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Article

Optimal Operation Strategy of ESS for EV Charging Infrastructure for Voltage Stabilization in Secondary Feeder of Distribution System

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Abstract: The introduction of electrical vehicle charging infrastructure including EV charger, renewable energy resource at secondary feeder in distribution system has been increased as one of countermeasure for global environmental issues. However, the Electric Vehicle Charging (EVC) infrastructure may act as the peak load in distribution system, which can adversely impact on the voltage stability when the electric vehicle is quickly charged. Therefore, to keep within the limit capacity of secondary feeder and allowable limit for feeder voltage, this paper proposes a stabilization method by the Energy Storage System (ESS) control strategy at secondary feeder in order to be not violated over than lower and upper limit. Also, this paper presents the estimation method to keep the proper standard value of State of Charge (SOC). From the simulation results, the voltage stabilization operation by ESS should make the feeder voltages of the distribution system(secondary feeder) introduced EVC Infra keep better voltage conditions, also estimation method to keep the proper standard value is confirmed that the SOC of ESS when is the standby condition could be exactly kept within the proper reference range. Therefore, it is confirmed that this strategy is effective tool to solve the voltage problems by ESS.

Keywords: electrical vehicle charging infrastructure; State of charge; stabilization method; ESS control strategy; coordination operation; violation of voltage; Energy Storage System

1. Introduction

As power systems have been deregulated and decentralized according to the technology development of small-scale electric vehicle charging infrastructure including EV charger, Renewable Energy Resource (RES) have been actively interconnected and operated at secondary feeder in distribution systems. Therefore, many power quality and allowable capacity at feeder problems such as voltage variations and acceptable capacity in secondary feeder may be occurred, when EVC infra including RES are interconnected at secondary feeder in distribution system [1-4]. Specifically, When EV infra including the RES is operated in the secondary feeder, the feeder voltage is increased or decreased than allowable limit by the EV charging capacity and the output of the renewable energy resource. For example, when the output of renewable energy is better than the customer power, the feeder voltage is increased by the reverse power flow. Also, when the EV charge capacity and the customer power are increased, the feeder voltage has a characteristic to be dropped by heavy load.

A charging price based EVC strategies have been proposed to mitigate the impacts of EV charging on the distribution system [5-13]. In [5], EV charging demand is constructed by means of the route characteristics of EV users, and the charging price is determined considering the voltage deviation of distribution system. Therefore, the area where a high EV charge demand is expected is priced high, and accordingly the EV charging demand become low so that grid voltage could stay in stable range. And Time-of-Use (TOU) pricing scheme is introduced to decrease the peak load demand and alleviate overloading on the transformer [6-12]. In addition, an automatic demand response (ADR) strategy was proposed as a real-time price-based method [13]. Minimizing the cost of EV

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charging price, while self-consumption of PV generation, and reducing the impact on voltage of distribution system. However, above studies have a limitation that it is difficult to respond immediately to the voltage fluctuations caused by the EV charging loads in distribution system.

In another approach, the EV battery charging process in EV charger is operated to support grid voltage. The Fast Charging Station (FSC) is composed of two converters, AC/DC and DC/DC internally [14-16]. The grid connected converter (AC/DC) is controlled to inject the reactive power into the grid for voltage regulation and EV charger (DC/DC) is performed charging process based on a constant current/reduced constant current method [14-15]. These studies have addressed the bi-directional EV charger concept to improve the grid voltage quality. In [16], suggested a decoupled concept between grid side converter and EV chargers. The grid side converter is in charge of reactive power, AC system voltage and DC-link voltage. And EV chargers control the constant voltage (CV) and constant current (CC) to EV battery. Despite the advantages of directly controlling the grid voltage by supplying reactive power, above researches have constraints on the use of commercial product due to the DC-link voltage and the need for customized EV chargers. Therefore, in order to keep within the limit capacity of secondary feeder and allowable limit for feeder voltage, this paper proposes a stabilization method at secondary feeder by the ESS control strategy which is operated as the charging mode when RES output should be violated for feeder capacity, or the discharge mode when customer power and EV power should be higher than limit capacity of feeder.

This paper presents Electric Vehicle Infra stabilization (EVI) algorithm to keep allowable limit for power and voltage of secondary feeder through the ESS introduction with electric vehicle and renewable energy resource at end of section. Also, this paper proposes the estimation method to keep the proper standard value of SOC (it is named the State of Reference, SOR) considering ESS operation condition when ESS is not operated by EVI-algorithm. Based on the modeling of EVI-algorithm and SOR algorithm by MATLAB/SIMULINK software, it is confirmed that feeder voltages in distribution system (secondary feeder) can be maintained within allowable limit and to be keep as proper SOC. Meanwhile, the voltage stabilization operation by ESS should make the feeder voltages of the distribution system (secondary feeder) introduced EVC Infra keep better voltage conditions, also estimation method to keep the proper standard value is confirmed that the SOC of ESS when is the standby condition could be exactly kept within the proper reference range under coordinating situation. Therefore, the case study results show that this strategy is effective tool to solve the voltage problems by ESS operation.

2. Introduction necessity of ESS for voltage regulation at secondary feeder with EV infra

When the electric charging system including the renewable energy resource is operated in the secondary feeder, the feeder voltage is increased or decreased than allowable limit by the EV charging capacity and the output of the renewable energy resource. For example, when the output of renewable energy is upper than the customer power, the feeder voltage is increased by the reverse power flow. Also, when the EV charge capacity and the customer power are increased, the feeder voltage has a characteristic to be dropped by heavy load. Therefore, in order to keep within the limit capacity of secondary feeder and allowable limit for feeder voltage, this paper proposes a stabilization method at secondary feeder by the ESS control strategy which is operated as the charging mode when RES output should be violate the feeder capacity. Also, it is controlled the discharge mode when customer power and EV power should be higher than limit capacity of feeder. And, this paper presents the estimation method to keep the proper standard value of SOC considering ESS operation condition when ESS is not operated by voltage stabilization function.

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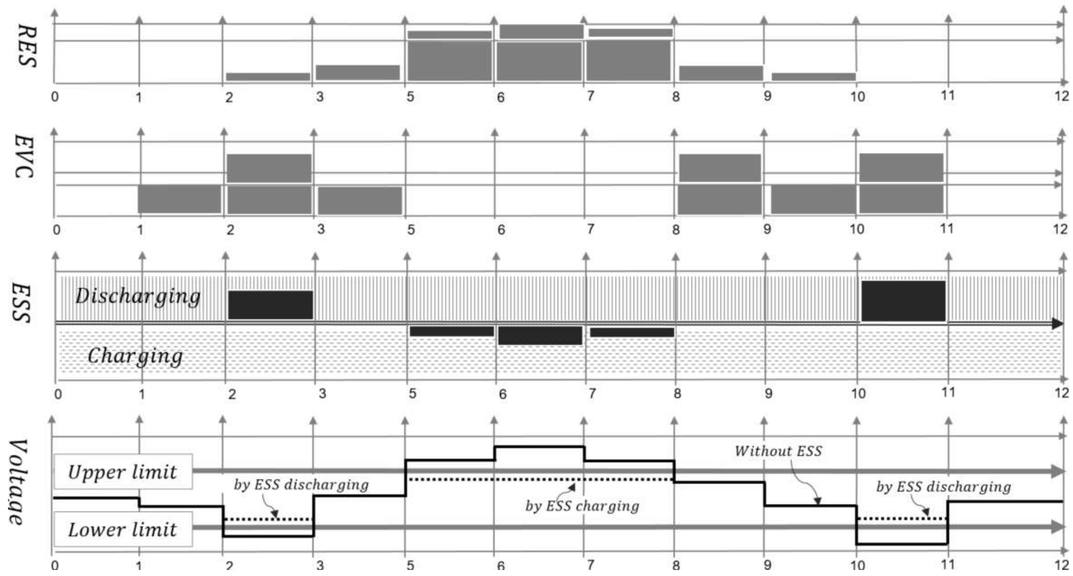
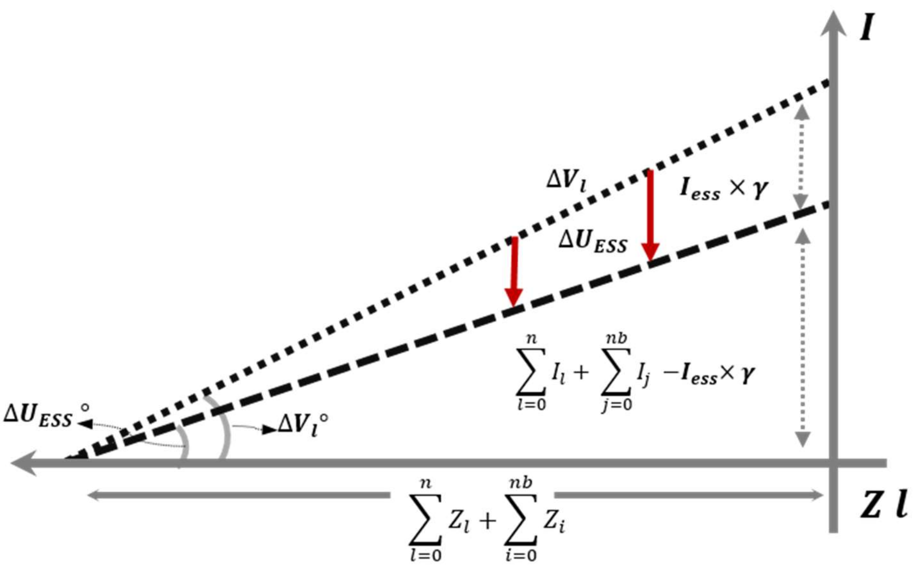
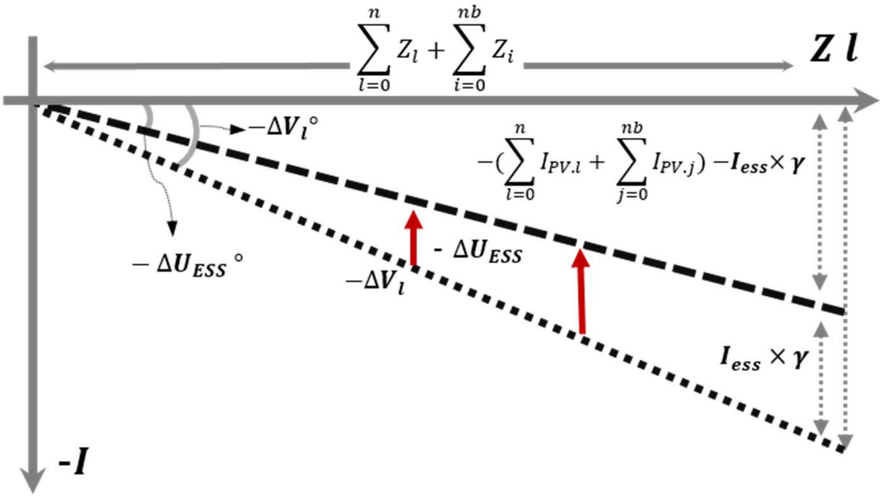


