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RESEARCH ARTICLE

Frequency Stability-Based Penetration Limit Evaluation of Variable Energy Resources in Power Systems for Online Application

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ABSTRACT While aiming to increase the dispatch of variable energy resources (VER) during the operation of a power system, the stability of the power system should be maintained, which can be realized by evaluating the penetration limit of the VER. This paper proposes a method for evaluating the penetration limit of VER. When a disturbance such as a generator trip occurs, the frequency stability depends on the inertia energy secured by generators, the characteristics of the primary frequency response, and the load response, which would change owing to an increase in the VER of the power system. In the proposed evaluation method, the frequency response performance of the power system is analyzed based on the historical operation data, and the penetration limit of VER is evaluated by applying the frequency criterion to maintain the frequency stability of the power system. Therefore, the potential penetration limit of VER can be estimated depending on the operating conditions. In addition, the effectiveness of the proposed evaluation method is verified by comparing the simulation results based on the Korean power system model-based simulation, and the online application is evaluated by applying it based on the real system operation data.

INDEX TERMS Critical inertia, operating reserve, penetration limit, power system operation, variable energy resources.

I. INTRODUCTION

The power system paradigm is changing owing to the reduction policy of fossil fuel-based generators because of the restriction of carbon dioxide emission regulations and the potential risks of nuclear generators [1]. Accordingly, many power systems have been promoting the application of variable energy resources (VER), such as photovoltaic (PV) and wind power generators (WTG), as a policy [2], [3]. However, increasing the VER, which has a physically asynchronous character in the power conversion system (PCS), may cause system degradation in stability when the synchronous generator is substituted [5].

The traditional power system mainly manages stability based on a frequency control mechanism [4]. In addition, the inertia energy possessed by the synchronous generator participating in dispatch has usually endured sudden frequency variations. Therefore, even if the power system operates the specific frequency reserve according to the power system requirement, in high penetration of VER in the power system, the frequency criterion may be violated during the disturbance because of the decreasing system inertia [6]. Moreover, as VER has intermittent and uncertain output characteristics, maintaining the balance of power supply and demand as

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a volatile factor can be affected. Due to these influences, transmission system operators (TSO) worldwide are paying attention to the risk of large-scale blackouts caused by the high penetration of VER in power system operation and focusing on ensuring stable operation [7].

Many studies are also being conducted on operational measures to secure the stable operation of the power system [8], [9]. In particular, various approaches, such as enhancing the prediction technology for the generation of VER [10], [11], securing flexibility in the power system [12], and introducing an energy storage system (ESS) or other resources [13], many kinds of solution have been proposed [14], [15], [16]. However, there is still a need for further research and practical implementation in this area. In this study, the focus was on reviewing the inertia limit conditions in terms of power system frequency stability and managing the penetration limit of VER.

The increasing penetration level of VER results in the degradation of the inertia energy of the system, and therefore, the importance of inertia management increases. Consequently, it becomes imperative to institute a dedicated evaluation framework for power system operation, as proposed in [17]. The framework would enable practical assessments of both VER penetration and frequency operation simultaneously, ensuring the preservation of frequency stability in adherence to operational rules. For frequency stability, the power system should establish a method for estimating the penetration limit of VER that can maintain the frequency within the allowable frequency range. For this purpose, as suggested in [18] and [19], an analysis of the relationship regarding the maximum frequency deviation during power system failures should be conducted. Since estimating the penetration limit of VER based solely on the proposed formulas is not possible, the relationship of the critical inertia, as presented in [20], needs to be derived. Subsequently, utilizing this relationship, it is necessary to establish a method for estimating the penetration limit of VER, as suggested in [21]. Additionally, this study aims to propose a method for evaluating and managing the inertia of the power system by extending the approach of estimating the inertia of individual generators and small-scale systems in an online environment from studies such as [22], [23], and [24]. In this process, it is necessary to consider the dynamic characteristics of various elements in addition to synchronous generators in the power system. As suggested in [25] and [26], it will be necessary to consider the dynamic characteristics of the load based on voltage and frequency variations immediately after disturbances. Furthermore, as demonstrated in [27], [28], [29], and [30], the power system should also consider the potential contributions to the operational performance of the power system from equipment such as VER or ESS providing frequency response. Various studies focused on inertia and frequency control performance for VER, including wind turbines [31], [32], [33], indicating the need for their consideration in future power system operations [34], [35]. Therefore, this study proposes a method to assess the permissible penetration level of VER in power systems based on frequency stability and historical operation data.

The contributions of this study are as follows.

1. Proposing a method to estimate the critical inertia and penetration limit of VER by reflecting the inertia of the power system and historical operation data.

2. Evaluating the practical penetration limit of VER based on online operating conditions of the power system.

3. Providing a VER penetration limit reference metric for power systems applicable in assessing the need to secure inertia requirements or other response resources for operational stability.

This study proposes a method to estimate the critical inertia and penetration limit of VER in real-time operating environments. The primary objective of critical inertia monitoring in an online environment is to contribute to power system operation and management by considering variations in operating states of power systems that may occur during real-time operation, ensuring stable operation, and preparing for contingencies. For this purpose, the proposed method considers system characteristics concerning frequency stability in the Korean power system based on historical operation data. Furthermore, its effectiveness was verified through simulation using the power system simulator for engineering (PSS/E) tool by Siemens PTI, a large-scale power system analysis program. Finally, the proposed method was analyzed by applying an online evaluation based on the historical operation data of the Korean power system. Based on this, the proposed method evaluates the VER penetration limit in the power system in an online environment, and provides operational conditions for securing the targeted VER capacity in power system operations.

II. FREQUENCY STABILITY OF THE POWER SYSTEM CONNECTED WITH VER

A. FREQUENCY RESPONSE CHARACTERISTIC IN THE POWER SYSTEM

The main operational purpose of a power system is to provide electric power according to demand without supply interruptions. This equilibrium state between power generation and load demand can be expressed in terms of frequency. However, the disturbance can induce an unexpected frequency drop. Therefore, the frequency should be maintained within the specific boundary to ensure stability. If no further measures are taken to arrest or recover the frequency, the frequency drop can cascade to load shedding, generator relay operation, and even blackout. Thus, the system operator should focus on the reliable operation of frequency, even in the dynamic state.

The dynamic state of the power system is affected by the imbalance between the power generation and load demand. The initial dynamic frequency characteristics are especially affected by the inertia-secured kinetic energy in the synchronous generator. However, as the inertia is difficult to intentionally control, system operators have to secure

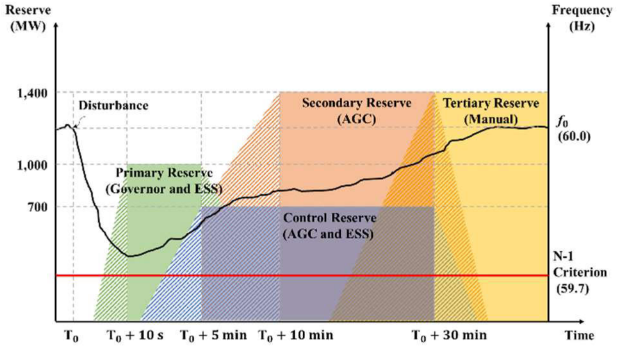


FIGURE 1. Frequency reserve and its response criteria in the Korean power system.

frequency reserves. The frequency reserve is typically composed of the primary frequency reserve through the governor response of the generator, the secondary frequency reserve through the power adjustment performance by the automatic generation control (AGC), and the tertiary frequency reserve by manual power adjustment. By using these schemes, the frequency is arrested to the nadir, and the frequency is restored to its normal operating range.

