applied sciences

MDPI

Article

Stochastic Approach to Hosting Limit of Transmission System and Improving Method Utilizing HVDC

Dongyeong Lee, Junghun Lee and Gilsoo Jang *

School of Electrical Engineering, Korea University, Seoul 02841, Korea; dy_250@korea.ac.kr (D.L.); ejh1015@korea.ac.kr (J.L.)
* Correspondence: gjang@korea.ac.kr; Tel.: +82-02-3290-4766

Abstract: According to the global de-carbonization trends, renewable energy integration has become an increasingly important issue in power systems. To achieve 100% renewable energy integration and operate a system with these resources, it is necessary to appropriately evaluate the system hosting capability and prepare appropriate planning and operation strategies using the evaluation result. So far, these interests have focused particularly on distribution-level systems. However, although the hosting limit in transmission-level systems requires further consideration, previous study is limited. This study introduces the constraints on the transmission-level hosting limit. In addition, a stochastic estimation of the hosting limit methodology in the transmission system and the use of a high voltage direct current system to improve hosting capacity are proposed and evaluated. Moreover, these methodology-based simulations are conducted using possible scenarios on the IEEE 39 bus system with some constraints, and the simulation results are presented herein. The results showed that the HVDC location selection and operation using the proposed method and optimization technique is appropriate. The strategy can be used to integrate more renewable energy. Furthermore, the proposed methodology can be applied to renewable energy integration scenario establishing a plan.

Keywords: hosting capacity; renewable energy integration; transmission system; stochastic analysis; HVDC system; operating strategy; power system planning

Citation: Lee, D.; Lee, J.; Jang, G. Stochastic Approach to Hosting Limit of Transmission System and Improving Method Utilizing HVDC. *Appl. Sci.* **2022**, *12*, 696. https://doi.org/10.3390/app12020696

Academic Editors: Pooya Davari, Enrico Cagno, Mohsen Soltani and Edris Pouresmaeil

Received: 19 November 2021
Accepted: 6 January 2022
Published: 11 January 2022

1. Introduction

Due to the climate crisis, energy issues are emerging, and in response, our power grids are rapidly changing from fossil fuel generation-based to eco-friendly renewable energy-based systems. To integrate more renewable generation and achieve carbon neutrality, policies have been developed to accelerate this transition [1]. In addition, as the final consumption of energy is electrified, the total demand and power generation in the grids increase steadily [2]. Concerns related to grid stability and reliability deterioration are emerging owing to the variability and uncertainty of distributed energy resources (DERs) because many fossil fuel-based synchronous generators are decommissioning.

Several impacts of these variable DERs on the grid stability and reliability have been presented [3]. When these DERs are integrated in small amounts into the grid, the effects on stability and reliability are insignificant. However, if the penetration capacity gradually increases and reaches a certain penetration level, the negative effects of the integration also increase. As a result, the resultant grid stability and reliability could deteriorate. For example, it may lead to serious voltage swell or sag, harmonics, resonance, and thermal overloading of network components, and introduce protection scheme malfunctioning [4,5]. Many studies have been conducted to cope with the effects of DER integration on the system. A study on optimal distribution system planning considering the uncertainty of solar power output by climate conditions was conducted [6]. In response to the continuously changing solar output, a study was conducted to improve the voltage-related stability for each load level considering the energy storage [7]. Moreover, numerous studies continue to address these problems, with several studies using a probabilistic method to evaluate the volatility and uncertainty. The generation output characteristics of solar energy, which depend on the locational property, were evaluated using a stochastic approach [8]. The generation output characteristics of wind energy were analyzed using probabilistic load flow modeling [9]. Moreover, to respond appropriately to these negative effects, the importance of accuracy for generation forecasts has increased. By utilizing these prediction results, a power generation schedule and reserve plans have been properly established to prevent unforeseen situations, such as demand and supply imbalance and under-frequency load shedding (UFLS), in worst-case power outages [10].