Figure 1. Strategy of power stabilization in secondary feeder by ESS.

Meanwhile, voltage stabilization method by ESS is based on the principle of the following feeder voltage characteristics. The feeder current of each section is controlled by operation of ESS that feeder current decreases when ESS is operated as discharging mode and feeder current increases in case ESS is operated as charging mode as shown in figure 2. At this time, the secondary feeder voltages are dropped or raised by the relationship between fixed impedance and the current capacity at the prior sections of an ESS site.



(a) Current characteristic in the grid in case of the ESS charging.



(b) Current characteristic in the grid in case of the ESS discharging.

Figure 2. Current characteristic in the grid according to the ESS operation.

Therefore, this paper presents method to expand the acceptance of EV charging infrastructure through ESS operation, and presents a stabilization strategy of power to keep the feeder voltage within the allowable limit in secondary feeder. Also, this paper proposes the proper standard range of ESS SOC to operate the ESS at all time.

3. Line impedance decision algorithm for operation of voltage stabilization ESS

The feeder voltage of the distribution system is changed by the current magnitude with the variation value and the line impedance with the fixed value. At this time, feeder voltage has a characteristic which is increased by the reverse power flow when the output of renewable energy is better than the customer power and is dropped by heavy load when the EV charge capacity and the customer power are increased. Under these concept, to presents a stabilization strategy of voltage to keep the feeder voltage within the allowable limit in secondary feeder, decision problem of line impedance is very important in proposed algorithm.

Therefore, in order to operate the ESS introduced in the electric charging system, this paper presents method to determine the line impedance based on the voltage and the passing current on the existing secondary feeder with RES and EV infra. Specifically, Optimal line impedance value have a general relationship with pole transformer voltage and power common coupling voltage at EVS infra including passing current as shown in equation (1). Therefore, the optimal line impedance values can be calculated by solving the equation for $U_{p.tr}$, U_{ci} and I_{ci}.

$$Obj.to\ Z_n = lr\left[\sum_{t=0}^{m}\sum_{i=1}^{n}\frac{U_{p.tr}(t) - U_{ci}(t)}{I_{ci}(t)} \times COS\theta_{ci}(t)\right] \tag{1}$$

Where, Z_n is line impedance value, lr is liner regression method, $U_{p.tr}(t)$ is pole transformer voltage, $U_{ci}(t)$ is power common coupling voltage at EV infra, $I_{ci}(t)$ is passing current at secondary feeder, $COS\theta_{ci}(t)$ is Power factor at secondary feeder, m is measuring time, n is ESS site (EV infra) section number of secondary feeder.

Solving the equation for Z_n in equation (1) cannot provide a linear function and has wide distribution characteristic as depicted in Figure 4. Therefore, the solution of optimal line impedance values is equivalent to finding coefficients of the first order equation of equation (2). It is desirable to minimize the differences between optimal line impedance value and the first order equation. The Least Square Method (LSM) is now introduced in order to find optimal Line impedance. The squared summation of differences is formulated as:

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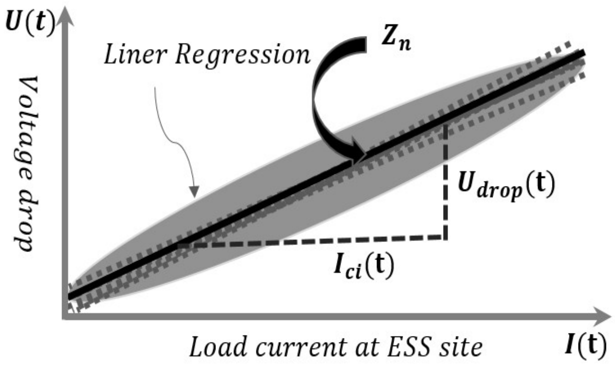

Figure 3. Distribution characteristics of line impedance

$$Min\ q = \sum_{t=1}^{T}\left[Z_n(t) - \frac{U_{drop}(t)}{I_{ci}(t)}\right]^2 \tag{2}$$

$$Subj.to\ U_{drop}(t) = U_{p.tr}(t) - U_{ci}(t)$$

where, q is error function and T is total number of time interval.

By minimizing q in Eq. (3), Z_n can be obtained as:

$$\boldsymbol{Z_n} = \frac{\left[\sum_{t=1}^{m}(\sum_{i=1}^{n}\left(\left(\boldsymbol{U_{p.tr}(t) - U_{ci}(t)}\right) \times \boldsymbol{cos\theta_{ci}(t)}\right) - \boldsymbol{T}\sum_{t=1}^{m}\left(\left(\boldsymbol{U_{p.tr}(t) - U_{ci}(t)}\right) \times \boldsymbol{cos\theta_{ci}(t)}\right)\right]}{(\sum_{t=1}^{m}\boldsymbol{I_{ci}(t)})^2 - \boldsymbol{T}(\sum_{t=1}^{m}\boldsymbol{I_{ci}(t)})^2} \quad \textbf{(3)}$$

4. Optimal operation algorithm of ESS for voltage regulation

4.1. EVI-Algorithm of ESS for voltage regulation

Figure 4 assumed that the ESS is installed at the end of the secondary feeder, distribution system (secondary feeder) model is expressed that stabilizes the voltage of the distribution system by the ESS operation. Meanwhile, this paper presents method to keep allowable limit for power and voltage of secondary feeder through the ESS introduction with electric vehicle and renewable energy resource at end of section.

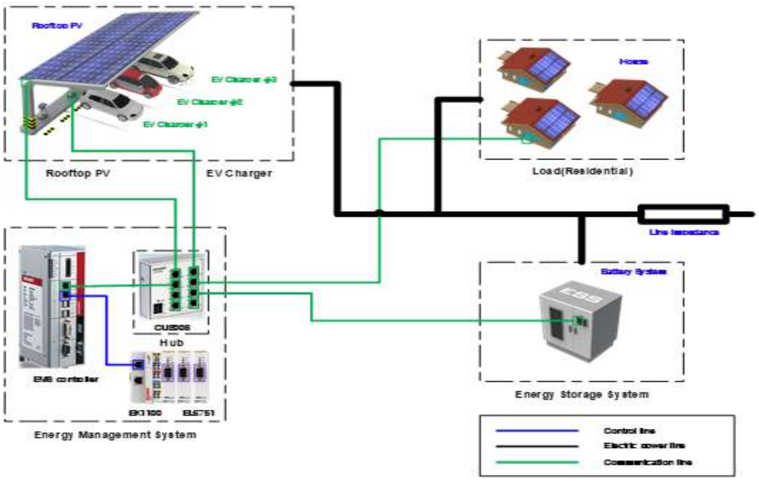

Figure 4. Configuration of secondary feeder with EV infra for proposed method.

As mentioned earlier, the concept of proposed strategy can be follows as;

Firstly, it is confirmed the rated capacity (maximum current) of secondary feeder through the visual inspection. And, the voltage characteristics from the pole transformer to the end section are analyzed by each voltage characteristics for heavy load and maximum output of renewable energy resource. After that, secondary feeder voltages with EV infra are controlled within allowable limit

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(upper limit, lower limit) by charging and discharging of ESS As much as the voltage (ΔU_{ESS}) out of the limit capacity of the secondary feeder. This concept is expressed in figure 5.