In the Korean power system, the frequency reserve is categorized according to the specific response time of the resource and control purposes, as shown in Fig. 1 [36]. As the Korean power system has the frequency criterion of 59.7 Hz according to the single largest generator trip, the system operator should secure a specific amount of frequency reserve. The frequency control reserve mainly contributes to the stable operation of the system in the dynamic state [37].

The primary frequency reserve provides the fastest response to arrest the frequency drop. According to the criteria, this response should be activated within 10 s after the disturbance. In other words, the initial dynamic frequency characteristic is mainly affected by inertia secured in the power system during the 10 s before the full activation of the primary frequency reserve. According to market operating rules, the primary frequency reserve requires 1,000 MW of reserve capacity to respond to a frequency deviation of 0.2 Hz, calculated based on speed droop and head-room capacity.

However, as the penetration level of VER increases, the synchronous generator can be excluded from dispatch, thereby reducing the inertia of the power system. Therefore, even if the reserve force of the power system is constantly secured, the frequency standard is violated before the reserve fully responds because of the decrease in inertia. In this study, the critical inertia of the power system is defined as the minimum inertia necessary to secure frequency stability. Furthermore, the penetration limit of VER is determined as the maximum capacity of VER at the critical inertia of the power system. To ensure stable operation, it is crucial to analyze the penetration limit of VER, considering the characteristics of the power system, including the calculation of critical inertia based on the system inertia, governor response performance of generators, and load response characteristics.

TABLE 1. Grid connection code of VER for frequency response.

Index	National Grid (GBR)	EirGrid (IRL)	Tennet (DEU)	KPX (KOR)
Frequency dead-band (mHz)	< 500	< 15	< 500	< 36
Speed droop (%)	2 – 12	3 – 5	2 – 12	3 – 5
Initial responding time (s)	< 15	< 10	< 30	< 10
Available reserve (%)	< 15	< 10	1.5 ~ 10	N/A

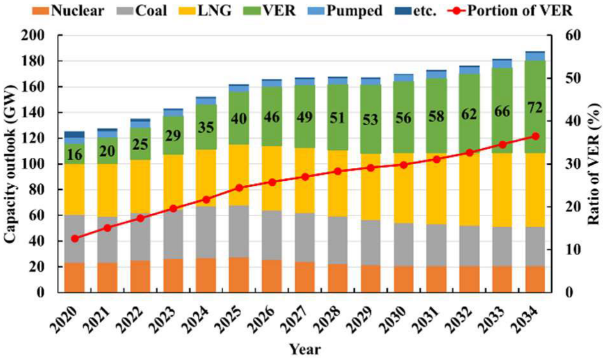


FIGURE 2. Capacity outlook depending on the generation type in the Korean power system.

B. GRID CONNECTION OF VER IN THE KOREAN POWER SYSTEM

In many countries, it has been declared that part of the power supply in the power system will be provided by VER. The Korean power system aims to have 20% of the power generated by VER by 2030. The penetration targets are set incrementally, aiming for 40% and 60% VER penetration by 2040 and 2050, respectively.To achieve this VER expansion goal, the Ministry of Trade, Industry, and Energy periodically announces these policies in the system plan for the next 15 years. Accordingly, the annual VER penetration goal of the Korean power system is shown in Fig. 2 [38].

In the Korean power system, it is expected that the total VER facilities of 56 GW in 2030 will be expanded with a focus on PV and WTG. In particular, the expansion of PV is expected to prevail over WTG owing to the climatic conditions in Korea. The power system should operate stably even when the expected VER is penetrated. For stable operation, the system operator specifies the performance requirements for the VER as a standard. The most typical performance requirement is the provision of frequency response. In this regard, it can be summarized and compared by the organization operating the system, and expressed as described in Table 1 [39], [40], [41], [42].

Although the frequency response differs according to the operating standard of each power system, each power system requires a similar response sensitivity to the thermal power generator, which is the main resource for providing reserve. However, in the case of the Korean power system, the standard for reserve power is insufficient. Moreover, as there is no way to consider the frequency response performance of VER in the market operating system, the frequency response provision through VER is not yet realized.

Additionally, the standard for reactive power supply to VER is also specified. VER needs to supply reactive power with a maximum power factor of 0.95 when supplying active power within the voltage operating range. In the connection code, voltage ride-through, frequency ride-through, and various performance conditions are required for VER operation. In this study, the grid connection code of VER required by the Korean power system was applied and analyzed.

III. FREQUENCY STABILITY-BASED EVALUATION METHOD FOR CALCULATING THE PENETRATION LIMIT OF VER

A. FREQUENCY STABILITY-BASED PENETRATION LIMIT OF VER

The system inertia plays an important role in arresting the rapid frequency drop immediately after an instantaneous disturbance in the power system. The inertia can be commonly expressed as generator equivalent inertia constant ($H_{gen,i}$), a ratio between the stored kinetic energy and the rated capacity of each synchronous generator, as shown in (1). From the power system perspective, the equivalent generator inertia constant (H_{sys}) can be defined as (2) by calculating the weighted average value as the ratio between the total kinetic energy of synchronous generators and the size of the power system:

$$H_{gen,i} = \frac{E_{gen,i}}{S_{gen,i}} = \frac{\frac{1}{2}J\omega^2}{S_{gen,i}}, \tag{1}$$

$$H_{gen} = \frac{\sum_{i=1}^{n} H_{gen,i}S_{gen,i}}{S_{sys}} = \frac{\sum_{i=1}^{n} E_{gen,i}}{S_{sys}}, \tag{2}$$

where, $E_{gen,i}$ is the stored kinetic energy in the ith generator that can be calculated using inertia moment J and angular velocity ω, $S_{gen,i}$ is the rated MVA of the ith generator, and S_{sys} is the size of the power system including the non-synchronous generator.

The relation between the system inertia and frequency can be defined by the swing equation of the power system, as shown in (3),

$$\frac{d\Delta f}{dt} = \frac{f_0 \Delta P}{2H_{sys}S_{sys}} = \frac{f_0 \Delta P}{2E_{sys}}, \tag{3}$$

where, $d\Delta f/dt$ is the rate of change of frequency (RoCoF) immediately after the disturbance, f_0 is the nominal frequency, ΔP is an imbalance between generation power and load demand, H_{sys} is a system inertia constant, and E_{sys} is the total inertia energy in the power system.

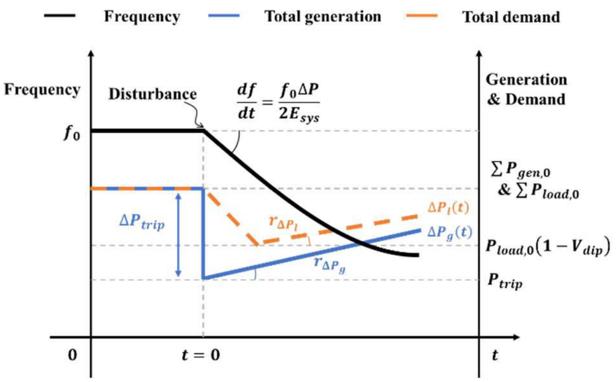


FIGURE 3. Variation example of frequency and generation in power system after the disturbance.

