An EV-based Wind Power Curtailment Scheme Utilizing the Power Sensitivity of the Distribution Network

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ABSTRACT With the increased usage of different types of renewable energy based on variable output characteristics, power curtailments have become a major problem in grid operation. The advanced controllers in distribution networks are significant in reducing the uncertainties caused by renewable generators. Along with this, at the operational level, the determination of the appropriate amount of curtailment for the stability and economics of the system was taken into account. The paper proposes an adaptive curtailment method in order to improve the accuracy of the power flow coming from the distribution network, with the signal created according to the system operator based on the response of the electric vehicle (EV). The method covers the economic loss caused by the curtailment process through the compensation profits. The main determinant reference proposal concerns the sensitivity and ability to increase the stability and economic feasibility of the interconnected power system. The benefits generated by the EV charging are provided to wind turbine operators in the scenario to compensate for excessive constraints. The whole method is applied in the IEEE-69 bus system to verify the effect with MATLAB.

INDEX TERMS Curtailment, Distribution system, EV charge, Power sensitivity, Wind system

I. INTRODUCTION

A. MOTIVATION

The proportion of renewable energy in the grid is continually increasing, thus necessitating an operation method that is developed from the existing plan. Recent working groups have dealt with balancing issues with the large-scale wind farm to mitigate the impact on the grid. Here, the particularly important was to prepare for a curtailment condition derived from an environmental fluctuation of those energies [1].

Some wind systems rely on auxiliary sources such as energy storage systems (ESSs) to compensate for unexpected output fluctuations [2], [3]. Further, charging the electric vehicle (EV) is used to compensate for the instability and the economic losses in the power system caused by the excess power [4], [5]. However, not all power systems have enough ESSs and EVs installed to cover the wind system output variability; therefore some distribution systems have reached their renewable energy acceptance limits and must continue performing curtailment. Further, there is generally no compensation for curtailment. The compensation for curtailment is currently changing in many regions and remains a crucial issue for wind system operators [6], [7]. As a result, it was determined critical to develop techniques that can effectively perform curtailment to ensure the efficient operation of power systems. Depending on the operation of the grid, it is essential to dynamically consider ancillary equipment, as is research on economic compensation for curtailment.

B. LITERATURE REVIEW

Recently there has been substantial research undertaken to investigate curtailment control strategies, and these studies can be broadly divided into active power control strategies and strategies that utilize auxiliary devices. The active power control strategy reduces the occurrence rate of curtailment or performs optimum curtailment by directly controlling the active power. Despite the significant electrical losses in the distribution system by the active power supply, an advanced
technique for allocating electrical assignment in terms of optimal solutions has not yet been throughout the management process. An active power regulation technique based on real-time wind speed information and dynamic classification of operating situations was proposed in [8]. Since it takes into account frequent periods of shutdowns and implements control, this control approach can reduce the overall number of wind turbine stops. Nevertheless, because the dynamic classification criteria is a broad approach, it is difficult to precisely control the active power of individual wind turbines. In [9], an enhanced power curve (v-p) is presented that improves the error that occurs during the curtailment of the wind turbine by using the density-based spatial clustering of applications with noise (DBSCAN). Wind turbines operated according to the power curve presented in this study are expected to show a more flexible response to curtailment. However, this study only focuses on the stability of the power system and it does not consider issues connected with the economic loss of operators caused by the performance of curtailment. In [10], an active power distribution algorithm was presented showing hierarchical active power control (HAPC), and the results showed that using this method improved the operational efficiency of large-scale wind farms. This method is not suitable for controlling a wind turbine installed in a microgrid or a distribution system. Individual operators generally install approximately 1 MW wind turbines in recognition of the capacity constraint of the distribution system. Moreover, since the magnitude of the load in the vicinity of the wind turbine is different, it is difficult to apply the wind farm control plan.