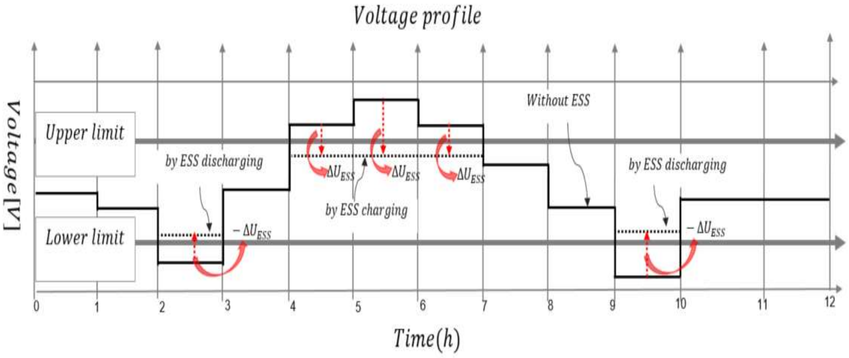
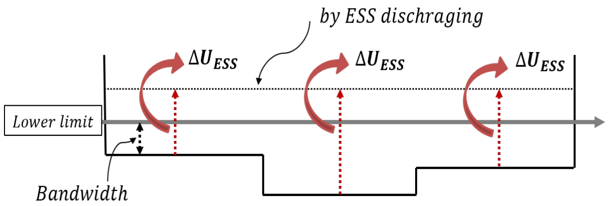
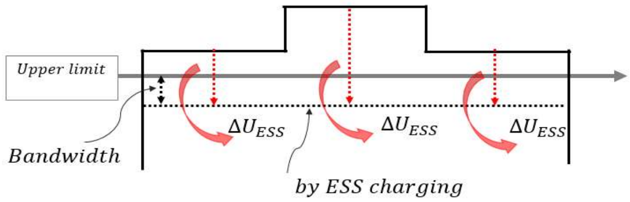


Figure 5. Operation concept of proposed method.

On the other hands, the voltage is compensated by the ESS as much as the voltage voltage (ΔU_{ESS}) limit capacity of the secondary feeder that is defined as the Voltage Compensation Rate (VCR). In this case, secondary feeder is stabilized by ESS operation with a charging/discharging value in which the VCR is converted into active power. However, ESS can has problems by frequent operation when VCR is terminated to the upper limit and lower limit warnings. Therefore, this paper presents a setting method of VCR with margin as shown in figure 6. Specifically, the margin (Bandwidth) is applied to the under area of upper limit and over area of lower limit, and ESS is operated by considering VCR and bandwidth coefficient.



(a) VCR considering margin(Bandwidth) in case of discharging



(b) VCR considering margin(Bandwidth) in case of discharging

Figure 6. Concept of VCR considering margin (Bandwidth).

Therefore, proposed EVI-algorithm by ESS can be summarized as shown in figure 7.

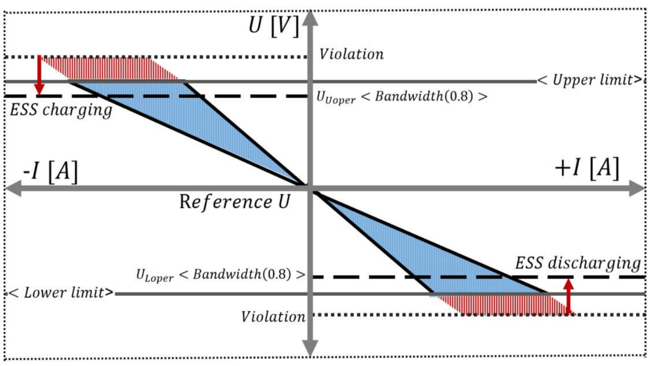


Figure 7. Concept for EVI-algorithm by ESS.

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4.2 SOR-Algorithm of ESS for voltage regulation

The charging and discharging operation of the ESS are generally carried out based on 50%SOC (SOC, state of charge) in order to operate ESS during the 24h. However, the ESS introduced for voltage stabilization in the distribution system including secondary feeder has a problem in operating standard value as the fixed SOC because the number of charges and discharges is different per hour. If the operating standard value of SOC is calculated by real-time per daily or hour, it is possible to stable operation than existing method like 50% of SOC. Therefore, Also, this paper proposes the estimation method to keep the proper standard value of SOC (it is named the State of Reference, SOR) considering ESS operation condition when ESS is not operated by EVI-algorithm as shown in Figure 8. Meanwhile, The proper SOR is continuously estimated from result value of the previous hour or daily operation pattern of ESS that charging and discharging operation of ESS is performed based on fixed SOC when operate the ESS for the first time.

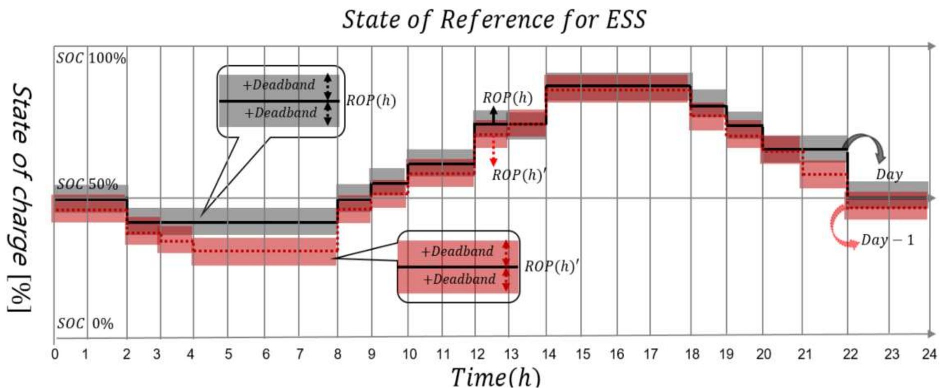

Figure 8. Concept of estimation method for State of Reference of ESS.

Under these concept, SOR is calculated as the sum of 50% SOC (initial value of ESS) and the rate of change in [kWh] charging and discharging capacity [%] of ESS for each time period as shown in Figure 8. And, Statistic calculation method for SOR (State of Reference, SOR) estimation is expressed in equation (4).

$$\mathrm{SOR_{th}(h)} = \sum_{y=1}^{th}\left\{\left[\frac{\sum_{t=1}^{sec} P_{ESS-charge}(y,t) - \sum_{t=1}^{sec} P_{ESS-discharg}\,(y,t)}{\sum_{t=1}^{sec} P_{ESS-charge}(y,t) + \sum_{t=1}^{sec} P_{ESS-discharg}\,(y,t)} \times 100[\%]\right] + 50[\%]\right\} \quad (4)$$

where, $\mathrm{SOR_{th(h)}}$ is proper standard value of SOC each time period, $P_{ESS-charge}$ charging capacity of ESS for one time, $P_{ESS-discharg}$ is discharging capacity of ESS for one time, th is application time zone of SOR.

If the setting width of SOR is very small, ESS can has problems by frequently the operation when the ESS is controlled to proper standard value. To solve the problems, this paper proposes a method to apply the margin of $\pm DB$(Deadband, DB) to the SOR of ESS in equation (5).

$$\text{baundary of } \mathrm{SOR_{th}}(h)[\%] = \ \mathrm{SOR_{th}}(h)[\%] - DB[\%] \leq \mathrm{SOR_{th}}(h)[\%] \leq \mathrm{SOR_{th}}(h)[\%] - DB[\%] \quad (5)$$

where DB [%] is margin of SOR

4.3 Coordination control strategy between EVI-algorithm and SOR-algorithm for ESS

In this paper, operation of ESS by proposed coordination control strategy between EVI-Algorithm and SOR-algorithm are classified into three categories as bellows;

[Category 1] When the voltage in secondary feeder violates the upper limit and lower limit.

Case l. Only one voltage is not kept within upper limit and lower limit

Case 2. Multiple voltages are not kept within upper limit and lower limit

[Category 2] When ESS is performed as SOR-algorithm operation

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The voltage in secondary feeder for ESS operation is the measured voltage for each section. This concept is summarized as follows;

A. In case voltage in secondary feeder violates the upper limit and lower limit;

Firstly, in case of voltage to be violated in only one section, ESS is operated after determination of capacity as much as voltage compensation range at violated section as shown in figure 9.

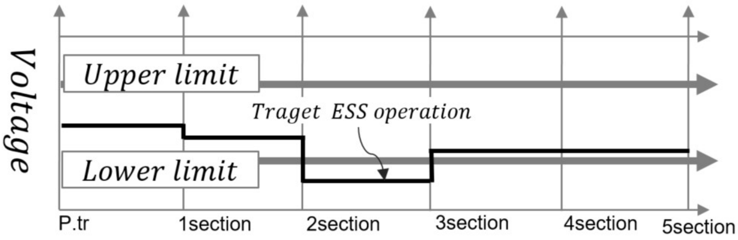

Figure 9. Case of voltage to be violated in only one section.

And, when is the voltage to be violated in multiple section, voltage compensation range of ESS is determined based on the largest voltage at violated feeders shown in figure 10.

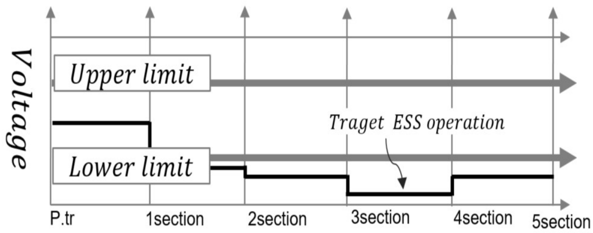

Figure 10. Case of voltage to be violated in multiple sections.

B. In case ESS is performed as SOR-algorithm operation;

ESS preforms SOC operation by SOR-algorithm when has a relationship between to be not operated as stabilization method and to be not kept within SOR boundary as expressed in figure 11.

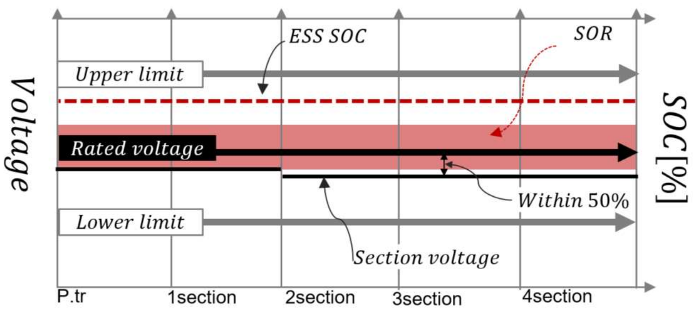

Figure 11. SOC operation of ESS within SOR.