In addition, based on the integration of (3), it can be rearranged as the relation between the frequency deviation and inertia in the time domain. However, to reflect the dynamic characteristics, the offset between the disturbance and the frequency response by resources in the power system should be considered. This study assumed that the frequency response resource contributes to the power system as the equivalent response performance after the disturbance, as shown in Fig. 3.

When the generator in the power system that supplies the initial generation ($\sum P_{gen,0}$) trips, the tripped generation (P_{trip}) is applied as an instantaneous imbalance. At this time, as shown in (3), the initial RoCoF is determined depending on the system inertia. Thereafter, the frequency imbalance is alleviated in response to changes in the generation resource of the power system and load demand. The response characteristics of each component correspond to the time-varying equivalent generation ($r_{\Delta P_g}$) and load demand ($r_{\Delta P_l}$) [18]. Indeed, variations in generation and load are affected by system factors such as frequency and voltage. Therefore, representing the overall response characteristics as values proportional to time can be inaccurate. However, the response characteristics right after the disturbances can be validly approximated as proportional to time. It is important to apply different coefficients based on the operating conditions of the system and the magnitude of the disturbance for a more accurate assessment.

The response by the governor, which is the frequency response on the generation side, can be the most representative. In addition, the frequency response can include other resources, such as VER and energy storage systems. In the case of the demand-side, the load demand has varying characteristics of not only frequency but also voltage change, depending on the load-type composition [43]. Therefore, the time-varying characteristics of power generation ($\Delta P_g(t)$) and load demand ($\Delta P_l(t)$) are formulated as follows:

$$\Delta P_g(t) = r_{\Delta P_g} t, \tag{4}$$

$$\Delta P_l(t) = -P_{load,0}\left(1 - V_{dip}\right) + r_{\Delta P_l} t, \tag{5}$$

$$\Delta P = -P_{trip} + \Delta P_g(t) - \Delta P_l(t), \tag{6}$$

where, $P_{load,0}$ is the initial load demand immediately before the disturbance occurs, V_{dip} is the instantaneous voltage dip on the demand-side, and P_{trip} is the MW of the tripped generation. Here, the voltage-dependent term is expressed as $\Delta P'_{load,t_0}$.

Therefore, the relationship between frequency deviation and inertia can be expressed as (7), including the contribution of the frequency response resource after disturbance to the imbalance of the power system in the integration form (3):

$$\Delta f\ (t) = -\frac{\left(P_{trip} - \Delta P'_{load,t_0}\right) f_0}{2E_{sys}} t + \frac{\left(r_{\Delta P_g} - r_{\Delta P_l}\right) f_0}{4E_{sys}} t^2. \tag{7}$$

From this relation, the time of the nadir frequency can be determined using the first-order derivative, such as (8). Using (8), the expression can be derived by arranging the equation in the relationship between the nadir frequency and system inertia as (9):

$$t_{\Delta f_{max}} \cong \frac{P_{trip} - \Delta P'_{load,t0}}{r_{\Delta P_g} - r_{\Delta P_l}}, \tag{8}$$

$$\begin{aligned}\Delta f_{max} &= -\frac{\left(P_{trip} - \Delta P'_{load,t_0}\right) f_0}{2E_{sys}} \left(\frac{P_{trip} - \Delta P'_{load,t0}}{r_{\Delta P_g} - r_{\Delta P_l}}\right) \\ &\quad + \frac{\left(r_{\Delta P_g} - r_{\Delta P_l}\right) f_0}{4E_{sys}} \left(\frac{P_{trip} - \Delta P'_{load,t0}}{r_{\Delta P_g} - r_{\Delta P_l}}\right)^2 \\ &= \frac{-\left(P_{trip} - \Delta P'_{load,t0}\right)^2 f_0}{4E_{sys}(r_{\Delta P_g} - r_{\Delta P_l})},\end{aligned} \tag{9}$$

where $t_{\Delta f_{max}}$ is the time at the nadir frequency point, and Δf_{max} is the maximum frequency deviation after the disturbance.

Therefore, the dynamic characteristics of the frequency after the disturbance can be analyzed using the inertia-frequency characteristics. Moreover, it can be confirmed that inertia is a significant factor that determines the penetration limit of VER according to the frequency criteria. Based on this relationship, the power system must be able to operate with the penetration of VER while satisfying the required frequency operation standards, even in severe cases of frequency disturbance. In addition, for the reliability of the power-system dynamic characteristics, the frequency was applied using the center of inertia of frequency based on the information of the entire operating generator. Therefore, by using this relationship, the critical inertia of the power system can be calculated and managed. To accomplish that, the penetration of VER requires a method that can analyze the margin between the existing and critical inertia and evaluate the penetration limit of VER.

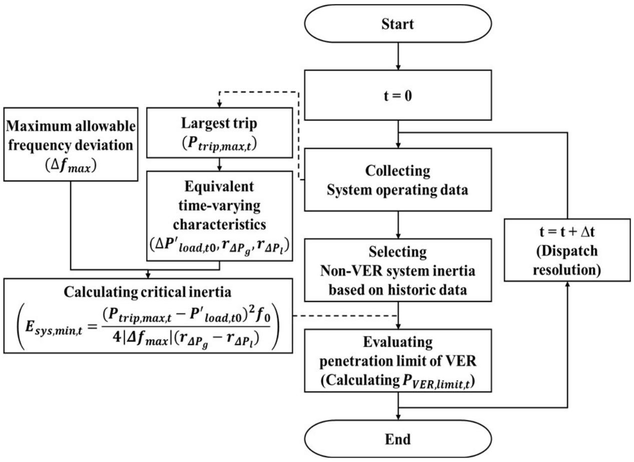


FIGURE 4. Procedure of the proposed method for evaluating the penetration limit of VER in the power system.

B. PROPOSED EVALUATION METHOD FOR CALCULATING THE PENETRATION LIMIT OF VER

As mentioned in the previous section, if the penetration of VER increases, the power system may exceed the frequency criteria owing to a decrease in inertia even when the power system operates under the same reserve. Therefore, to maintain frequency stability, the penetration limit of VER should be determined through the relationship between inertia and frequency characteristics. Thus, this study proposes an evaluation method, as shown in Fig. 4.

1) COLLECTING THE SYSTEM OPERATING DATA

To calculate the penetration limit of VER using the proposed evaluation method, acquisition of system operation information is required to calculate the critical inertia.

First, as the system inertia depends on the number of synchronous generators dispatched in the power system, and its portfolio depending on the fuel type, this information should be collected to consider these characteristics.

Second, the frequency operation criteria are required to analyze the critical condition of the power system. In most power systems, the allowable frequency deviation is defined after the disturbance. That is, the operating limit condition is determined according to the frequency operation criteria.

Finally, the equivalent time-varying characteristic that can represent the response of the power generation and load demand in the power system needs to be applied. Various methods are available, but the value is applied based on several historical operational data collected in this study.

It is crucial to note that the parameters values applied during calculations are based on past operational data; therefore, sufficient data is required to ensure representativeness. Although the minimum number of data points to be collected may vary depending on the characteristics of the power system, historical data covering at least one year, including faults under various load conditions, causing frequency fluctuation, should be obtained. For instance, considering that the Korean power system experiences generator faults of 500 MW or more once or twice per month, an analysis based on a minimum of 20 fault history data is required to derive meaningful results. It is important not to simply use the average values from past failures when applying the proposed method, but to apply suitable values by weighing them based on the current operating conditions throughout the overall operational trends.