There are known technological strategies applying auxiliary devices, such as ESS and EV to reduce curtailment and improve economic effects. In [11], the authors proposed an efficient storage size of the BESS based on the updated forecast generation using battery ESS (BESS); the proposed BESS improved system stability meanwhile reducing output fluctuations. The microgrid operating method via BESS using the Distributed Consensus Algorithm was presented in [12]. This solution was particularly focused on the transmission loss reducing. The authors of [13] study proposed a real-time model of prediction control (MPC) and multi-objective cross-entropy (MOCE)-based MPC-MOCE energy management algorithm (MMEMA) in order to control the HESS based on power output function extraction. The method was shown to reduce the storage system's costs while minimizing the fluctuation of wind system output. In [14], the authors described the operation strategy that included the HESS consisting of batteries and fuel cells at the point of interconnection (POI) of the wind power plant (WPP). The proposed HESS reduced the fluctuations of generation and energy conversion losses, thus increasing the system stability. It also showed the effects of storage scale reduction, including the fast dynamic response. However, there are a number of limitations that hinder the active commercialization of the ESS. Among them, the high cost is often mentioned in related papers. Although most studies estimate the appropriate storage capacity using the proposed method, the problem has not yet been resolved from the economic point of view [15], [16]. Research is nowadays particularly active with two important goals to be achieved: improving the stability of wind turbines and ensuring economic efficiency. Table I summarizes the comparison of the proposed method with previous studies.

### C. NECESSITY OF THE RESEARCH

For the operation strategy of such a wind turbine, it is necessary to determine the appropriate value for each turbine taking into account both stability and economic compensation. The generally recommended method performs operations considering only a particular effect (stability or economics). However, this may cause a communication burden and bias toward one side.

As a complex countermeasure against this, the authors of [17]-[20] studies proposed a simultaneous approach to wind turbines and EV charging. This approach was based on examining whether the output of wind turbines could be met by the demand for EV charging. The improved flexibility of the power system operation was verified by reducing the impact of wind turbine variability on the power system through EV charging. This approach includes a recharging scheduling plan that considers the number of EVs in a curtailment situation and that aims to charge at a reasonable price. However, because of the characteristics of the distribution system, it is possible that the wind turbine operators will be different, and no research has yet been done in this area. As a result, there is a need for research that additionally takes into account the benefits distribution of individual wind turbine operators.

| TABLE I | COMPARISON OF THE PROPOSED METHOD WITH OTHERS DESCRIBED IN REFERENCES |
| --- | --- |
| Improved grid stability | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Improved grid economic (curtailment decrease) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Consideration of wind turbine operator's benefits | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Applicable to a distribution system | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Operation strategies | Ac, ESS, ESS, ESS, EV, EV, EV, Ac, EV |

Active power control (Ac), ESS control (ESS), EV control (EV).
D. MAIN CONTRIBUTION

This paper presents a power sensitivity-based method that aims to mitigate the limitations of stability and economics of the power system. Power sensitivity is an indicator by which a change in power from a particular bus affects the electrical state of another bus. This indicator can show the effect of the output of the wind turbine on the power flow at the point of common coupling (PCC). System stability can be effectively improved by calculating the limit of each wind turbine based on the power sensitivity and capacity. Moreover, due to the power sensitivity, EV charging was used as an additional control to improve the economy. EV charging can compensate for the power losses caused by curtailment, and it is possible to balance the economic losses of wind turbine operators. The main contributions of this study are as follows:

a) Contrary to conventional studies, in this paper, the appropriate output of each wind turbine is determined based on the power flow information. By allocating the output of the wind turbine based on the power sensitivity and capacity, the curtailment required by the grid operator can be accurately and efficiently performed. This contributes to improving system stability by reducing the error between the system operator’s order and the actual power flow.

b) Previous studies using EV charging as an auxiliary device have been carried out focusing on the balance of supply and demand of the network and its economic benefits. However, studies on the compensation of output limitation are still insufficient. For wind energy users, it can be beneficial to apply methods, such as reducing the curtailment of the wind turbines by charging EVs at night. In this paper, the economic gain obtained by reducing the output constraint caused by EV charging is used as compensation for individual wind energy companies and is distinguished from existing research.

E. ORGANIZATION AND STRUCTURE OF THE PAPER

This paper is composed of five main sections: Chapter 2 discusses separately the need and operation of distribution and transmission systems. Chapter 3 defines the power sensitivity and covers related mathematical modelling. Chapter 4 discusses the method of charging EVs; here, an algorithm for curtailment and EV charging is presented, based on the mathematical modelling discussed in the previous chapter. Chapter 5 describes the MATLAB simulation that is performed to verify the effectiveness of the proposed method. Finally, Chapter 6 presents the conclusions, expected results and future research directions.