As mentioned earlier, coordination control operation procedure of ESS to stabilize power and voltage of secondary feeder is categorized by 8 steps as below.

[STEP 1] In order to determine voltage range($U_{violation}$) from rated voltage to the upper limit and lower limit in secondary feeder with EV infra, it is calculated as multiply of the maximum allowable current in secondary feeder, estimated value of line impedance from chapter 3, load factor as shown in equation (6). Here, load factor is based on the heavy load (LF: from 0.7 to 0.8) voltage range. And also, voltage range in each section has as same value because of linear characteristic of voltage based on the current variation.

$$U_{violation} = I_{max} \times Z_n \times LF \quad (6)$$

where, $U_{violation}$ is voltage range in secondary feeder, I_{max} is maximum allowable current and LF is load factor at heavy load.

[STEP 2] The upper limit and lower limit which are allowable limit value is determined by rated voltage and voltage range that calculated by the [STEP 1] considering capacity of secondary feeder as expressed by equation (7) and Equation (8).

$$U_U = U_n + U_{violation} \quad (7)$$

$$U_L = U_n - U_{violation} \quad (8)$$

where, U_U is upper limit of voltage, U_L is lower limit of voltage and U_n is rated voltage in secondary feeder based on the 1 phase 2 wire.

[STEP 3] ESS is difficult to frequent operation as instantons value within 1sec because of lamp late time of the pcs for ESS and the life cycle of the electric device. Also, generators for frequency regulator are operated as an average power value over 10 seconds. Under these concept, this step secures the stability of ESS through the time interval for ESS operation as applying average real- time voltage value at secondary feeder during the set time as show in equation (9). Merely, operation time of ESS is only determined by set time to calculate average real- time voltage value.

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

where, $U_{ci-t}(tx)$ is average voltage in secondary feeder during t_x time, t_x is continuous operation time before next operation time of ESS and $U_{ci}(t)$ is real-time voltage in secondary feeder.

[STEP 4] Based on the calculated voltage in equations (9) earlier, the stabilization operation signal by ESS is recognized by condition of charging mode and discharging mode. Meanwhile, ESS is operated as charging mode in which alpha value is "1" and beta value is "0" when the average voltage of Eq. (9) is exceeded the upper limit. And also, ESS is operated as discharging mode in which alpha value is "0" and beta value is "1" when the average voltage of Eq. (10) is kept below the lower limit. At the relation equation (10), because voltage compensation rate determined at previous time period is summed at average voltage, it is applied in condition equation. However, in the initial operation of the ESS, the voltage compensation range of the previous time is assumed to be zero value.

$$\alpha(t_x), \beta(t_x) = \begin{bmatrix} U_{ci-t}(t_x) + \Delta U_{ESS}(t_x - 1) > U_U & \alpha = 1, \beta = 0 \\ U_{ci-t}(t_x) + \Delta U_{ESS}(t_x - 1) > U_L & \alpha = 0, \beta = 1 \\ U_L \le U_{ci-t}(t_x) + \Delta U_{ESS}(t_x - 1) \le U_U & \alpha = 0, \beta = 0 \end{bmatrix} \quad (10)$$

where, $\alpha(t_x)$ is the charging mode signal for voltage stabilization by ESS and $\beta(t_x)$ is the discharging mode signal for voltage stabilization by ESS.

[STEP 5] On the other hand, when the ESS does not operated as a voltage stabilization function, it is possible to determine the SOR operation. Firstly, in case all section voltages of secondary feeder is satisfied within allowable limit, changing and discharging signal of ESS must be determined as $\alpha = 0$ and $\beta = 0$ from the [STEP 2]. And, all feeder voltages should be kept within target ± value ($U_n \pm Tm$) range which is the set value between the rated voltage and limit voltage (upper limit and lower limit). Therefore, when all of the above conditions are satisfied, the primary condition signal (γ) for the SOR operation of ESS becomes "γ=1" as expressed by equation (11). Where, In order to prevent operation frequently at SOR operation condition, target ± margin which means proper

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value between the rated voltage and limit values is applied to setting voltage range for SOR operation. And, charging and discharging of ESS for SOR operation will be determined at next step.

$$\alpha(t_x),\beta(t_x),\gamma(t_x) = \begin{bmatrix} (U_L-U_n)\times Tm+U_n \le U_{ci-t}(t_x) \le (U_U-U_n)\times Tm+U_n & \alpha=0,\beta=0,\gamma=1 \\ else & \alpha=0,\beta=0,\gamma=0 \end{bmatrix} \quad (11)$$

where, γ is primary condition signal(γ) for the SOR operation and Tm is proper value between the rated voltage and limit values.

[STEP 6] In this step, charging or discharging signals of ESS for SOR are determined based one primary condition signal(γ) of ESS SOR operation at [STEP 5]. Meanwhile, from the proposed SOR algorithm of the chapter 4.2, ESS is carried out charging mode (1/4 kW value of ESS rated capacity) when the SOC is lower than SOR range considering DB. And also ESS is performed as discharging mode (1/4 kW value of ESS rated capacity) when the SOC of ESS is upper than SOR range. Under these concept, operation signal SOR operation is formulated by;

$$\epsilon(t_x),\delta(t_x) = \begin{bmatrix} SOC(t_x) > SOR(t_x)+DB & \epsilon(t_x)=1,\delta(t_x)=0 \\ SOC(t_x) < SOR(t_x)-DB & \epsilon(t_x)=0,\delta(t_x)=1 \\ SOR-DB \le SOC(t_x) \le SOR(t_x)+DB & not\ operate \end{bmatrix} \quad (12)$$

where, $\epsilon(t_x)$: is charging signal for SOR operation,$\delta(t_x)$ is discharging signal for SOR operation and DB is margin of SOR.

Therefore, condition for voltage stabilization and SOR operation are classified by bellows;

Table 1. Operation signal classification of ESS.

Classification	Signal Condition				
	α	β	γ	ϵ	δ
Charging operation of voltage stabilization	1	0	-	-	-
Discharging operation of voltage stabilization	0	1	-	-	-
Charging operation within SOR range	0	0	1	0	1
Discharging operation within SOR range	0	0	1	1	0
Not opertion	0	0	0	0	0
	0	0	1	0	0
	0	0	0	1	0
	0	0	0	0	1

[STEP 7] Determination of voltage compensation rate considering Bandwidth

Based on the determination for voltage stabilization operation of ESS, the decision problem for the voltage compensation range is defined in equation (13). In other words, the voltage compensation rate($\Delta U_{ESS}(t_x)$) to maintain from violated voltage to allowable limit are calculated by limit voltage at [STEP 2], margin of voltage (Bandwidth), measured average voltage at [STEP 3], voltage compensation rate of previous time, charging/discharging signal of ESS when operation of ESS is decided as voltage stabilization function. Here, voltage compensation rate of previous time is assumed as "zero" in case the ESS has not been operated in the previous time or initial time. Also, the + $\Delta U_{ESS}(t_x)$ means a compensation range value for ESS discharging and - $\Delta U_{ESS}(t_x)$ means a compensation range value for ESS charging.

$$\Delta U_{ESS}(t_x) = \alpha(t_x)(U_{ci-t}(t_x)-U_U+Bw)-\beta(t_x)(U_{ci-t}(t_x)-U_L-Bw) + \alpha(t_x)(\Delta U_{ESS}(t_x-1)+\beta(t_x)(\Delta U_{ESS}(t_x-1) \quad (13)$$

where, $\Delta U_{ESS}(t_x)$ is voltage compensation rate by the ESS and Bw is margin for voltage compensation rate.

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[STEP 8] Voltage and Stabilization operation of ESS

On the other hands, the output of the ESS when ESS voltage stabilization is operated as afunction.as shown in Equation (14) is determined by the impedance value from the chapter 2, voltage compensation rate from the [STEP 7], measuring average voltage from the [STEP 3].

$$P_{ESS}(t_x) = (\frac{\Delta U_{ESS}(t_x)}{Z_n} \times U_{ci-t}(t_x)) \times 3phase \quad (14)$$

where, $P_{ESS}(t_x)$ is output of ESS.

[STEP 9] SOR operation of ESS

In this step. SOR operation of ESS expressed by equation (15) is carried out when the ESS does not operated as a voltage stabilization function. In order words, ESS is performed about 1/4 of ESS rated capacity [kW] when is assumed as signal(γ)=1, signals (ϵ,δ)=1,0 or (ϵ,δ)=0,1. Here, γ signal, ϵ and δ signals are results value occurred from the [Step 5] and [Step 6]. Also, the + value of $P_{ESS}(t_x)$ means ESS discharging state and - value means ESS charging state.

$$P_{ESS}(t_x) = \epsilon(t_x)\delta(t_x)\left(\frac{ESScapacity[kW]}{4}\right) - \epsilon(t_x)\delta(t_x)\left(\frac{ESScapacity[kW]}{4}\right) \quad (15)$$

[STEP 10] After operation of all step, procedure is returns to [STEP 2] and re-decides whether to operate ESS.