2) CALCULATING THE CRITICAL INERTIA OF THE POWER SYSTEM

The critical inertia of the power system is determined by the threshold condition in which the frequency deviation is within the allowable frequency deviation after the disturbance. As shown in (10), it is defined as the critical inertia that needs to be secured in the power system according to the frequency operation criteria based on the operation information acquired from the power system, according to (9):

$$E_{sys,min} = \frac{\left(P_{trip} - \Delta P'_{load,t0}\right)^2 f_0}{4\left|\Delta f_{max}\right|\left(r_{\Delta P_g} - r_{\Delta P_l}\right)}, \tag{10}$$

where, $E_{sys,min}$ is the critical inertia required to comply with the allowable frequency deviation.

In other words, the critical inertia required to prevent the violation of the frequency standard is calculated using a mathematical relationship and applied as a standard for the amount of allowable penetration of VER in the power system.

3) EVALUATING THE PENETRATION LIMIT OF VER

The facilities supplying generation power for the demand–supply balance in the power system can be broadly categoryized into synchronous generators, which provide inertia, and VER, which do not provide inertia, as shown in (11). Based on this, the evaluation of the penetration limit of VER is performed based on the relation between the critical and secured inertia by the generators. That is, the power system inertia must be operated above the critical inertia to maintain frequency stability, as shown in (12).

$$S_{Sys} = S_{SG} + S_{VER} \tag{11}$$

$$E_{sys,min} = H_{sys,min} S_{Sys} \leq H_{SG} S_{SG} \tag{12}$$

where, $H_{sys,min}$ is the critical inertia constant of the power system, H_{SG} and S_{SG} are the equivalent inertia constant and apparent power of the synchronous generators, respectively.

However, VER is limited in contributing to inertia response by its decoupled characteristics. Moreover, other inertia support components, such as the rapid response of the governor and load, are less predictable and controllable. Therefore, the secured system inertia primarily relies on the synchronous generator, as shown in (12).

Accordingly, based on the relation between the synchronous generator and VER in the power system, the penetration limit of VER in the power system can be determined by (13) from (12):

$$P_{VER,limit} = \frac{\left(H_{SG} - H_{sys,min}\right) \times S_{sys} + KE_{etc}}{H_{SG}} \times p.f. \tag{13}$$

where KE_{etc} is equivalent inertia energy from additional inertia response resources.

Moreover, in the power system, demand response, energy storage systems, and synchronous condensers can be applied as additional frequency response resources. These resources may not directly participate in power supply but can contribute in terms of inertia. If their contribution is convertible into inertia, they can be incorporated into the proposed method. However, in such cases, the inertia energy provided by these resources can be considered by calculating an equivalent inertia transposed into the same domain as the inertia secured by synchronous generators.

Therefore, the penetration limit of VER in the power system can be calculated using the degree of margin to the critical inertia based on the secured inertia by the synchronous generator before the VER connection. In addition, the penetration limit of VER can be applied by converting it to active power, considering the reactive power supply required for the performance according to the grid connection code of the VER, as discussed in Section II.

IV. SIMULATION RESULTS AND ANALYSIS

A. OPERATING PARAMETERS FOR POWER SYSTEM ANALYSIS

To analyze the proposed evaluation method, a simulation was performed based on the future planning database (DB) of the Korean power system in 2030. This analysis has been conducted with a focus on the Korean power system, where the effective application of the proposed method is possible due to the requirement for extensive historical operational data. If a sufficient amount of operational data is available, the method's application is not limited to a specific system and can be universally applied. It is verified by comparing its performance with the simulation results derived based on PSS/E. The data used for analysis are presented in Table 2. The dispatched power generation configuration for each load condition is illustrated in Fig. 5.

This configuration is designed to meet the 2030 demand based on the composition of the current power system. The system operator has established and manages a DB distinguishing the integration status of VER. In this analysis, the simulations were started by increasing the capacity of VER from conditions where VER integration was not considered. The Korean power system generates electricity primarily using nuclear and coal-fired power plants as base-load generators. Power supply capacity is secured by additional gas-fired power plants, as well as hydro and pumped-hydro power plants. The reserve capacity that the power system needs is typically secured through coal-fired power plants, with gas-fired power plants supplementing any shortage in reserve; however, there may be differences in composition ratios depending on the system operation conditions.

TABLE 2. Specification data for analysis and simulation.

Index	Parameter		Value
Frequency reserve	PFR		1,000 (MW)
Frequency stability criteria (N-1)	Δf_{max}		0.3 (Hz)
	$\Delta P_{trip,max}$		1,460 (GW)
DB-based system condition	Off-peak	S_{sys}	73.216 (GVA)
		P_{sys}	61.570 (GW)
		H_{SG}	4.54 (s)
	Medium	S_{sys}	95.326 (GVA)
		P_{sys}	79.794 (GW)
		H_{SG}	4.76 (s)
	Peak	S_{sys}	120.379 (GVA)
		P_{sys}	98.921 (GW)
		H_{SG}	4.76 (s)

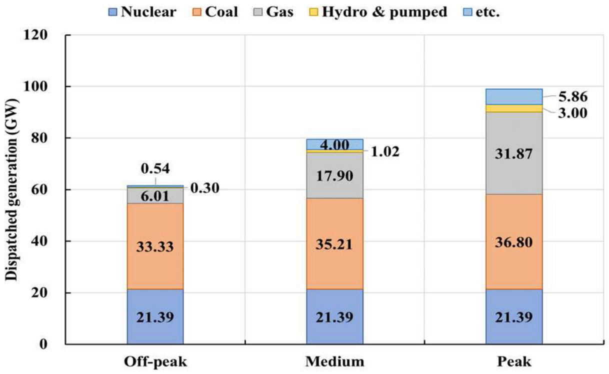
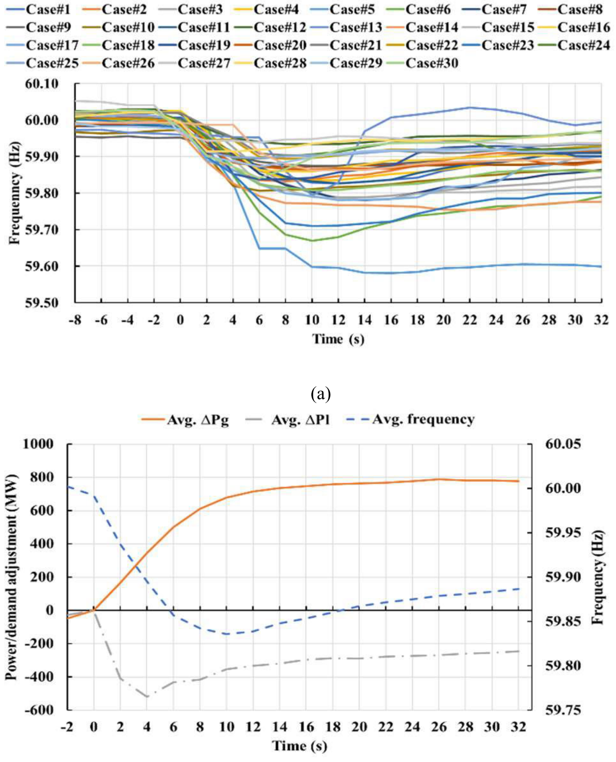


FIGURE 5. Generation profile in DB-based system condition.

The Korean power system should maintain a frequency higher than 59.7 Hz by N-1 criteria. The analysis is accompanied by the tripping of 1.46 GW of the largest generator. Based on these conditions, this study analyzed the penetration limit of VER depending on the proposed method, according to the system demand level in 2030.