While efforts are being made to solve these problems through analytical approaches, operational and planning strategies have also been developed. These efforts include establishing a flexible operating strategy, limiting the output of DERs, and introducing special facilities, such as flexible AC transmission system (FACTS), high voltage direct current (HVDC), energy storage system (ESS), to reinforce the system [11–14]. Moreover, newly constructed renewable energy facilities may be concentrated in specific areas because of public acceptance related to location restrictions and issues of available natural energy sources. In this case, HVDC can be an effective solution for integrating and transmitting the generation from large-scale renewable energy resources, such as photovoltaic (PV) and offshore wind farms, to demand areas [15,16].

Many studies have been conducted on the hosting capacity of distribution systems through stochastic methods [17–19]. However, there is limited research on transmission systems. The hosting limit estimation of the transmission system has been carried out, and the dynamic characteristics of DERs, reactive power support related to voltage problems, and detailed load model have been analyzed [20]. This shows that the hosting limit of the entire system is highly dependent on these consideration options.

In addition to the considered options of the distribution system in the renewable energy integration, some factors such as generator decommissioning, re-dispatch, operational reserves, inertia, or frequency, need to be considered in the transmission system hosting limit based on the grid code.

Therefore, this study, proposes a method that evaluates hosting capacity in a transmission system, extended from that in the distribution system with considered options of what has been mainly performed in the distribution system to the transmission system evaluation, by reflecting the matters to be considered in the large-scale transmission system. In this way, the proposed method not only considers the probabilistic characteristics of DERs but also suggests an optimization problem of where to install the HVDC system by the implementation of large-scale renewable energy and which operational strategy should be taken. Different optimization problems were applied to the calculation of the installation location and operating point of HVDC, and the power flow sensitivity analysis was utilized in this process.

In the simulations, the simulations were performed in various scenarios. e.g., a change in generation system that occurs as penetration level increases, the large DERs integration, which is concentrated on a specific region because the hosting limit is highly scenario dependent. This study can help operators to evaluate the hosting capability of the current transmission system and to establish an effective transmission expansion plan that could maximize the hosting limit.

The remainder of this paper is organized as follows. Section 2 introduces the stochastic approaches of DERs, their utilization to estimate the hosting limit of the system, and sensitivity knowledge for the proposed method is introduced. Moreover, a method to evaluate the hosting limit of the transmission system and a method to find the optimal operating point and construction points to improve the hosting capacity are introduced. In Section 3, the simulation scenarios description and results are presented with discussion on the IEEE 39 bus test system. Finally, in Section 4, the conclusions of this study and future works are presented.

2. Background Knowledge

2.1. Stochastic Modeling of DER Generation

Renewable energy-based DERs exhibit characteristics, such as variability and uncertainty; therefore, a stochastic approach is required to describe the generation output of these resources. For example, the PV output characteristics can be described by the beta distribution function in Equation (1) [8].

$$f_x(x, \alpha, \beta) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} x^{\alpha-1}(1-x)^{\beta-1} \tag{1}$$

where α and $\beta > 0$ are parameters of the beta distribution. In this study, we have adopted this probability density function (PDF) as the generation output of the DERs with the parameters $\alpha = 2$ and $\beta = 1.5$.

2.2. Probabilistic Hosting Capacity

Hosting capacity refers to the possible maximum penetration capacity of DERs that a renewable energy resource can accommodate in a grid without any serious negative phenomenon and operate satisfactorily [21]. If the penetration capacity of DERs gradually increases and the penetration reaches a certain level, reliability violation occurs, and the total penetration capacity at that time can be chosen as the hosting limit. Even under the same operating conditions, the estimated hosting capacity may vary depending on the selected criteria for determining the hosting limit. The possible criteria include the following [22]:

- Voltage and current limit;
- Equipment thermal overloading;
- Protection scheme malfunctioning.

There are additional criteria for the transmission system cases. As the output of the DERs fluctuates, the scheduling of the generator changes, and the reserve needs to be dealt with dynamically [23]. In addition, the allowable range of the voltage or current may be different from the grid code according to each voltage level. In the Ireland system operator, EirGrid, the proportion of the DER generation was managed using an indicator called system nonsynchronous penetration [24]. Some of the criteria include:

- Supply and demand balance;
- Frequency and transient stability;
- Adequate reserve procurement.