As mentioned earlier, coordination operation procedure between EVI-algorithm and SOR-algorithm for ESS is expressed by;

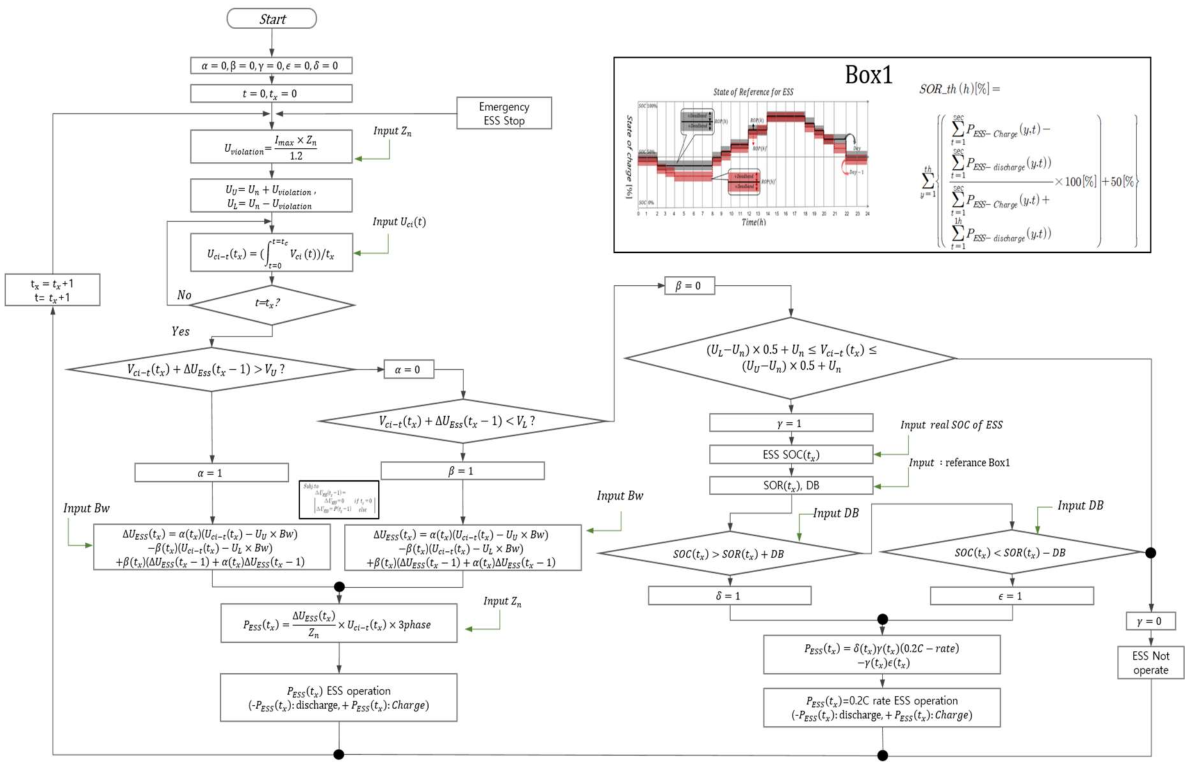

Figure 12. Flowchart of coordination control strategy between EVI-algorithm and SOR-algorithm for ESS.

5. Modeling of electric vehicle charging infrastructure at secondary feeder

In order to perform the verification of the coordination control strategy between AVI-algorithm and SOR algorithm at secondary feeder in distribution system proposed above, this chapter present the simulation modeling of the low voltage distribution system, ESS, photovoltaic system, loads, and the proposed algorithm for the electric vehicle using MATLAB/SIMULINK. In this simulation model, it is assumed that there is no harmonic and frequency variation, and only the positive sequence is considered. Therefore, the RMS based phasor model is suitable under this environment and also is able to simulate for long-term scenarios.

5.1. Battery Energy Storagy System modeling for voltage stabilization

The ESS for voltage stabilization, which is connected to the EVC infra in low voltage distribution system, consists of a battery that is able to charging and discharging energy and a DC/DC converter that is responsible for bi-directional power flow through voltage control, and an inverter that is in charge of synchronizing with AC system. As shown in figure 13, the ESS modeling is constructed to follow the command value from the supervisory controller like an Energy Management System (EMS). Therefore, that it is controlled by the proposed algorithm.

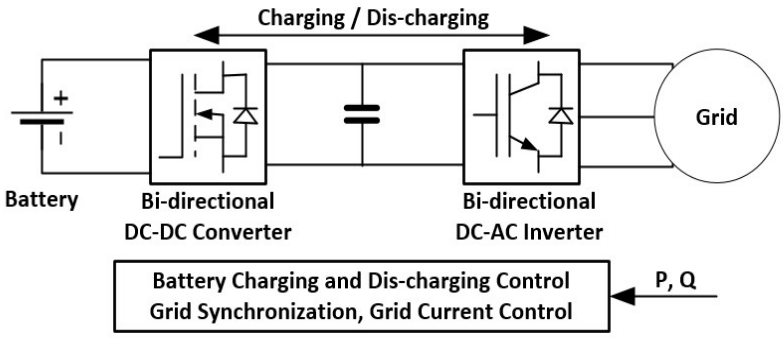

Figure 13. Bi-directional grid connected Inverter model with ESS.

5.2. Loads(Consumer) and EV Loads(Charging) modeling

The loads are limited to the general customer and the electric vehicles, all assumed to be the general resistive load. In general, load patterns vary according to weather, season, and even hour, so it is modeled to make output followed the input values. Consumers and EV load patterns for various scenarios are generated for each hour, based on 24 hours a day. Here, the EV loads is limited to one-way direction so that the energy flows from load to secondary feeder.

5.3. Photovoltaic power generation modeling

The photovoltaic system consists of a solar panel and a power converter, and DC output power from solar panel is determined by the irradiation and temperature. In this step, MPPT (Maximum Power Point Tracking) control of the power converter extracts maximum energy and transforms it to the AC output. The combination of the photovoltaic module changes the output characteristics of the voltage and current of the DC power, and it determines the topology of the photovoltaic power converter. In this paper, it is assumed that the photovoltaic system operates by the MPPT through equations (16) to (17) [20].

$$I_{mp} = I_{pv} - I_o\left[\exp\left(\frac{V_{mp} + I_{mp}R_s}{N_a V_T}\right) - 1\right] - \frac{V_{mp} + I_{mp}R_s}{R_{sh}} \tag{16}$$

$$-\frac{I_{mp}}{V_{mp}} = -\frac{I_0}{N_a V_T}\left(1 - \frac{I_{mp}}{V_{mp}}R_s\right)\left[\exp\left(\frac{V_{mp} + I_{mp}R_s}{N_a V_T}\right)\right] - \frac{1}{R_{sh}}\left(1 - \frac{I_{mp}}{V_{mp}}R_s\right) \tag{17}$$

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where, V_T is the thermal voltage, R_s is the series resistor, I_o is the reverse saturation current, R_{sh} shunt resistance, V_{mp} and I_{mp} are voltage and current levels at maximum power point respectably.

5.4. Control Algorithm modeling

The EVC infra 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. Depending on the unpredictable generation of renewable energy and consume the loads like an EV, the voltage could be reached to an unstable state occasionally, and an emergency stop may be necessary in case of the 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 14.

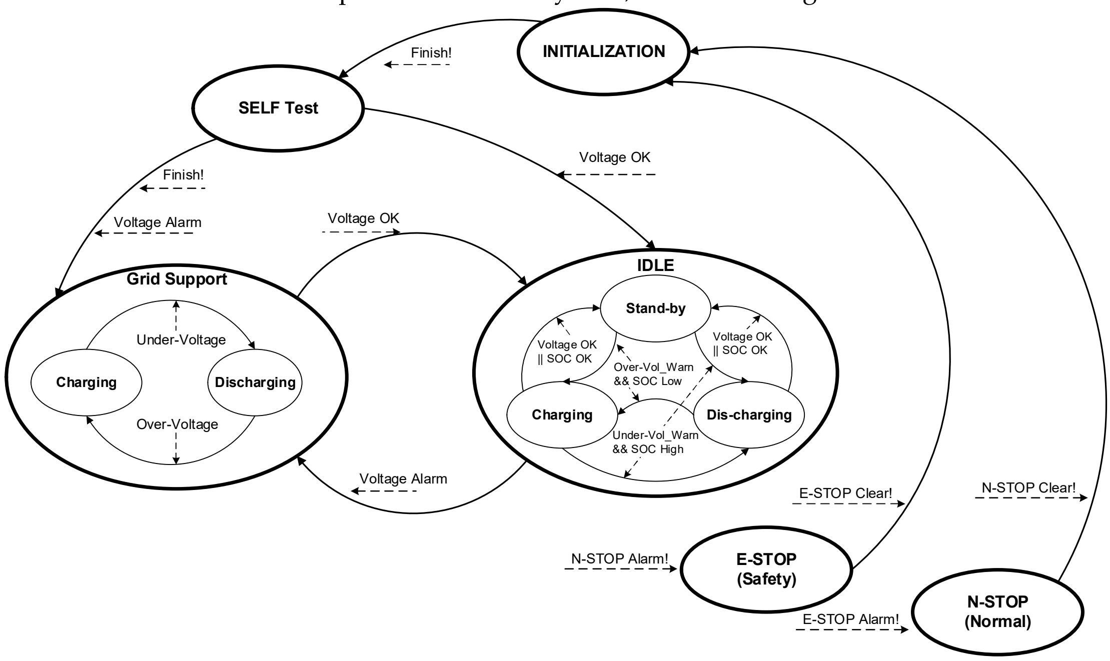

Figure 14. State machine of EMS for EV Charging Infrastructure.