II. DISTRIBUTED WIND SYSTEM OPERATION

A. WIND SYSTEM OPERATION STRUCTURE IN DISTRIBUTION SYSTEM

The distribution system operator (DSO) is expected to be necessary to proactively operate the future distribution system and issues related to the operator are often discussed in the literature [21]. Small-scale wind turbines connected to the distribution system differ from large-scale wind farms in that the power generating operators are either installed to use electricity directly or act to sell the electricity generated. Therefore, the operation of the distribution system and emergency orders (e.g., curtailment) is directly related to the benefits of the wind turbine operators. Consequently, it is necessary to have a DSO that gives priority to the power system stability and operates the system in a fair and neutral manner. Moreover, rather than simply following the instructions of the transmission system operator (TSO), it is necessary to have the ability to independently formulate and implement the best power supply and power system operating plan for the DG.

Fig. 1 shows a general conceptual diagram depending on the grid operation. The TSO will then commission the DSO to adjust the power generation in order to balance the supply and demand of the grid. The TSO’s order determines the total power generated by the DSO, but the amount of power distributed to each wind turbine is left to the discretion of the DSO. The economic benefit will then be distributed to the wind turbine operators based on the electricity market established by the TSO of the previous day.

If curtailment is required in a distribution system where the wind turbines are spread, the output value should be appropriately distributed among the individual wind turbines. The distribution that does not consider the characteristics of the individual turbines and components of the located bus can cause system stability problems. Also, distribution without a clear base can lead to dissatisfaction with wind turbine operators. The DSO executes the order from TSO to operate the distributed system in a stable manner and is obliged to establish a control structure to respond.

B. CURTAILMENT OF WIND SYSTEM

If the DG output in the distribution system increases and the mismatch with the load is outside of a certain acceptable
range, system instability may occur. In particular, compared to wind systems, for which the output increases at night, power demand decreases more at night than during the day. This means that there is a high possibility of oversupply and the phenomenon of overvoltage or reverse power flow may intensify. In this case, the system operator is forced to order curtailment to ensure the stable operation of the power system [22].

The limitation can be accomplished by the technique of removing the wind turbine from the power system and the technique of reducing the transmitted power by controlling the turbine’s output. With the first technology, the sudden disconnection of the wind turbine from the power system may cause instability of the power system for reasons such as frequency drop. Therefore, many wind systems have implemented the technique of reducing the output by a certain amount. The technology is carried out considering the power system stability, but the economic effect is reduced as the output quantity is forcibly limited. Therefore, a method should be used that considers both system stability and economic viability in reducing the output of the wind turbine during curtailment. The DSO should establish the general curtailment order and allocate the appropriate output value to individual wind turbines in the distribution system. The DSO processes the curtailment order and distributes the power value to individual wind turbines based on the turbine output, the value of the distributed system loan, information about the system impedance and the operating parameters of the connected power system. The output of the wind turbine according to the curtailment order can be expressed as (1).

\[
Total(P_{cur,W_{tn}}) = \sum_{n=1}^{N} P_{WT_{n}} - P_{cur,order}
\]  

where \( P_{WT_{n}} \) is the power of wind turbine \( n \), \( P_{cur,order} \) is the total curtailment power according to the operator order, and \( P_{cur,W_{tn}} \) is the power according to the curtailment command from the \( n \) wind turbine.

This article presents a method of improving the accuracy of power flow when curtailment and providing economic compensation to wind turbine operators. The proposed method is then analyzed and compared to the general method for verification.

### III. CURTAILMENT SCHEME WITH EV

This paper identifies the power sensitivity of individual wind turbines and assigns an appropriate curtailment value to each wind turbine. The benefits of EV charging are distributed based on the algorithm to compensate for the economic loss due to the curtailment.

#### A. POWER SENSITIVITY

To begin, the power sensitivity of the wind turbine output located on a specific bus to the power flow at the PCC was investigated. We calculated the appropriate output value for each wind turbine in the curtailment situation based on the analyzed power sensitivity. Wind turbines installed on buses with high power sensitivity have a more significant effect on the power flow [23]. This means that the accuracy of the power flow can be improved according to the DSO order when using the power of the appropriate wind turbine. In other words, having a wind turbine located on a bus with high power sensitivity allocate high power can significantly contribute to the stability of a power system.