To apply the proposed method, the response characteristic of the synchronous generator governor is required; the representative value is calculated by analyzing the response performance of the synchronous generator governor based on 30 historical operation data samples obtained during 2013∼2021, as shown in Fig. 6.

As shown in Fig. 6. (a), the frequency characteristics are derived differently depending on several factors, such as the system demand level, dispatch condition, and failure size of the generator. Based on this, the average characteristics of the governor response, load variation, and frequency for each operation result are shown in Fig. 6. (b). The total governor response increases in proportion to the frequency deviation, and the characteristic that the load varies according to the voltage and frequency deviation can be confirmed. At this point, it can be confirmed that although individual elements may show differences in response, there is significant linearity from the overall perspective of the power system within the interval until the formation of the nadir frequency. In this study, an analysis was conducted using these response performances of the power system.



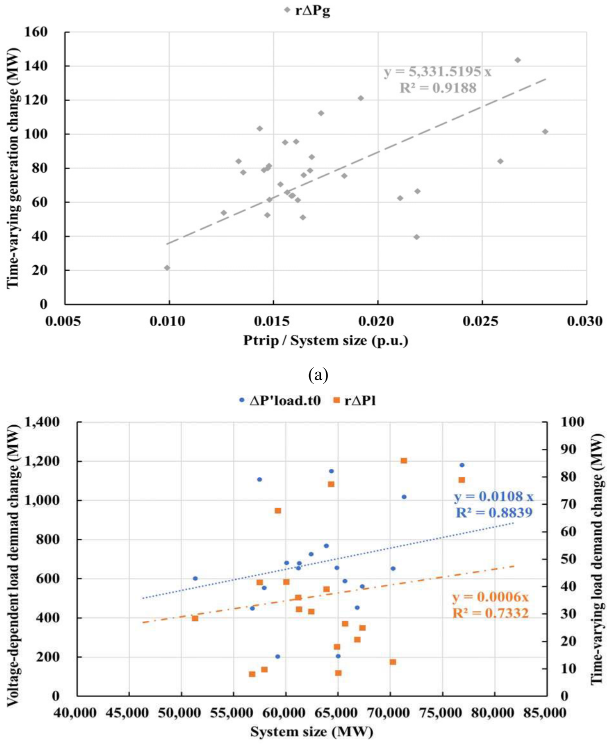
(a)

(b)

FIGURE 6. Historical operation data after the generator trip in the Korean power system: (a) frequency; (b) average characteristics.

The governor response and load variability correlate with the scale of the system, and in particular, the governor response also has an additional correlation with the size of the failure generator. To analyze that, we approximate the response performance using the least-squares method, as shown in Fig. 7.

Consequently, as shown in Fig. 7. (a), the governor response performance has a significant linear relationship with the ratio of the size of failure to the size of the power system. Fig. 7. (b) shows a linear correlation between power demand and the instantaneous demand fluctuation due to voltage changes following power system failures. Furthermore, the load variation caused by frequency deviation exhibits a consistent linear relationship with the size of the power system. As power systems have complex characteristics, it is difficult to define a perfect linear relationship. Analysis of the historical operation data confirmed that a relationship with a high R-squared value can be derived for each of the frequency- and voltage-dependent performance indicators according to the system operating conditions. Therefore, based on such correlations, analyzing the operational outcomes of the power system enables the estimation and



(a)

(b)

FIGURE 7. Historical operation data-based least-square estimation of the response performance: (a) governor response; (b) demand response.

analysis of dynamic characteristics of the power system for target operating conditions. This involves applying values such as the maximum generator failure capacity and demand of the power system, allowing for an estimation of the dynamic characteristics of the power system. It was applied in the calculation of the penetration limit of VER by referring to the relationship between the power system response performance and the system operating conditions.

B. VERIFICATION OF THE PROPOSED METHOD FOR CALCULATING THE PENETRATION LIMIT OF VER

This section presents the calculation of the critical inertia for securing frequency stability by reflecting the governor response performance into the proposed method and the derivation of the penetration limit of VER. According to the procedure of the proposed method, the critical inertia can be calculated using the operating status and criteria of the power system. The medium-level system load, which is a typical operation state, is targeted. In this evaluation condition, the critical inertia only relies on the operating criterion, which is the allowable frequency, as the operating condition remains the same. Consequently, the critical inertia according to the allowable frequency and the penetration limit of VER are obtained, as shown in Fig. 8.

The frequency stability can be secured with low inertia when the power system has a large allowable frequency deviation. In this operating condition, the synchronous generators,

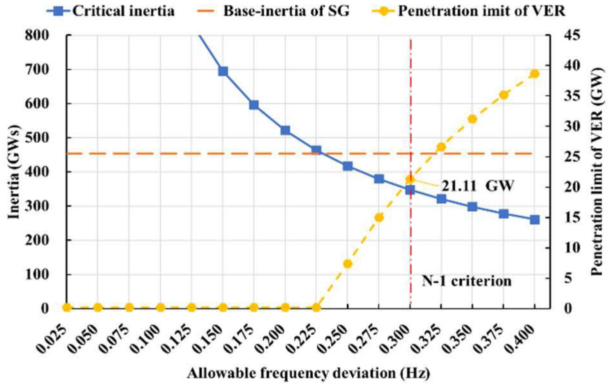


FIGURE 8. Critical inertia and penetration limit of VER depending on the allowable frequency in the power system.

which have an inertia of at least 347.86 GWs, ensure a frequency higher than 59.7 Hz. From this result, it can be inferred that VER can expand up to 21.11 GW according to (13).

The effectiveness of the proposed method is verified by comparing it with the simulation-based results. Referring to the VER expansion plan of the Korean power system, the proportion of WTG and PV facilities is reflected, and the power portfolio of synchronous generators is modeled. For the VER modeling of this simulation, Type 4 of WTG and PV models recommended by the Western Electricity Coordinating Council (WECC) working group are used [44], [45]. The frequency stability is analyzed by gradually increasing the capacity of VER in the power system, and the results are shown in Fig. 9. and Table 3.

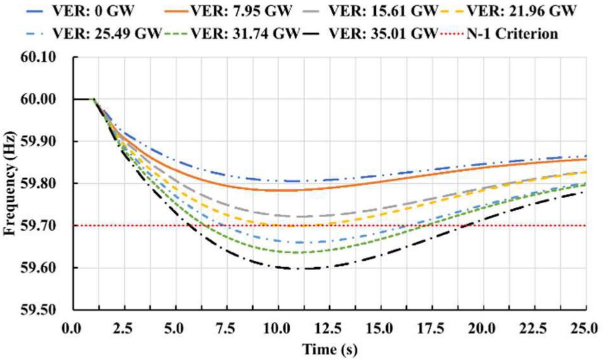


FIGURE 9. PSS/E simulation results concerning frequency response characteristics depending on the increase in the penetration of VER in the power system at medium demand.

Although a certain level of primary reserve is secured according to the operating standards of the power system, both RoCoF and the nadir frequency continue to decrease because of the decrease in inertia as the penetration level of VER increases. In this simulation, when the VER capacity exceeds 21.96 GW, the frequency stability violates the frequency criteria, and further penetration of the VER is limited.