Basically, state machine for electric charging infrastructure consists of 'INITIALIZATION', 'SELF Test', 'Grid Support', 'IDLE', 'N-STOP', and 'E-STOP'. At first, receive measurement data from each component of the EVC infra, then process the raw data through post processing and check the alarm state based on it. For instance, if the voltage is reached on out of the upper and lower limit boundary in EV charging Infrastructure, the state move to 'Grid Support' and execute the internal algorithm which is expressed in figure 15.

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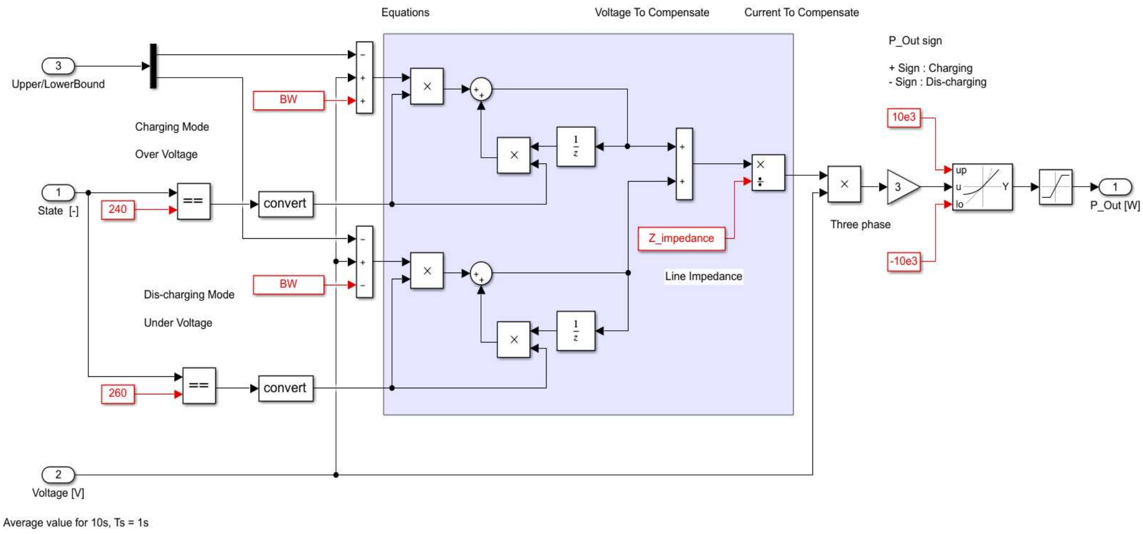

Figure 15. Voltage Compensation algorithm in 'Grid Support' state.

Combining LV distribution system, PV, ESS, load, EV, and EMS with the proposed algorithm, the entire simulation model is generated using MATLAB/SIMULINK as shown in figure 16.

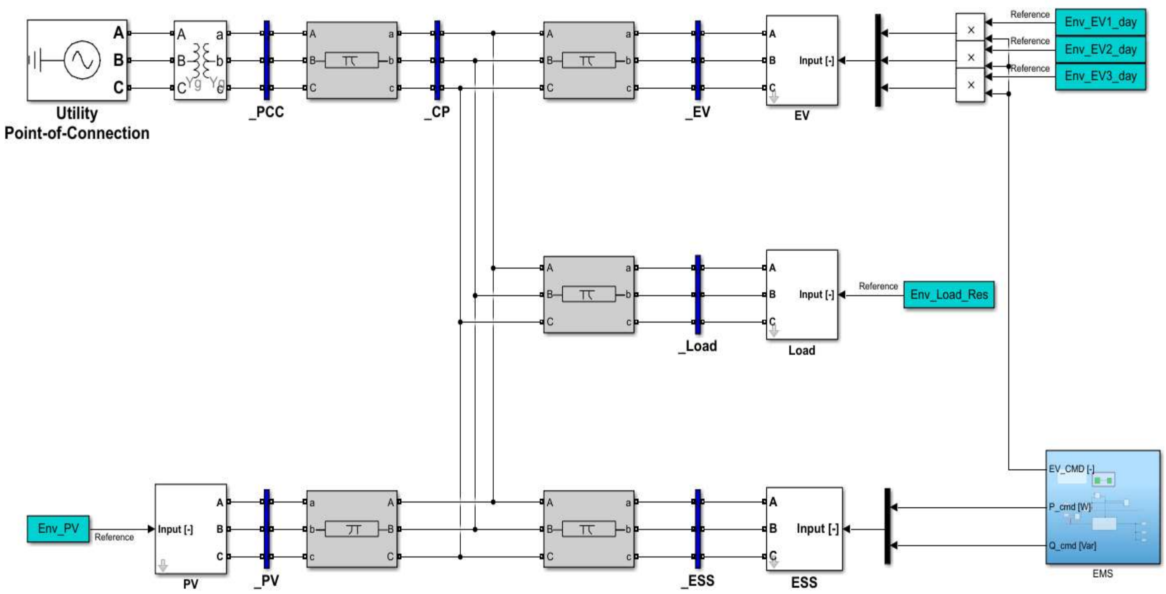

Figure 16. PV-ESS based EV Charging Infrastructure model (MATLAB/SIMULINK).

6. Case studies

6.1. Performance index

The characteristic of feeder voltage distributions can be evaluated by the degree of how close feeder voltages are maintained to the rated voltage. Therefore, a performance index can be defined as a form of the squared differences between the rated voltage and feeder voltages in secondary feeder as bellows;

$$\boldsymbol{PI(t_x)} = \sum_{t_x=1}^{T} \sum_{i=1}^{N} [\{\boldsymbol{V_{ci-t}(t_x, i)} - \boldsymbol{V_{rated}}\}^2]. \tag{18}$$

where, $V_{ci-t}(\boldsymbol{t_x})$ is the feeder voltage in the secondary feeder at i section, V_{rated} is the reference voltage (220 V), T is the total operation time, and N is the total amount of the section.

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6.2. Simulation condition

The electric vehicle charging infrastructure presented in this paper is a system which is connected to the low voltage distribution system, and power cables and transformers should be configured in accordance with power characteristic and capacity. In addition, the low voltage distribution system should be properly modeled because the X/R ratio of the line impedance is low compared to transmission system, so that the magnitude of the active power is dominant to voltage fluctuation. To verify the proposed algorithm, the configuration of EVC infra is modeled as distribution grid, transformer, and line impedance as shown in Figure 17. And the dynamic voltage variation caused by the line impedance according to the power flow between the EV charging infrastructure and the PCC (Point of common coupling) of the distribution grid is shown in chapter 3.

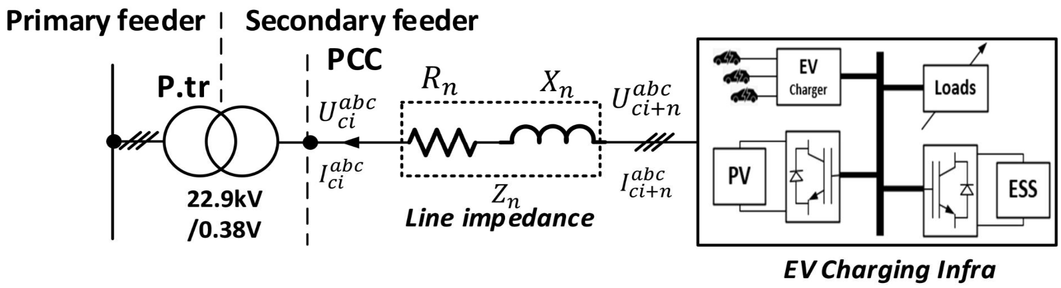


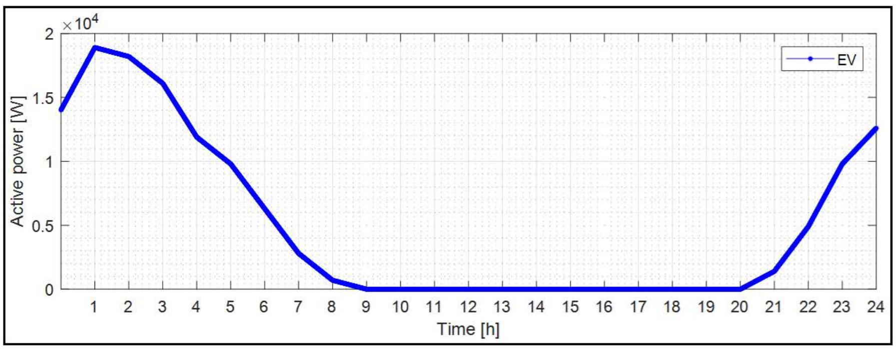
Figure 17. Configuration of secondary feeder with EV infra.

Based on the model of the secondary feeder with EVS infra, system parameter and section date of the secondary feeder are assumed by table X. here, pole transformer ratio of incoming point from the primary feeder is considered as 13,200V/230V and line impedance (X/R) ratio is assumed as value of resistance bigger then value of reactor according to the general characteristic of secondary feeder.

Table 2. Simulation Data.

Section Number	Impedance		Length (km)	Power Factor	Load (kW)	RES(PV System (kW)	EV Charger (kW)
	R (Ω/km)	X (Ω/km)					
1 (total)	**0.40**	**0.027**	**1**	**1**	0–15.0	0–30.0	0–18.9
1-1(load)	0.40	0.027	0.03	1	0–15.0	-	-
1-2(RES)	0.40	0.027	0.05	1	-	0–30.0	-
1-3(EVC)	0.40	0.027	0.05	1	-	-	0–18.9
1-4(ESS)	0.40	0.027	0.08	1	-	-	-

The load pattern, output of RES with the PV system and demand pattern of EV charger is predicted as shown in Figure 18. The above patterns are simulated by the operation characteristics under the 30kW scale based on the EVC infra capacity. EV charging is assumed as standard 3 EV chargers having 7.7kW capacity. Also PV system assuming renewable energy resource is considered as equal capacity of total EV charger capacity. Also, load pattern is assumed by residential profile in KOREA.



