flow. Based on the control characteristics results of ESS, it is clear that the proposed control strategy of ESS for VPL operation is a useful tool. Further, it is clear that the introduction of ESS for VPL function can also expect an indirect benefit such as reduction of the investment cost by the effective utilization of distribution feeder facilities.

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