The DSO calculates the power flow to support the distribution system and the power sensitivity can be derived based on the Jacobian matrix, which is the information obtained at that time. Thanks to this, it is possible to obtain the curtailment distribution without the need for the DSO to perform separate calculations [24]. The P-Q equation used to determine the power flow in the power system is presented below.

\[
\begin{bmatrix}
\Delta P
\
\Delta Q
\end{bmatrix} =
\begin{bmatrix}
\frac{\partial P}{\partial V} & \frac{\partial P}{\partial \theta}
\
\frac{\partial Q}{\partial V} & \frac{\partial Q}{\partial \theta}
\end{bmatrix} \cdot
\begin{bmatrix}
\Delta V
\
\Delta \theta
\end{bmatrix}
\]

(2)

(2) can be transformed as (3).

\[
\begin{bmatrix}
\Delta V
\
\Delta \theta
\end{bmatrix} = \begin{bmatrix}
\frac{\partial P}{\partial V} & \frac{\partial P}{\partial \theta}
\
\frac{\partial Q}{\partial V} & \frac{\partial Q}{\partial \theta}
\end{bmatrix}^{-1} \begin{bmatrix}
\Delta P
\
\Delta Q
\end{bmatrix}
\]

(3)

The sensitivity of the wind turbine output located on a specific bus to the power flow at the PCC is defined as (4)

\[
s_n(t) = \frac{\partial P_{pcc}(t)}{\partial P_{WT_{n}}(t)}
\]

(4)

where \( P_{pcc} \) is the power flow at the PCC. By applying the Chain rule to (4), it can be expressed as (5). As the first bus—the PCC point—is a slack bus, the equation was derived by considering the known value.

\[
\frac{\partial P_{pcc}}{\partial P_{WT_{n}}} = \frac{\partial P_{12}}{\partial P_{WT_{n}}} = \frac{\partial P_{12}}{\partial V_{12}} \frac{\partial V_{12}}{\partial P_{WT_{n}}} + \frac{\partial V_{12}}{\partial \theta_{12}} \frac{\partial \theta_{12}}{\partial P_{WT_{n}}}
\]

(5)

With the Jacobian matrix used to calculate power flow, the power sensitivity equation can be expressed as (6)

\[
s_n(t) = Y_{12}V_{1}(t) \left( \cos \theta_{12} \frac{\partial V_{1}(t)}{\partial P_{WT_{n}}} - \sin \theta_{12} V_{2}(t) \frac{\partial \delta_{2}(t)}{\partial P_{WT_{n}}} \right)
\]

(6)

#### B. DISTRIBUTION OF INDIVIDUAL TURBINE CURTAILMENT VALUES

Wind turbines that are located on a high power sensitivity bus may more closely match the curtailment order required by the DSO. However, taking into account the power sensitivity, it is also necessary to investigate whether the wind turbines can meet the assigned curtailment value. If a high output value is allocated after considering only the power sensitivity, then it is possible to assign a value higher than the turbine output value; this may degrade the accuracy of the power flow when executing the curtailment. Therefore, in this paper, the curtailment weight is calculated by considering both the power sensitivity and capacity of the
wind turbine. The proposed weighting takes into account the Rank sum method and can be expressed as (7). The method can be used when several objects are considered [25]. The index is determined according to the weight of the object under consideration, and weight is calculated based on this index. Since the securing power that can perform curtailment is a priority, the capacity of individual turbines is set as the first priority and the power sensitivity is set as the second priority because securing the power that may cause curtailment is the priority

\[
b_j = \frac{m+1-j}{\sum_{k=1}^{m} k} = \frac{2(m+1-j)}{m(m+1)} (j = 1, 2, \ldots, m) \tag{7}
\]

Here, \( b \) is the Rank sum method unit, \( k \) is the object to be considered, \( m \) is the total number of considerations, and \( j \) is an important indicator. We can define the allocation ratio to perform the curtailment as derived in (8) in consideration of \( (7) \). In this case, the individual weights are expressed as (9) and are based on the sum of the total 1

\[
w_n(t) = \frac{\sum_{n=1}^{N} \frac{CAP_{WT_n}}{\sum_{n=1}^{N} CAP_{WT_n}} b_1 + s_n(t)b_2}{\sum_{n=1}^{N} \frac{CAP_{WT_n}}{\sum_{n=1}^{N} CAP_{WT_n}} b_1 + s_n(t)b_2} \tag{8}
\]

\[
\sum_{n=1}^{N} w_n = 1, \quad (0 < w_n < 1) \tag{9}
\]

where \( CAP_{WT_n} \) is the capacity of the \( n \) wind turbine, \( b_2 \) is the first important Rank sum method unit, \( b_2 \) is the second important Rank sum method unit, \( s_n \) is the power sensitivity of bus \( n \), and \( N \) is the total bus number. The curtailment value for each turbine is calculated as follows:

\[
P_{W_n}(t) = (\sum_{n=1}^{N} P_{WT_n}(t) - P_{order}(t)) w_n(t) \tag{10}
\]

The curtailment value of the entire distribution system is determined according to the grid operator’s order. The total wind turbine output of the distribution system is determined considering the curtailment value and the current generation of the entire wind turbine. By applying (8) to the total wind turbine output, the output ultimately distributed to the individual wind turbines is determined.