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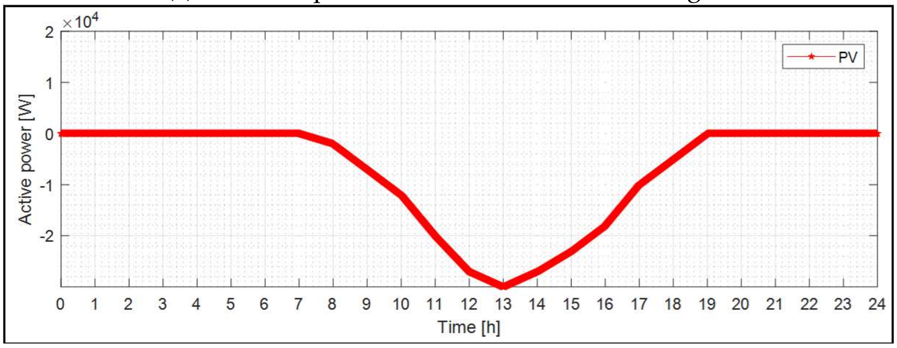
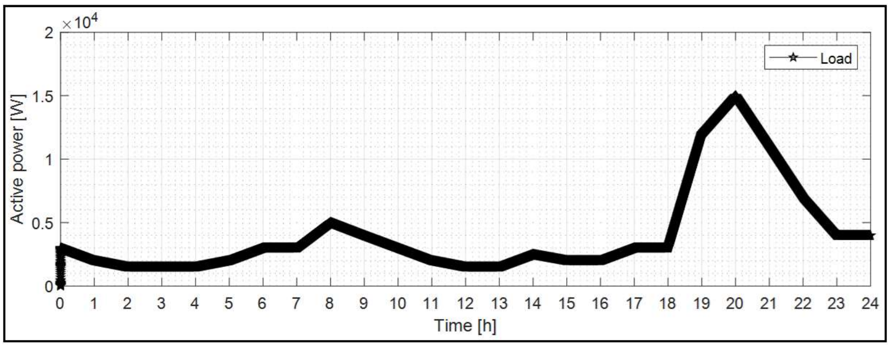
(a) Demand pattern characteristic of EV charger.



(b) Output characteristic of PV system.



(C) Load characteristic of residential area.

Figure 18. Output pattern of the EV charger, PV system and customer Load.

6.3. Analysis of the secondary feeder voltage characteristic by volatge stabilization operation of ESS

(1) Verification of the EVI algorithm for volatge stabilization Strategy

Based on the AVI-algorithm, control characteristic of ESS is analyzed for voltage stabilization operation when the feeder voltage was not kept at an allowable limit. In this case, it is confirmed that ESS has been exactly controlled by the operation determination signal which is ($\alpha(t_x)$: $charging$) and ($\beta(t_x)$: $discharging$) in figure 19. At the time, ESS outputted as much as capacity of voltage compensation rate for voltage stabilization in figure 20. Therefore, it was clear that the EVI algorithm of ESS for voltage stabilization was useful tool.

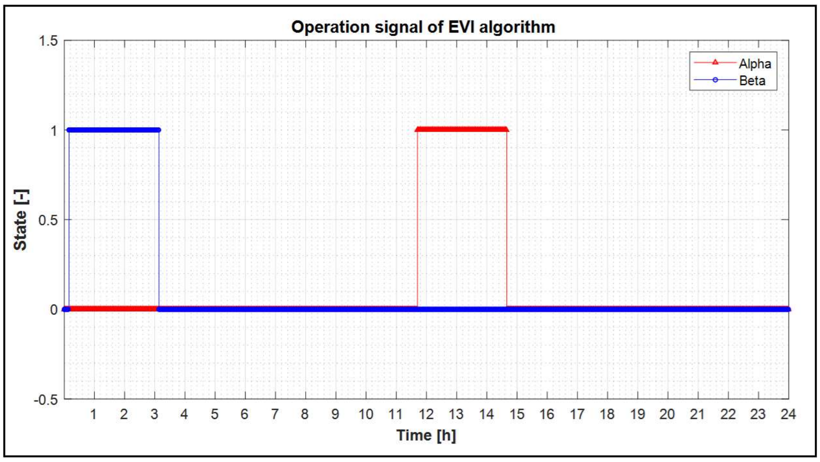


Figure 19. Operation signal of EVI algorithm.

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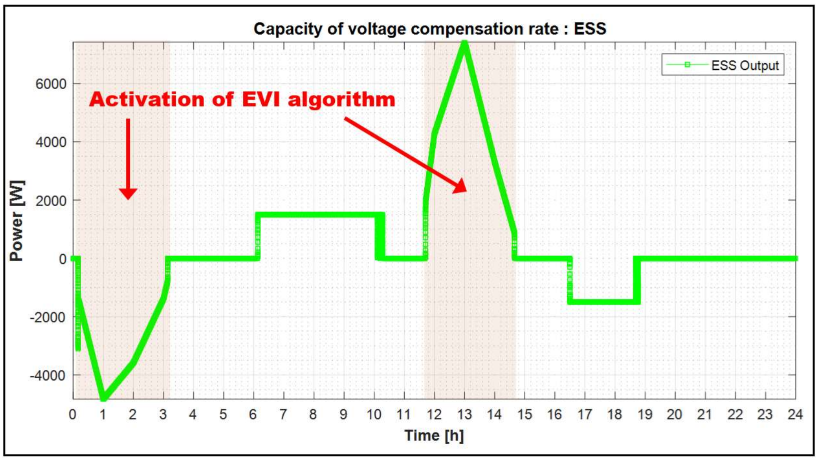

Figure 20. Capacity of voltage compensation rate for voltage stabilization.

(2) Analysis of the feeder voltage characteristic by intrduction of ESS

Figures 21 means the feeder voltage characteristics at EVC section, consumer section and PV section in EVC Infra site without ESS. Here, the feeder voltage was analyzed as average value per 10minute from 00:00 to 24:00 (all time). From the results of the simulation, it is shows that the feeder voltage could not be maintained to reasonable conditions (over voltage phenomena) at 11:50–14:20 when the PV system generated the maximum output as shown in Figure 21. Also, at 00:00–03:00 the feeder voltage was also less than the lower limit due to energy demands of EVC and costumer. Therefore, the feeder voltage could not exactly be kept within the allowable because the voltage was not compensated by the ESS.

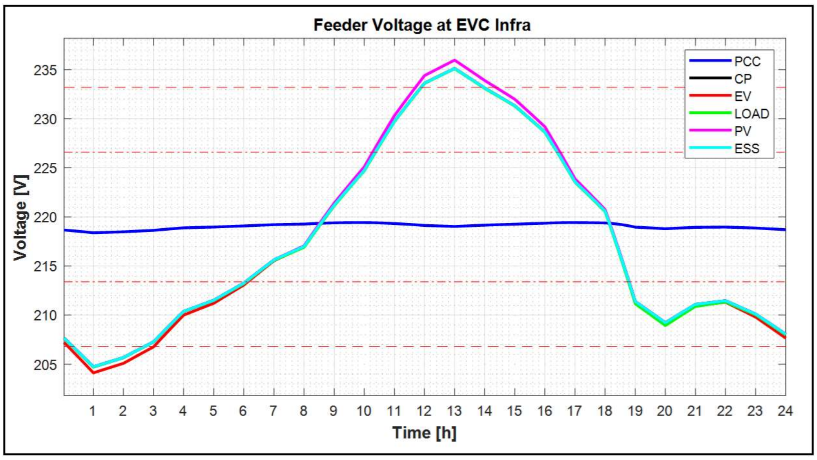

Figure 21. Analysis of the feeder voltage characteristic at EVC infra without ESS.

Figures 22 means the feeder voltage characteristics at EVC section, consumer section and PV section in EVC Infra site with ESS. Based on the simulation result using the MATLAB/SIMULINK, all of the feeder voltages at PCC section including all section could be perfectly kept within the allowable limits by the EVI-algorithm of ESS. Meanwhile, from the over voltage (from 11:50 to 14:20 and low voltage (from 00:00 to 03:00) phenomena, it is confirmed that were solved by voltage stabilization operation of ESS expressed by Figures 22. Therefore, the voltage stabilization operation by ESS should make the feeder voltages of the distribution system(secondary feeder) introduced EVC Infra keep better voltage conditions.

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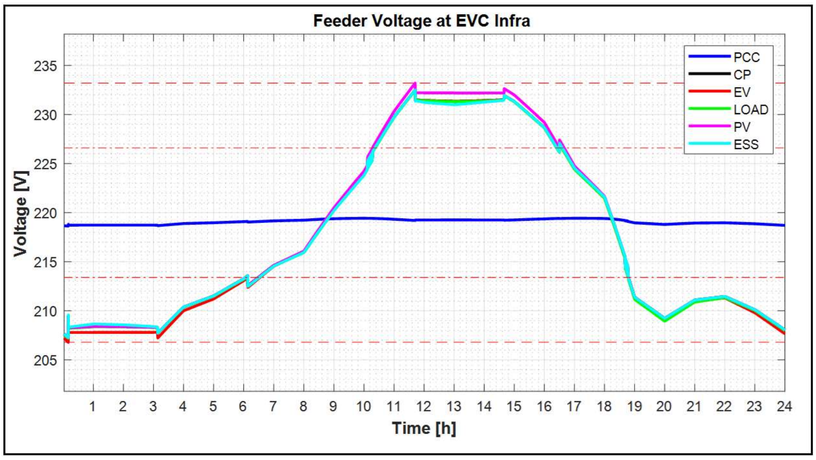

Figure 22. Analysis of the feeder voltage characteristic by ESS operation at EVC infra.