Further, if the deterministic approach is chosen, instead of the probabilistic hosting capacity, the smallest amount among the determined capacities based on each criterion is the hosting capacity of the system. This is illustrated in Figure 1. In this case, the hosting capacity (HC) number 1 is the hosting limit. In contrast, if the probabilistic approach is chosen, the result is also accepted probabilistically; moreover, when operating near the point with the highest probability, it is operated with a most likely to violate criteria and is called the average probabilistic hosting capacity. In addition, it is possible to obtain the cumulative distribution function (CDF) of the results for operating decision-making.

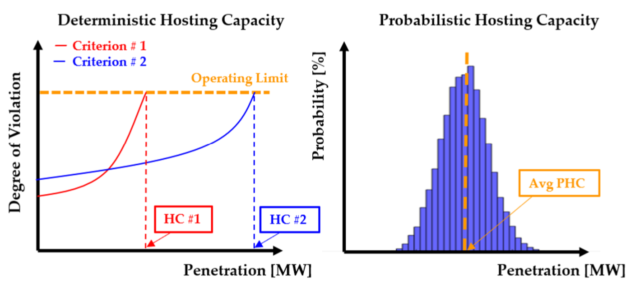


Figure 1. Concept of deterministic and probabilistic hosting capacity.

2.3. Sensitivity Approach on HVDC Allocation and Operation

In general, HVDC operates to deliver quantities determined by market operations. However, it is necessary to ensure flexible operation, such as increasing the utilization rate of the surrounding lines by fully utilizing the power flow control ability compared to the alternating current (AC) line of the HVDC line. Moreover, various attempts have been made to reduce the adverse effects of the fixed operating point of the HVDC. The improvement in the stability is discussed through the control that emulates the AC line by focusing on the transient stability [25]. To determine the operating point to increase the limitations determined by the above approaches, we proposed a methodology using a sensitivity-based approach called power transfer distribution factors (PTDFs) for transmission expansion and operation using HVDC. This sensitivity analysis was conducted based on the DC power flow, topology, and some assumptions as follows; more details can be found in [26].

- Transmission line conductance G is negligible (reactance X is larger than resistance R)

$$G_{l,k} = 0\ (X >> R) \tag{2}$$

- The system operated ideally in the bus i voltage V_i aspect

$$|V_i| = 1\ p.u. \tag{3}$$

- Voltage angle differences between adjacent buses l and k are small (linearization)

$$\sin(\delta_l - \delta_k) \ \approx \ \delta_l - \delta_k \tag{4}$$

$$\cos(\delta_l - \delta_k) \ \approx \ 1 \tag{5}$$

Based on the above assumptions, the sensitivity analysis can be conducted as follows:

$$f_{l,k} = (\delta_l - \delta_k)\ B_{l,k} \tag{6}$$

$$\Delta\delta = B^{-1}\Delta P \tag{7}$$

$$\psi^i_{l,k} = B_{l,k}\ (\Delta\delta_l - \ \Delta\delta_k) \tag{8}$$

$$\Delta f_{l,k} = \psi^i_{l,k}\ \Delta P^i \tag{9}$$

where δ_l is the angle of bus l, $f_{l,k}$ is the branch flow from buses l to k, $B_{l,k}$ is the susceptance of the transmission line from buses l to k, and $\psi^i_{l,k}$ is the PTDF when power injected into the bus i. These DC PTDFs can be calculated from the system impedance matrix (i.e., based on the system topology). Figure 2 shows the sensitivity analysis results for each injection case in the test system used in this study.