**C. EV SUPPLY EQUIPMENT (EVSE)**

Our goal is to minimize the economic losses that occur during curtailment and reduction of the curtailment power, by using the combination of the wind turbine and EV charging patterns. The allocation curtailment based on the power sensitivity may show excellent performance in terms of power system stability. But since it is directly related to the profits and losses of the individual wind turbine operators, unreasonable results can be obtained. Therefore, it is possible to deliver the profits generated by charging the EVs to wind turbines that perform excessive curtailment. Our goal is to utilize excess power to charge EVs based on the power sensitivity weight.

The net profit from EVs charging will depend on the size of each wind turbine’s investment in the EVSE; the EVSE can be broadly classified into Level 1, Level 2, and Level 3 depending on several factors, such as the level of charging equipment, vehicle range and battery power capacity. Levels 1 and 2 are slow AC chargers while level 3 is a DC fast charger (DCFC). Table II lists information for each EVSE level [26].

**D. EV CHARGING SCHEDULE**

In this study, the economic feasibility and stability of the system are improved by charging EVs with the excess power in the distribution system that is generated by oversupply from the wind system. At this time, the charged power is determined by considering both the balance of power flow in the grid and the SOC. EVs charging can significantly reduce the curtailment, but if the EVSE’s efficiency is poor or there are not enough units installed, the curtailment may still be necessary. At this point, the optimal output value for each turbine is assigned based on the proposed weighting, as this ensures better power system stability. Moreover, the economic losses resulting from the curtailment are compensated by the benefits obtained from EV charging. The compensation value is calculated on the basis of the losses obtained by a single wind turbine, which can promote economic improvement. This study aims to verify the effectiveness of this system by conducting a simulation based on the balance of power flows in the distribution system. The relevant configuration was formalized as expressed in (11)-(17) [27]. The discrete-time dynamical equation of the SOC is described as (11). The constraint on EV charging is defined by (12) as the upper and lower limits of the SOC.

\[
SOC(t + 1) = SOC(t) + \frac{P_{charge}(t) - P_{discharge}(t)}{B_{battery}} \tag{11}
\]

\[
SOC_{min} \leq SOC(t) \leq SOC_{max} \tag{12}
\]

where \( P_{charge} \) and \( P_{discharge} \) are the charging and discharging powers, respectively; \( B_{battery} \) is the battery capacity of the EV; \( SOC_{min} \) and \( SOC_{max} \) are the SOC minimum and maximum values of EV. (13) shows the charging limitations according to the output of the wind turbine. The upper and lower limit conditions for charging to match the power flow balance are in (14). The total charging power according to the power flow of the power system is represented by (15). The charge value is derived by considering the total output by the wind turbine and the line loss.

\[
0 \leq P_{total} \leq P_{WT_n} \tag{13}
\]

\[
P_{PCC} \leq P_{charge} \leq P_{max} \tag{14}
\]