TABLE 3. **PSS/E based dynamic simulation results depending on the increasing penetration of VER in the power system.**

Penetration level (GW)	RoCoF (Hz/s)	System inertia (GWs)	Nadir Frequency (Hz)
0 (0.00%)	-0.0566	462.578	59.806
7.95 (10.00%)	-0.0680	410.168	59.783
15.61 (19.64%)	-0.0712	366.733	59.722
21.96 (27.62%)	-0.0777	327.941	59.700
25.49 (32.06%)	-0.0799	308.388	59.660
31.74 (39.30%)	-0.0846	278.973	59.636
35.02 (44.04%)	-0.0902	260.119	59.597

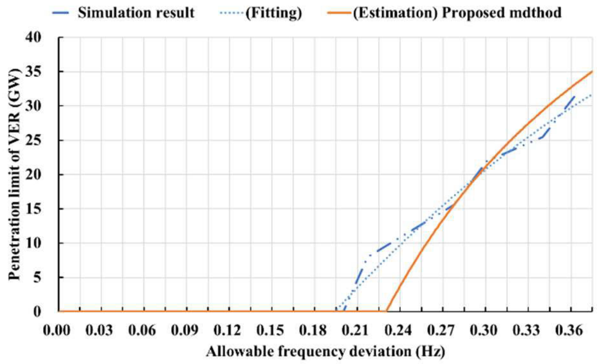
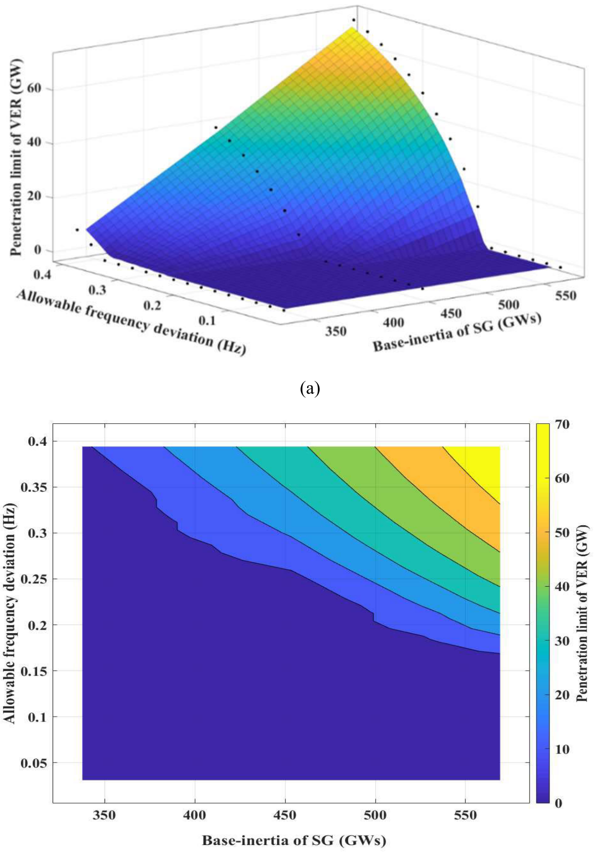


FIGURE 10. **Comparison of the penetration limit of VER between the simulation result and the proposed method depending on the allowable frequency.**



(a)

(b)

FIGURE 11. **Result of the penetration limit of VER depending on the base-inertia of SG and allowable frequency: (a) 3D-linear graph based on three operating conditions; (b) its contour-line graph.**

Therefore, the penetration limit of VER derived through the proposed method, aimed at securing the operational criteria of the power system, is slightly lower than the penetration limit obtained from time-domain simulation. This prevents the frequency from decreasing below 59.7 Hz.

In summary, Fig. 10 compares the results obtained based on the proposed method with the results of Fig. 8 and the PSS/E-based time-domain analysis results of Fig. 9 under the same operating conditions. For this comparison, the results obtained from Fig. 9 were rearranged as the results of the minimum frequency based on the VER capacity. The overall trends exhibit a similar pattern, and an additional analysis of relative error was performed based on the time-domain simulation results.

The mean absolute percentage error (MAPE) for the entire section(0.00–0.40 Hz) is 12.85%, showing relatively good accuracy [46]. The penetration of VER for each allowable frequency condition is especially different from that of the simulation in the range of 0.20–0.26 Hz. However, this range is not related to the frequency criterion. Excluding this range, mutual results showed a similar penetration limit of VER with an error level of 5.27%, showing high accuracy.

The results from the proposed method for the other system operating conditions (off-peak, peak level of demand) are shown in Fig. 11. By applying the proposed method, the penetration limit of VER can be calculated depending on the system operating conditions. That is, even for the same allowable frequency deviation, VER varies depending on the amount of inertia provided by the synchronous generator, which can be observed from the calculation of the low penetration limit of VER at low inertia.

To elucidate the efficiency of the proposed method, an analysis was performed through comparisons with other studies and methods. Since the constraints in selecting an appropriate counterpart for a comparison with the proposed method, the critical inertia comparison relies on the frequency nadir prediction presented in [19], focusing on operations within a 0.3 Hz frequency deviation (Scheme#1). Moreover, different methods were examined, incorporating the average dynamic characteristics of historical operational data and selectively considering system operating conditions. To achieve this, the analysis was conducted using a method that only considers factors related to the failure size (Scheme#2) and another method that solely considers factors associated with the system size (Scheme#3). The comprehensive results are shown in Fig. 12 and Table 4.

Firstly, in the case of Scheme#1, it is observed that the characteristic of the load, which can influence the initial dynamic characteristics, is not considered. Therefore, a higher

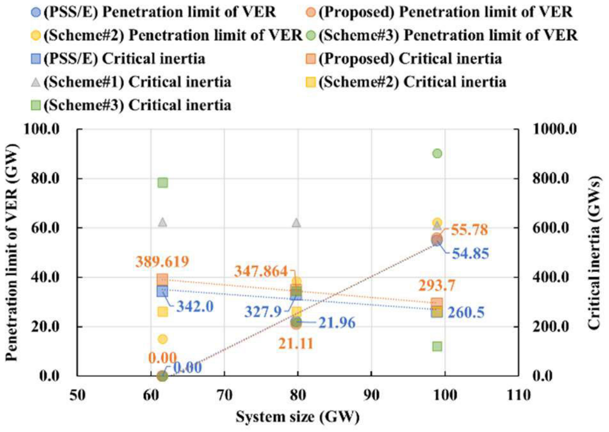


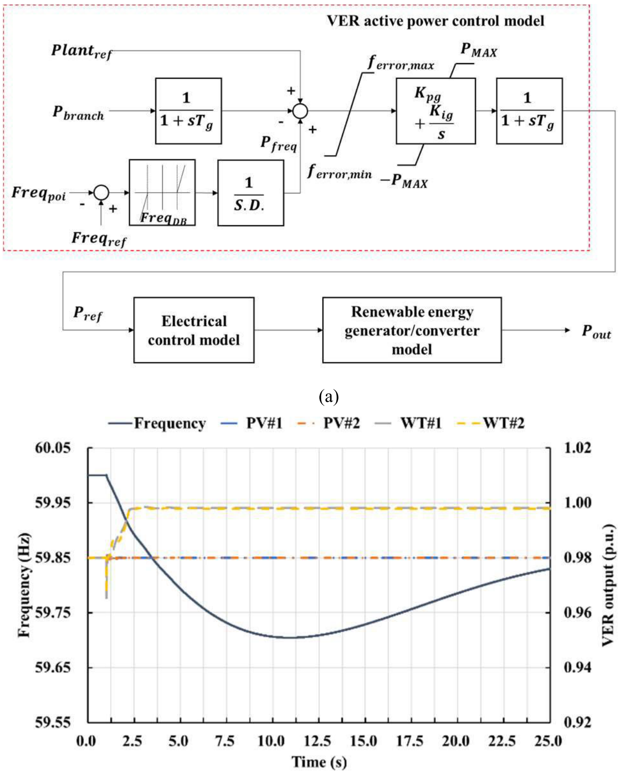
FIGURE 12. Comparison of inertia and VER penetration limit capacity between the proposed method, other schemes, and PSS/E simulation results under VER penetration limit conditions.