However, this has the disadvantage of accuracy owing to the above DC power flow assumptions. For simplicity and fast calculation in this study, this sensitivity analysis was adopted instead of AC PTDF through a Jacobian matrix with the additional assumption that voltage and reactive power problems are solved by themselves within each area. By using these sensitivity factors and determining the target integration and buses for new DER integration points, it is possible to evaluate the effect of these new generations on the transmission system. In this situation, an allocation candidate was selected by solving the optimization problem by comprehensively considering the target integration amount, connection points, capacity of the planned HVDC, average loading statistics of the current system, and impact on the power generation scheme. The results of the sensitivity analysis of the test system and a feasibility study result for this sensitivity are also included in the Appendix A.

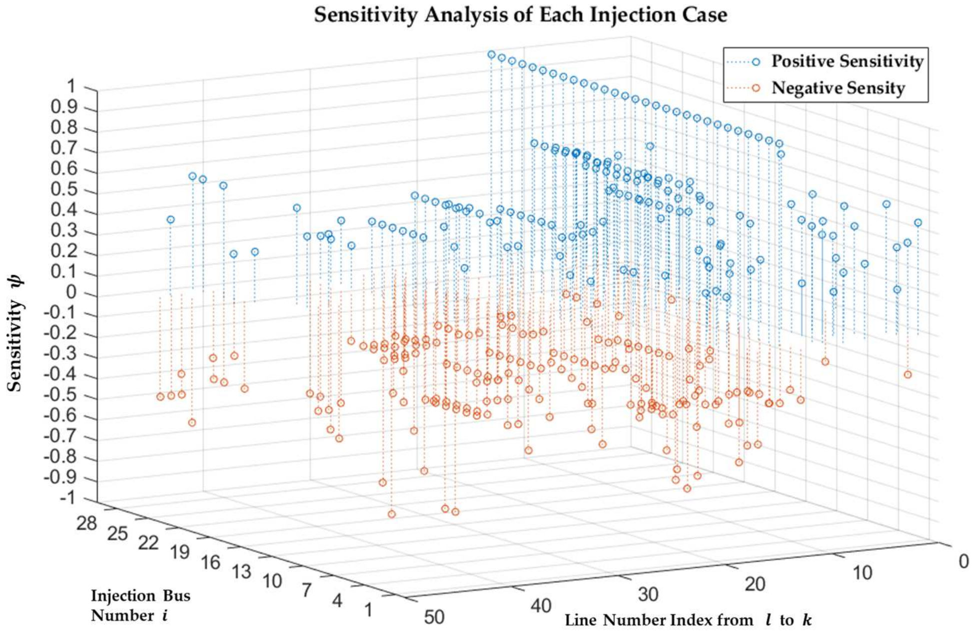


Figure 2. Sensitivity analysis result of test system.

In addition, the optimization method utilizes a mixed-integer non-linear programming (MINLP) method for determining location and mixed-integer linear programming (MILP) for finding operating point based on the linearity of the sensitivity. It is also possible to use a fast optimization method, such as the internal point method, for the real-time operation to dispatch the HVDC operating points. The process of solving this optimization problem is illustrated in Figure 3. The input data include all the information needed for this proposed method. As the DERs penetration level increases, estimated line loading is calculated based on expression as follow:

$$f_{l,k\ (estimated)} = \sum_{1}^{n} (DER_i \psi^i_{l,k}) + Generation\ Effect + Average\ Loading_{\ l,k} \quad (10)$$

where $f_{l,k\ (estimated)}$ is the resultant branch flow of the expected DER penetration at bus i, DER_i. It reflects the effect of the generator change owing to the penetrated capacity, $Generation\ Effect$, and the average load of branch between bus l and k, $Average\ Loading_{\ l,k}$, on the existing lines, as well as the effect of the DERs. The final goal of this optimization process is to increase the acceptable capacity of the DERs. To this end, HVDC power flow controllability was used to search for an optimal location to lower the overload rate and increase the utilization rate of the lines. The problem was configured as a minimax problem. It involves finding an optimization point that minimizes the maximum overload rate among the lines, which can be expressed as follows:

$$MIN\left[MAX\left(f_{l,k\ (Future)}\right)\right], f_{l,k\ (Future)} = f_{l,k\ (estimated)} + \sum_{1}^{n} Y_i X_i \psi^i_{l,k} \quad (11)$$

$$\begin{gathered} \text{s.t } P_{gen} + P_{DERs} = P_{Load} + P_{Loss}, \\ \sum_{1}^{n} X_i = 0,\ \sum_{1}^{n} Y_i = Number\ of\ Stations, \\ |X_i|\ \leq HVDC\ Station\ Rating\ of\ i, \\ 0\ \leq\ Y_i\ \leq 1 \end{gathered} \quad (12)$$

where $f_{l,k\ (Future)}$ is the result of the HVDC operation effect on the branch flows. Y_i is a binary variable indicating when a converter station exists at bus i, and X_i is the operating point of this station. Each of P_{gen}, P_{DERs}, P_{Load}, and P_{Loss} represents the total real power of synchronous generators, DERs, loads, and losses. When this problem is solved, the position of the converter is determined. Based on this position, a DER input simulation was performed, and the proposed methodology of the hosting limit evaluation procedure was conducted assuming that the installed HVDC operates through an optimal operating (OP) strategy to decrease the maximum overload rate of the lines. During this process, the DER penetration was used to predict future power flow based on the assumption that the power generation is directly proportional to the amount of the installed capacity.