**TABLE II**

| Level | Power [kW] | Voltage/Current [V/A] | Charging connector |
|-------|------------|------------------------|--------------------|
| 1(AC) | max 1.4    | 108-120/15-20          | NEMA 5.15          |
| 2(AC) | 7.2-25     | 208-240/10-30          | SAE J1772          |
| 3(DC) | 50, 150, 350 | 400-800/30            | CCS, CHA, deMO, Tesla supercharger |
where respectively; $P_{ch}^{W_n}$ is the charging power of the individual turbine; $P_L$ is the power consumption of the load, $P_{loss}$ is the transmission loss. The investment cost of the EVSE is (16), which is expressed in terms of the initial installation cost and the operation and maintenance (O&M) cost. The O&M cost covers various specific items, such as costs related to regular inspection and repair, safety manager labour, platform operating system and charger installation site [28], [29]. However, the aim is to verify, by simulation, the possibility of reducing the economic losses caused by the curtailment in the distribution system through charging the EVs. Thus the O&M cost was calculated as 5% of the installation price [30], [31]. We recognize that there is currently a lack of data on EVSE lifespans; therefore, we conservatively assumed the EVSE lifespan of EV charging stations is ten years. The equation for distributing the net gain from EV charging to each wind turbine operator is (17). The benefit from charging is deducted and distributed as a net gain, excluding EVSE’s investment cost. Since the low-weighted wind turbine generates a high economic loss due to the curtailment, it allocates a low maintenance cost and distributes a significant net profit. The weight used is in line with the time weight when the greatest curtailment occurred the day before. Since wind turbine operators with low power sensitivity attribute relatively severe economic harm during curtailment performing, high recharging benefits have to be obtained in inverse proportion to the power sensitivity.

$$C_{EVSE} = I_0 + OM$$

$$C_{WT_n} = \text{Benefit} \left( \frac{P_{ch}^{W_n} \text{CAP}_{WT_n}}{\sum_{n=1}^{N} \text{CAP}_{WT_n}} \right) - C_{EVSE}^{W_n}$$

where $I_0$ is the initial installation cost of EVSE, and $OM$ is the operation and maintenance cost of EVSE.

IV. SIMULATION

A. SIMULATION DESCRIPTION

Fig. 2 shows the algorithm used to perform the curtailment, including the EV charging. Calculating the power flow for power system operation and checking the TSO’s orders creates an operation plan for the distribution system. When the EV is connected to the charger, it fits the remaining value of the SOC and the excess power of the distribution system and then performs charging accordingly. After the algorithm for EV charging is completed, it checks if a curtailment directive is required. When the TSO requires a curtailment, the order of the DSO is determined. The Jacobian matrix obtained by calculating the tidal current is analyzed and the power sensitivity of each wind turbine is calculated on its basis. The weight of each turbine is calculated considering power sensitivity and turbine capacity. The output value of each turbine is derived from the calculated weight. The consistency of the individual turbine output values is checked based on the curtailment order. After completing all of these steps, the benefits of EV charging will be distributed to the respective wind turbine operators. If EV charging or curtailment is not performed, it is necessary to proceed with the following process to keep the system stable.

E. ALGORITHM

Fig. 2 shows the algorithm used to perform the curtailment, including the EV charging. Calculating the power flow for power system operation and checking the TSO’s orders creates an operation plan for the distribution system. When the EV is connected to the charger, it fits the remaining value of the SOC and the excess power of the distribution system and then performs charging accordingly. After the algorithm for EV charging is completed, it checks if a curtailment directive is required.

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An IEEE-69 Bus model was used to perform the simulation. It was assumed that 5 Type III wind turbines were deployed and arranged in the distribution system model. The capacity of each wind turbine to be located in this model was set at around 1 MW. Fig. 3 shows the floor plan of the wind turbine distribution system model. Table III shows the capacity of individual turbines and the number of buses on which the turbines are installed.

The aim of this paper is to verify by simulating the validity of economic compensation achieved by EV charging. It was assumed that there is a city bus stop serving as an EV charge station at the PCC point and that the plugged-in EV is only charged using excess power. Electric vehicles recharging at the EV charge station use lithium-ion batteries and the EVSE uses DCFC level 3 with a single port. The DCFC which has the best specifications among chargers on the market was chosen as the simulation model to prevent charging problems caused by the charger specification. Due to the single DCFC port, this model requires one DCFC per EV to be delivered. For city buses, EVs must go into charging mode at night when not in motion. Therefore, the EV charging schedule was set from 1:00 AM to 5:00 AM. Buses can be recharged intermittently by advantage of the time when they are not running, but this study has not covered this point for the sake of simplicity. DCFC charging costs are divided into costs associated with public charging stations and apartment and private charging ones. Currently, the EVs charging cost is constant regardless of time for public charging stations in the Republic of Korea (ROK). As the simulation was carried out based on data from Jeju Island, the same fee system as in ROK was applied.

It should be noted here that the United States, with a high penetration rate of EVs, uses a time differential rate system. According to the differential rate system, the high rate is applied during periods of high power consumption and the low rate is applied to light to medium loads with relatively low power consumption. When the system of differential rates is used, the income is expected to be measured lower [32]. Table IV presents the relevant information. The 2019 average load data for the Jeju Island region was rescaled and used as the distribution system model load data.