TABLE 4. Comparison of critical inertia and penetration limit of VER between schemes and examination of relative errors based on PSS/E simulation results.

Index	Critical Inertia (GWs) / Relative error (%)						Average error (%)
	off-peak		Medium		Peak		
PSS/E	342.05	N/A	327.94	N/A	260.51	N/A	N/A
Proposed	389.62	13.90	347.86	6.08	293.72	12.75	10.91
Scheme#1	624.92	82.70	622.10	89.70	610.66	134.41	102.27
Scheme#2	261.20	23.64	261.20	20.35	261.20	0.26	14.75
Scheme#3	784.65	129.40	345.00	5.20	120.92	53.58	62.73

Index	Penetration limit of VER (GW) / Relative error (%)						Average error (%)
	off-peak		Medium		Peak		
PSS/E	0.00	N/A	21.96	N/A	54.85	N/A	N/A
Proposed	0.00	0.00	21.11	3.87	55.78	1.69	1.85
Scheme#2	15.01	INF	38.40	74.89	62.26	13.51	44.20
Scheme#3	0.00	0.00	21.68	1.27	90.22	64.48	21.92

inertia is required to maintain a frequency operation standard (0.3 Hz). Additionally, the limitation in reflecting the diversity of the operational characteristics and system size causes a relative error with increase, resulting in an average error of approximately 102.27% for critical inertia. The results of Scheme#2 and #3, lacking considerations for system size and failure size, exhibit an average error of 44.2% and 21.92%, respectively, concerning the penetration limit of VER. In the case of Scheme#3, a relatively low relative error is observed for medium-level power demand. This is inferred to be the contribution of a high ratio of cases derived from historical operational data secured under medium-level power demand conditions. Consequently, the relative error of critical inertia increases during off-peak and peak power demand. On the contrary, there is no significant difference between the PSS/E-based simulation results for the same system operating conditions and the proposed method based on mathematical relationships. Although the calculated estimation error regarding the critical inertia during off-peak was found to be rather high, at 13.90%, the same penetration limit of VER was derived as 0 GW. For the other system operating conditions that were analyzed, it was verified that the results of the penetration limit of VER were only at an average of 1.85%, resulting in fairly similar results.



(a)

(b)

FIGURE 13. Example of implementing the frequency response capability of VER in PSS/E: (a) frequency control model for VER in PSS/E; (b) its PSS/E simulation result under the disturbance.

C. CONSIDERING THE FREQUENCY RESPONSE SUPPORT BY VER IN THE PROPOSED METHOD

VER should exhibit a frequency response performance according to the grid connection code. As mentioned in Section II, VER, which is connected to the transmission system, must have a certain level of frequency response performance. In the Korean power system, this mainly applies to WTG, whereas for PV, it is mostly connected at the distribution level and is required to comply with the standards of the distribution system.

This study assumed the minimum performance conditions of VER as required by the grid connection code. Based on this assumption, additional analysis was conducted by de-loading a certain capacity from the maximum operating point of the WTG to secure reserve power and applying droop-based frequency response. The frequency response performance was implemented by applying the grid connection code to the WTG, and simulation analysis was performed. The frequency response performance specified in the grid connection code

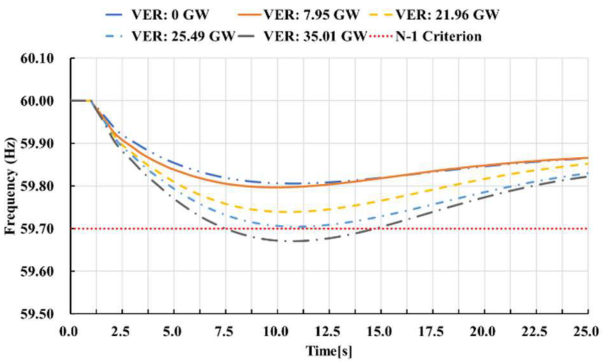


FIGURE 14. PSS/E simulation results concerning frequency response characteristics depending on the increase in the penetration of VER with frequency response capability in the power system at medium demand.

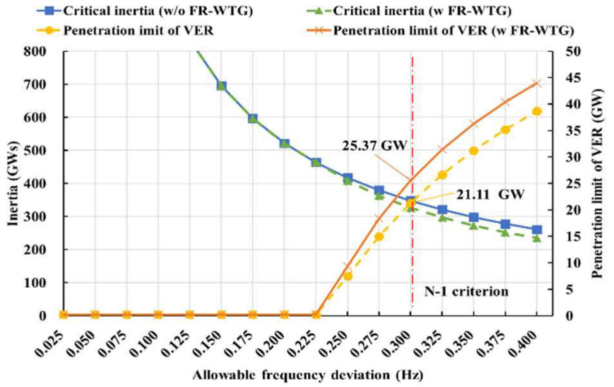


FIGURE 15. Calculating critical inertia and penetration limit of VER with frequency response capability depending on the allowable frequency.

was applied. However, there is no standard for reserve power in Korea's grid connection code; therefore, the operating standards of other power systems were analyzed and applied. This function was implemented in the REPCA1/REPCTA1 model of PSS/E, and the output example of VER is shown in Fig. 13 [47], [48].

The frequency response was modeled by applying the conservative value required by the grid connection code only to WTG (i.e., speed droop: 5%; frequency dead-band:0.06%). The reserve capacity was modeled assuming that 2% of the response capacity was always secured as a reserve capacity. However, the frequency response from PV was not considered in this analysis because most of them were connected to the distribution system.Consequently, the WTG exhibits a frequency response proportional to the frequency deviation. However, the PV does not exhibit a frequency response, but idles. In this analysis, to examine the effectiveness of the proposed method even with the frequency response of VER, the initial frequency response performance of VER is calculated based on simulation, and this is added to the existing value of the frequency response performance of the synchronous generator.

Then, the penetration limit of VER in the medium-level system obtained via the proposed method was analyzed. In addition, the results for each VER penetration level determined via simulation were analyzed, as shown in Figs. 14 and 15.

The analysis confirmed that the penetration level of VER from the two sets of results was similar under most operating conditions. In particular, under the permissible frequency deviation condition of 0.3 Hz according to the operating standard, the proposed method and the simulation have 25.37 GW and 25.49 GW of VER penetration limit, respectively. The difference was confirmed to be approximately 0.47%.

Through this analysis, the effectiveness of the proposed method was verified even when VER provided a frequency response. However, it is considered that effective values can be calculated only when the frequency response performances by VER and the governor of the synchronous generator are accurately derived. Therefore, the accurate analysis of the response performance of power supply sources requires the use of historical operation data of the real system.