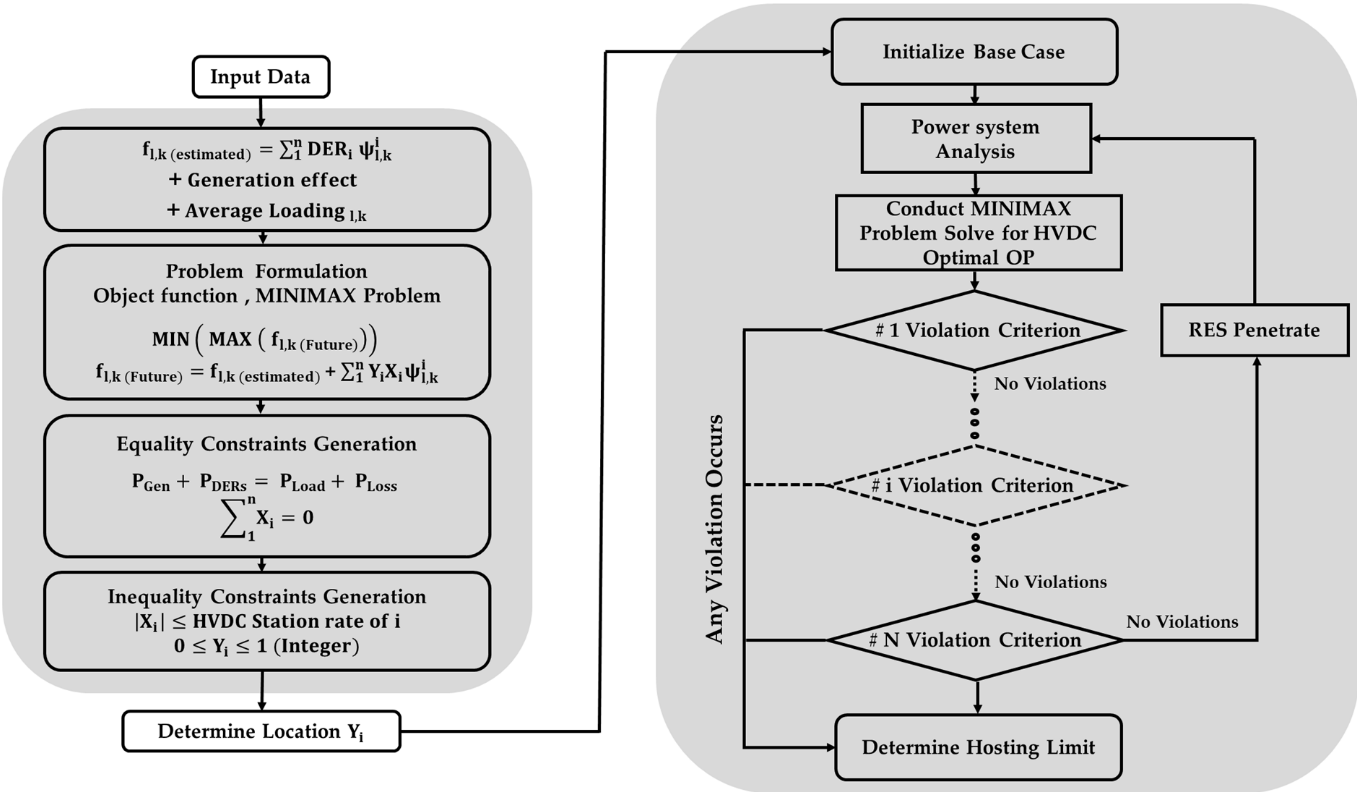


Figure 3. Proposed methodology conduct procedure.

2.4. Test System and Scenarios

The proposed methodology was simulated in the modified IEEE 39 bus test system illustrated in Figure 4 [27]. In this figure, regions can be seen to be divided to implement region-intensive integration scenarios.

In the base case, no line reinforcement was performed, and in the point-to-point (P2P) HVDC reinforcement case, HVDC was installed on buses 6 and 19, which are the locations searched for by the above process. Finally, the HVDC system was expanded to a multi-station case in which the multi-terminal HVDC system (MTDC) was implemented on buses 6, 19, and 26.

In addition, the simulation of the base case was performed for two scenarios in which the existing synchronous generator was converted to a synchronous condenser instead of retirement to evaluate the effect on the hosting limit due to the lack of reactive power from the retirement of the existing synchronous generator by the gradual integration of DERs. Experiments were performed for all scenarios using the proposed method via Monte Carlo-based simulations.