We scaled up the actual load data, considering the size of the IEEE-69 bus and the load allocated to the bus, and then we applied it to the distribution system model. The total load data used is shown in Fig. 4. Considering the characteristics of the Jeju Island region, it can be seen that the load is higher in the evening than during the day. The generation data was used by scaling the average wind turbine generation data of Jeju Island in 2019.

The applied total generation data is shown in Fig. 5, and the generation graph of individual turbines is shown in Fig. 6. Taking into account the characteristics of the wind turbine, we can confirm that it generates significant power due to the higher wind speed in the late-night and morning hours compared to the power produced during the day. As each turbine has a different capacity, the generation is assigned proportionally to its capacity. Since a turbine rarely outputs 100% of its capacity, the generation is distributed to the individual turbines according to the above-described pattern. Fig. 7 shows the respective power flow through the PCC point. Wind turbine generation increases rapidly with time, and there is a risk of reverse power flow due to oversupply in the morning when the load is small. As a result, at 3 am and 5 am, the PCC power limit of 600 kW is exceeded, which requires a curtailment.

```
| Parameter          | Value |
|--------------------|-------|
| EV battery capacity | 250 kWh |
| DCFC power         | 150 kWh |
| Charging efficiency | 90%    |
| Initial SOC        | 0.1 p.u. |
| Maximum SOC        | 0.9 p.u. |
| Minimum SOC        | 0.1 p.u. |
| Charge price       | 0.15 $/kWh |
| DCFC install price | 40,000 $  |
```

**FIGURE 4. Total load**

**FIGURE 5. Wind turbine total output**

**FIGURE 6. Output of each wind turbine**
The performed simulations focus on the accuracy between the operator’s order and the actual power flow. Fig. 8 shows the power sensitivity per hour of individual turbines derived from the equations listed in the previous chapter. As an example, we assumed that the load is applied evenly to each bus of the distribution system. In this case, the wind turbine1, located on bus No. 12, has the lowest equivalent impedance up to the PCC point, so the highest power sensitivity is calculated. There is no case where all buses have the same load value. This paper has attempted to create a simulation model corresponding to real situations. Therefore, based on the load of the IEEE-69 bus, we determined the different busloads in the simulation model. The highest power sensitivity of wind turbine5 was derived, and wind turbine 2 and wind turbine 3 were similarly derived.

We have compared the simulation results with those obtained using three methods to verify the validity of the proposed method. The first comparison method is the Event dispatch, in which each turbine is assigned a curtailment of the same value. It is distributed evenly among the individual turbines according to the curtailment order. The second method is the capacity ratio, which allocates the output proportional to the wind turbine capacity. The third method is the sensitivity ratio, which is proposed in the present work.

There is a surplus of power at 3 and 5 hours, which generates a curtailment signal to balance the system. The output values of each turbine according to the curtailment order are shown in Figs. 9 and 10. When applying the proposed method to the wind turbine 5, the power extraction from the turbine increase due to its high allocation ratio.

Fig. 11 shows the accuracy of the proposed control in terms of the imposed curtailment order. After applying the proposed method, an improvement in accuracy is visible. If the allocation ratio only considers the power sensitivity, contrary to the suggested method, then the accuracy improvement effect is much more significant. However, when a high curtailment value is ordered, the accuracy can be considerably decreased. Therefore, a wind farm located in the transmission system may be suitable because it has a large capacity. However, a small-scale wind turbine connected to the distribution system is considered unsuitable.

**B. EV CHARGING SIMULATION**

The simulation was carried out on six cases, and the relevant information is presented in Table V. We calculated the charging capacity by taking into account the fixed initial SOC and the maximum SOC. EVs should enter charging mode outside of the operational hours. Therefore, recharging takes place sequentially from 1 am to 5 am, which is the non-operating time of Jeju Island city buses. The case study classified the cases according to the number of EVs and...
The simulations were performed on a case-by-case basis. The weights suggested for the economic loss caused by the curtailment were used and the purpose of this study was to check whether the compensation could be proportional to the wind turbine operators. Table VI shows the quantification of the economic analysis derived as a result of the simulation in each case. A fixed fee per hour is applied because EVs are charged at public charging stations. The total benefit is the sum of the benefits earned by wind turbine operators during the day. The investment cost is expressed by scaling the total cost invested by wind turbine operators by one day, considering the EVSE lifespan. As the service life of the EVSE increases, the battery's performance may decline, which may increase O&M costs and reduce the annual net gain. However, we focused on simulated efficiency, and since we excluded the benefits of power balancing, we did not include the performance reduction in line with the lifespan in our calculations. As the number of cases increases, so do the overall benefits and investment costs.