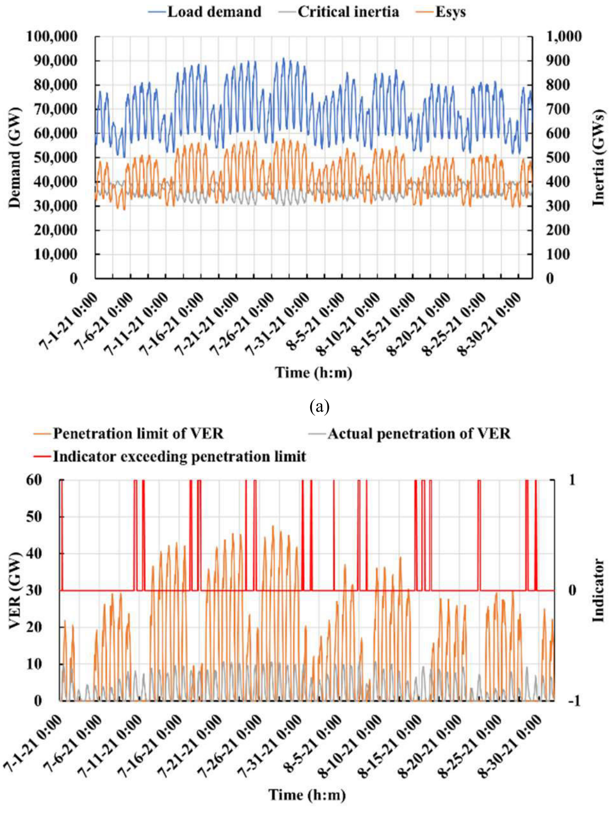
D. EVALUATING THE PENETRATION LIMIT OF VER IN ONLINE SYSTEM OPERATION

For stable operation of power systems, the proposed method is necessary to realize online management of the penetration limit of VER. The critical inertia and VER penetration limit required to satisfy the frequency operation criteria were reviewed by applying the long-term historical operation data acquired from the power system by using the proposed evaluation method.

The online application analysis of the proposed method is performed using the system operation information obtained from the system operator in the Korean power system. The analysis was based on the information acquired over two months, and the results are shown in Fig. 16. This period corresponds to around July to August when the demand level in the Korean power system is high.

As shown in Fig. 16. (a), the inertia of the power system has a similar pattern to the load demand variation because of the number of dispatched generators. Analyzing the critical inertia required to ensure frequency stability of the power system based on (8) typically reveals higher values during periods with fewer operating generators, such as late-night hours and weekends. Furthermore, the results of determining the penetration limit of VER are illustrated in Fig. 16 (b). Here, the average and maximum penetration limits of VER were confirmed to be 10.90 GW and 47.55 GW, respectively. In particular, for the maximum penetration limits of VER, it is considered that high penetration of VER is possible from a stability perspective, given that the demand in the power system exceeds 90 GW.

For cases exceeding the penetration limit of VER, indicated by the indicator as 1, it was observed to be at 5.92% for the entire period. This was primarily observed during periods with low numbers of operating generators, such as during late-night hours or weekends. Fortunately, no significant frequency violations occurred during these times as there



(a)

(b)

FIGURE 16. **The online-based application result of a penetration limit of VER depending on the operating condition in the power system: (a) inertia and critical inertia; (b) penetration of VER.**

were no generator failures. Conversely, if a large-capacity generator failures at that period, there is a high possibility that the frequency may decline below operational standards. Therefore, in the power system, it is necessary to explore additional measures to enhance stability. Thus, the proposed method can be a reference criterion for system operators to ensure stability. It can be considered a standard for taking additional measures, such as ensuring frequency reserve and managing VER generation, to maintain frequency stability.

V. DISCUSSION

This study aimed to introduce a methodology for calculating the penetration limit of VER using online-based operational data of the power system. We applied a method to calculate the critical inertial constant of the power system and determine the penetration limit of VER. Particularly, as shown in Fig. 12, we demonstrated the ability to calculate the penetration limit of VER at a level similar to PSS/E-based simulation results. Additionally, considering the frequency response of VER, as depicted in Fig. 15, we verified the capability to determine the penetration limit. Finally, as illustrated in Fig. 16, monitoring the operating conditions of the power system enables the assessment of the stability of VER levels. Based on these findings, system operators can assess the penetration level of VER.

Our study has several limitations. Firstly, for a more accurate analysis, a sufficient amount of historical operational data is required, and recent data is essential to consider the rapid changes in the power system. In particular, the relatively large errors in the low-allowable frequency deviation range (0.20~0.26 Hz) are attributed to the relative lack of these data. Therefore, effective operation requires the crucial management of historical operational data by system operator.However, it is challenging to obtain such data for anyone other than the system operators, limiting accessibility. Secondly, we acknowledge the limitation of not considering various resources contributing to inertia in the power system, such as synchronous condensers, ESS, and load-shedding services, among others. To address this limitation, we focused on reviewing the frequency response contribution of VER, which has the most significant impact on inertia degradation. lastly, since the proposed method considers inertia characteristics from an overall perspective of the power system, it may have limitations in reflecting regional or spatial variations in inertia. In this analysis, we based our study on historical data derived from a specific reference frequency bus observed by the system operators. To overcome this limitation, further validation may be necessary by conducting time-domain simulations that consider regional and spatial inertia characteristics based on operating conditions identified through the proposed method.

In conclusion, we demonstrated that the proposed method yields meaningful results in both simulation environments and historical data-based analyses. Through this, system operators can effectively assess operational conditions and implement appropriate measures. Based on this study, further studies are necessary to investigate all inertia resources in the power system. Particularly, responsive resources like ESS, widely used in various systems, require subsequent research for the inertia assessment in power systems. Additionally, research considering regional inertia characteristics is needed to identify regional impacts and enable system operators to perform more organically in power system management.

VI. CONCLUSION

This study proposed a method for evaluating the penetration limit of VER based on the frequency stability of the power system. The proposed evaluation method analyzes the frequency response characteristics of the power system and reflects the operating standards in the power system.

The inertia energy obtained from the power system is analyzed based on the collected operational data, such as past failures, and the primary frequency and load response characteristics are calculated to analyze the trend using the system operating conditions. In addition, the penetration limit of VER is evaluated based on the critical inertia requirement to ensure frequency stability by reflecting the frequency operation standard specified by the power system.

This study evaluated the effectiveness of the proposed method compared with the system model-based simulation results of the power system planning DB in Korea and showed that the results of the penetration limit of VER can be derived with high similarity. In particular, the online application result confirmed that the penetration limit of VER can be effectively evaluated even under the operating conditions of the power system that change continuously. However, as frequency stability deteriorates owing to lack of inertial energy caused by the generation composition during the late-night hours, management of the system operator is required under certain operating conditions.

As the penetration of VER is expected to increase according to the expansion plan, the proposed method for evaluating the penetration limit of VER will greatly contribute to the determination of the appropriate capacity to secure the frequency stability of the power system. However, to effectively apply the proposed method, its accuracy should be further improved through the management and update of the operational data of the power system. In addition, as the increase in VER penetration limit is affected by the frequency response of VER, the frequency response provision of VER should be effectively managed in the future to increase the penetration limit of VER.

TABLE 5. **List of abbreviations.**

Abbreviation	Explanation
AGC	Automatic Generation Control
DB	Database
DEU	Deutschland
ESS	Energy Storage System
FR	Frequecny Response
GBR	Great Britain
IRL	Ireland
KOR	Republic of Korea
KPX	Korea Power Exchange
MAPE	Mean Absolute Percentage Error
PCS	Power Conversion System
PSS/E	Power System Simulator for Engineering
PV	Photovoltaic
RoCoF	Rate of Change of Frequency
SG	Synchronous Generator
TSO	Transmission System Operators
VER	Variable Energy Resources
WECC	Western Electricity Coordinating Council
WTG	Wind Power Generators

APPENDIX

The list of abbreviations related to this study are listed in Table 5.

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