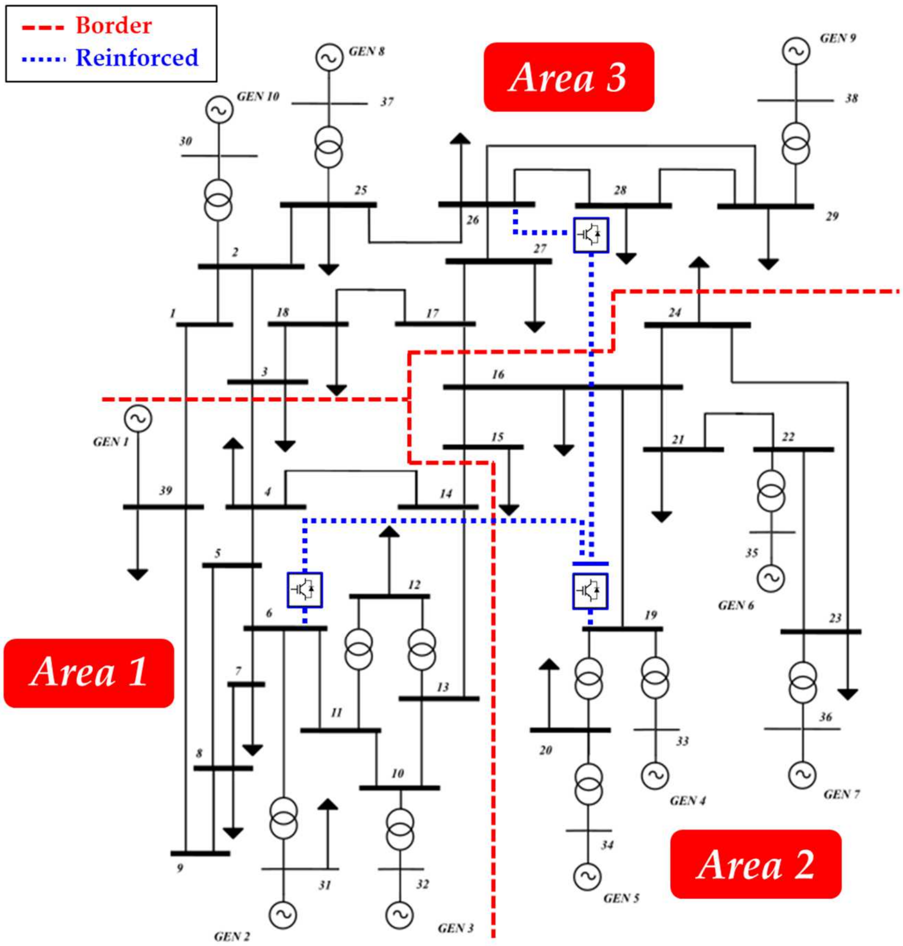


Figure 4. Modified IEEE 39 bus test system.

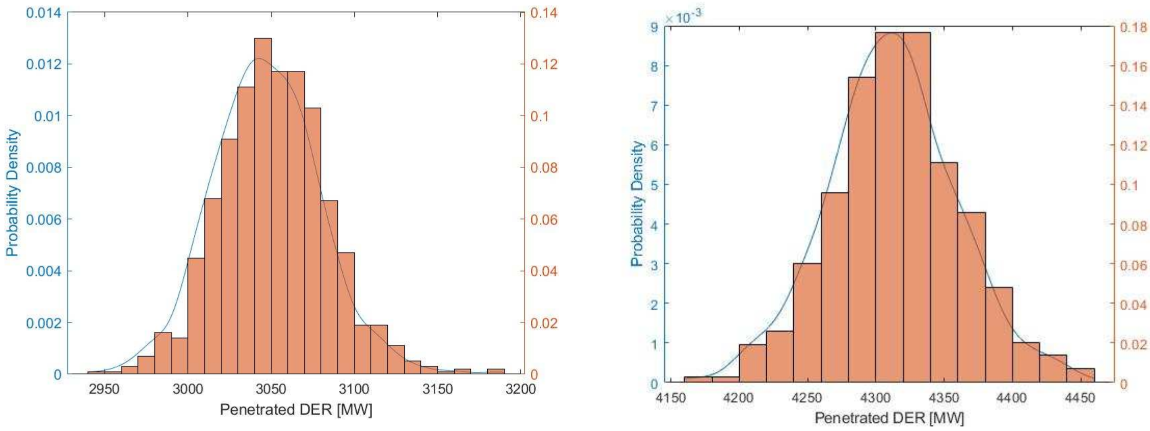
3. Results and Discussion

In this section, the hosting limit was obtained probabilistically by applying the proposed method to each case. The cases include the base case, keeping the synchronous generator as a synchronous condenser case, concentrating the DER input only in a specific area case, reinforced with a P2P case, and an overlay case. The simulations were conducted using Power System Simulator for Engineering (PSS®E). In all cases, the assumed order in which the generator is turned off was that the generator at bus 30 is turned off first, then that at bus 32, then bus 33 ... and finally, at bus 39; the slack bus was selected as the generator at bus 31. In the implementation process, when the line overload reached 100% or the voltage violation rate exceeded 10%, the point was determined as the limit.

As the purpose of the simulation was to determine the distribution of the hosting capacity limit, the number of iterations was determined 1000 times for each case. For the reinforced case, 3000 times were performed to better present the results. Although more precise results can be obtained above this number of iterations, no significant change in the distribution or probability of the capacity were recorded; therefore, this number of iterations was sufficient to obtain the desired limiting capacity range. In this simulation, whenever the unit input capacity of the DERs proceeds, it was divided for the capacity proportional to the short circuit level (SCL) of each bus, and the power generation for this capacity was applied based on the probabilistic DER modeling in Section 2.1. This method of the DER integration logic is based on the integrated process considering short circuit ratio (SCR) when linking DC facilities because renewable energy uses an interface based on power electronics. Concerning the reinforcement case, the lack of reactive power supply acts as a large acceptance limit factor, hence the P2P case and the abovementioned three-terminal MTDC case show similar hosting capacity limit values. Therefore, to show the effect of location selection using the proposed method, the comparison of the line utilization rate when the hosting capacity is reached in each case is also shown. From this result, it is suggested that as the number of stations increases, the degree of freedom in the power flow control selection increases, and thus, the effect of increasing the line utilization rate can be increased. Therefore, the overall flexibility of the system is increased.