6.4. Analysis of the SOC chareteristic of ESS according to the application of SOR algorithm

(1) Verification of the SOR algorithm for maintain of proper SOC opertion range of ESS

In order to verify performance of SOR algorithm when the ESS does not operated as a voltage stabilization function, figure 23 shows SOR operation signal which is γ, ε and δ signal at [STEP 5] and [STEP 6] in chapter 4. In this case, it is confirmed that ESS as shown in figure 23 has been operated until the proper reference range by the determination signal which is $\gamma(t_x) = 1, \varepsilon(t_x) = 1, \delta(t_x) = 0$ (charging mode) or is $\gamma(t_x) = 1, \varepsilon(t_x) = 1, \delta(t_x) = 0$ (discharging mode). At the time, operation of ESS is assumed as 1/4 of rated capacity to keep the proper reference range of ESS expressed by figure 24. Therefore, it was clear that the SOR algorithm to maintain the stable SOC condition of ESS was useful tool.

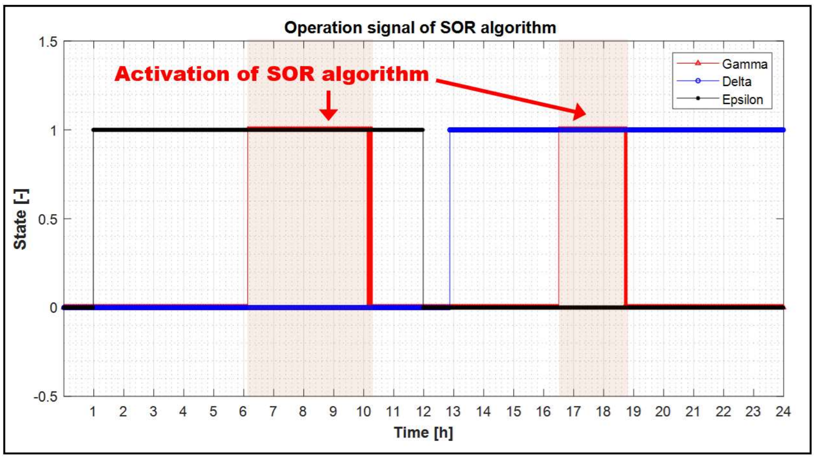

Figure 23. Operation signal of SOR algorithm.

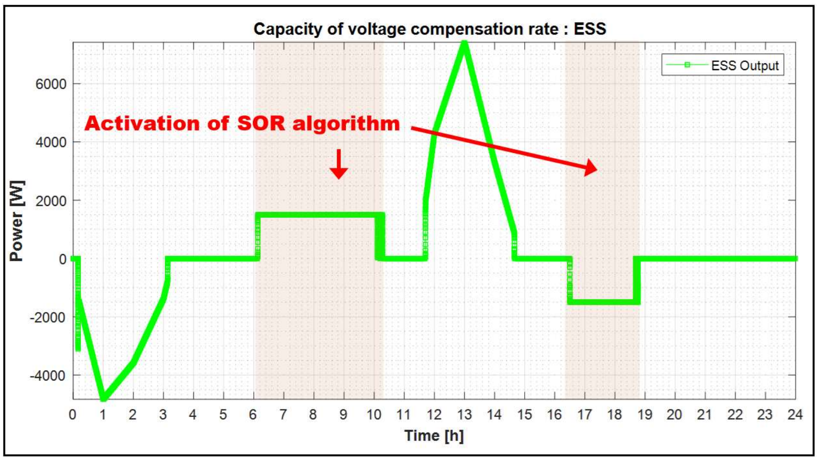

Figure 24. Capacity characteristic by operation of SOR algorithm.

(2) Analysis of the ESS SOC characteristic by SOR algorithm

Figures 25 shows the SOC characteristics of ESS during 24 hour. Meanwhile, when ESS does not operated as a voltage stabilization function and SOC of ESS violates the set SOR range, SOC pattern as shown in figure 25 is variated by the operation characteristic of ESS based on the operation signal of SOR algorithm earlier. From the result of simulation, it is confirmed that the SOC of ESS when is the standby condition could be exactly kept within the proper reference range.

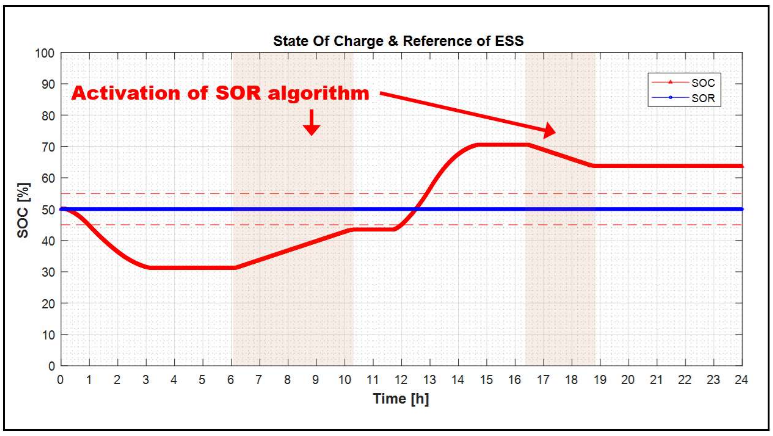

Figure 25. SOC pattern of ESS during the 24h.

6.5. Performance ecaluation for feeder voltage charateristic

Figure 26 and Table 3 show the performance index by the introduction of ESS at EVC infra site with renewable energy sources in secondary feeder. Based the result of the performance index based on Table 4, it is confirmed that feeder voltages in distribution system (secondary feeder) can be maintained within allowable limit. Therefore, the case study results show that this strategy is effective tool to solve the voltage problems by ESS.

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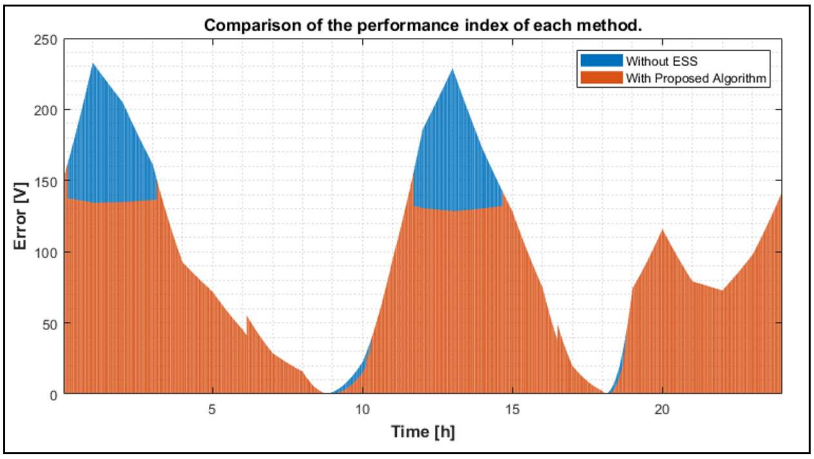

Figure 26. Comparison of the performance index for simulation results.

Table 3. Comparison of the performance index of each method.

	Not operation of ESS	ESS operation
Performance index value	8.2803e+06	7.0532e+06

7. Conclusion

The paper proposed Electric Vehicle Infra stabilization (EVI) algorithm to keep allowable limit for power and voltage of secondary feeder through the ESS introduction with electric vehicle and renewable energy resource at end of section. Also, paper presented the estimation method to keep the proper SOR considering ESS operation condition when ESS is not operated by EVI-algorithm. The main results are summarized as follows:

(1) To operate the ESS introduced in the EVS infra, this paper presents method to determine the line impedance based on the voltage and the passing current on the existing secondary feeder with RES and EV infra. Specifically, based on the Least Square Method, optimal line impedance value was determined by relationship between pole transformer voltage and power common coupling voltage at EVS infra including passing current.

(2) In order to overcome voltage problems at EVC infra in secondary feeder, voltage compensation method by ESS operation was proposed. Control characteristic of ESS is analyzed for voltage stabilization operation when the feeder voltage was not kept at an allowable limit. In this case, it is confirmed that ESS has been exactly controlled by the operation determination signal.

(3) Therefore, from the simulation results, it is confirmed that all of the feeder voltages at PCC section including all section could be perfectly kept within the allowable limits by the EVI-algorithm of ESS in case the feeder voltage could not be maintained to reasonable conditions (over/under voltage phenomena) by the maximum output of PV system, energy demands of EVC and load.

(4) when ESS does not operated as a voltage stabilization function and SOC of ESS violates the set SOR range, SOC pattern is variated by the operation characteristic of ESS based on the operation signal of SOR algorithm, based on the simulation, it is confirmed the that this strategy is effective tool to solve the no guarantee problems for operation papacy by ESS.

(5) Based the result of the performance index based, it is clear that feeder voltages in distribution system (secondary feeder) can be maintained within allowable limit. Therefore, the case study results show that this strategy is effective tool to solve the voltage problems by ESS.

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