Fig. 12 shows the economic feasibility analysis and curtailment power. Contrary to the total benefits and investment costs, the net profit obtained by the wind turbine operators in one day does not increase proportionally. This phenomenon occurs because the power that EV can charge is limited rather than infinite. Curtailment represents the total curtailment power performed for each case during the day. In Case 1, charging occurs at 3 AM, but curtailment is still required due to the restriction of the EV & DCFCs number. Cases 2, 3, and 4 show relaxed curtailment at 3 AM due to EV charging, but they still require curtailment at 5 AM. In Cases 5 and 6, we alleviated all the curtailment by loading a lot of power to the EV. However, in Case 6, we can see that the net gain decreased because the DCFC installation cost was over-invested. Based on the net gain, Case 5 is derived as the optimal case considered.

### TABLE V

| Case | EV & DCFC units | Charge capacity [kWh] |
|------|-----------------|----------------------|
| 1    | 10              | 1000                 |
| 2    | 15              | 2000                 |
| 3    | 20              | 3000                 |
| 4    | 25              | 4000                 |
| 5    | 30              | 6000                 |
| 6    | 35              | 7000                 |

### TABLE VI

| Case | Total benefit [$] | Investment cost [$] | Net gain [$] |
|------|-------------------|---------------------|--------------|
| 1    | 280               | 110.68              | 169.32       |
| 2    | 420               | 165.47              | 254.52       |
| 3    | 560               | 220.27              | 339.73       |
| 4    | 700               | 275.06              | 424.93       |
| 5    | 840               | 329.86              | 510.13       |
| 6    | 871               | 384.65              | 486.43       |

**FIGURE 12.** Curtailment and benefit by case

**FIGURE 13.** Curtailment and benefit of individual wind turbines – (a) Case 1, (b) Case 2, (c) Case 3, (d) Case 4, (e) Case 5, (f) Case 6
Fig. 13 shows the curtailment values of individual turbines and the net gain obtained from EV charging in each case. The net gain of each turbine is distributed based on the weight that takes into account the power sensitivity. Due to a lower weight factor, a wind turbine operator who will implement the significant curtailment will be economically compensated by a large allocation of the net gain from EV charging.

Distribution was performed using weights suggested by the power sensitivity. It has been shown that the application of the proposed method improves the stability and economics of the power system by decreasing curtailment. It is also estimated that each wind turbine operator will be able to reduce the economic loss resulting from curtailment by charging EVs.

V. CONCLUSION

In this paper, we presented the distribution method for the input order while assuming the DSO based on the curtailment operator's order. The proposed method can be used to deliver the economic benefits generated by EV charging to wind turbines which may constitute a failure to comply with the grid code. Failure to take into account the loss in the necessary to create an appropriate curtailment signal for each turbine. Failure to take into account the loss in the distribution network or the available capacity of a given wind turbine may constitute a failure to comply with the grid operator’s order.

The scenarios were designed to dispatch references based on the power sensitivity under the imposed curtailment signal. Our research confirmed that the wind turbine located in the bus with high power sensitivity significantly influences the power flow in the distribution system. Therefore, we calculated the weights in order to distribute relatively high output to wind turbines with high power sensitivity, and we took into account the available capacity of individual wind turbines. Weight-based control could be excellent in terms of power system stability. However, some system owners would face unreasonable economic burdens. Hence, we applied a method of delivering the revenue generated from EV charging to the wind turbines, which perform excessive curtailment. Five Type III wind turbines were placed in the IEEE-69 Bus model, and the simulation model was constructed from Jeju Island’s power generation and load data. We confirmed the advanced accuracy effect when the designed case performed a curtailment (at 3 AM and 5 AM) with the proposed method. We also performed the EV charging based on the suggested weight. The results showed that the EV charging schedule made it possible to reduce the curtailment load and thus the economic losses of individual wind turbine operators. However, since the net profit varies with the number of EVSEs, the income allocated to each wind turbine owner may vary depending on the network used.

Future research should investigate the optimal number of EVSEs and planning methods for flexible charging at the field site.

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