3.1. Base Case Simulation Results

Simulation results for the two cases of synchronous generators in base environment without any reinforcement are shown in Figure 5.



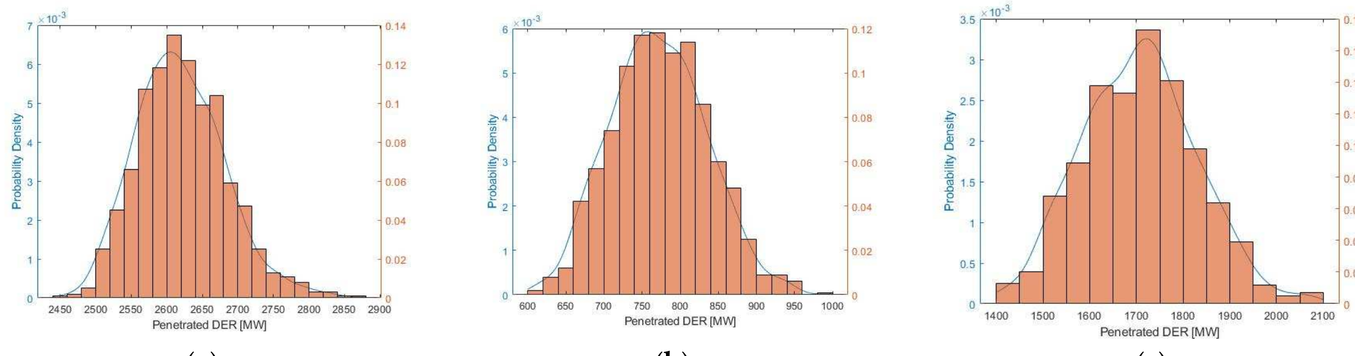
(**a**) (**b**)

Figure 5. Results of base case simulations: (**a**) No–synch condensers; (**b**) Synch condensers.

Unlike the base case, where the synchronous generator is simply de-committed as the penalty of the DER increases, the hosting capacity limit is increased when it is maintained as a synchronous condenser without being turned off. This is a result of the relaxation of the restrictions imposed by the voltage violation, while the synchronous condenser supports the reactive power. In the same vein, it can be inferred that more distributed power can be accommodated when the DERs that are integrated do not operate with a unity power factor but a support reactive power. The red histogram shows the number of times the result for each capacity appears, and the blue curve represents the PDF for the hosting capacity.

3.2. Regional Intensive Integration Case Simulation Results

Simulation results for the three regional intensive integration cases in base environment without any reinforcement are shown in Figure 6.



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

Figure 6. Results of simulations of intensive input in each region: (**a**) Area 1 case; (**b**) Area 2 case; (**c**) Area 3 case.

The above simulation results measured the hosting capacity by placing the DERs in each region, as the regions were divided in the test system illustrated in Figure 4. It can be seen from the above results that when new DERs are mainly placed in Area 1, more DERs can be accommodated, and the reinforcement of Areas 2 and 3 is more effective in increasing the overall capacity of the system. In addition, it is important to accommodate a large number of DERs using each area adequately because a larger amount can be integrated when the usable areas are properly arranged.

3.3. Reinforced Case Simulation Results

Figure 7 shows that in the reinforcement case, the P2P and overlay cases show a probabilistic hosting capacity with a very similar result distribution. This means that there is a limit to increasing the hosting capacity of the system only with the power flow controllability advantage of the HVDC. In other words, the absence of reactive power sources is the biggest limiting factor. Therefore, to increase the hosting capacity through the flexible operation of the power flow, an appropriate local-level reactive power supply must be accompanied. Moreover, the process of finding the location of multi-station case using the method presented in Figure 8 can improve the average line utilization rate.

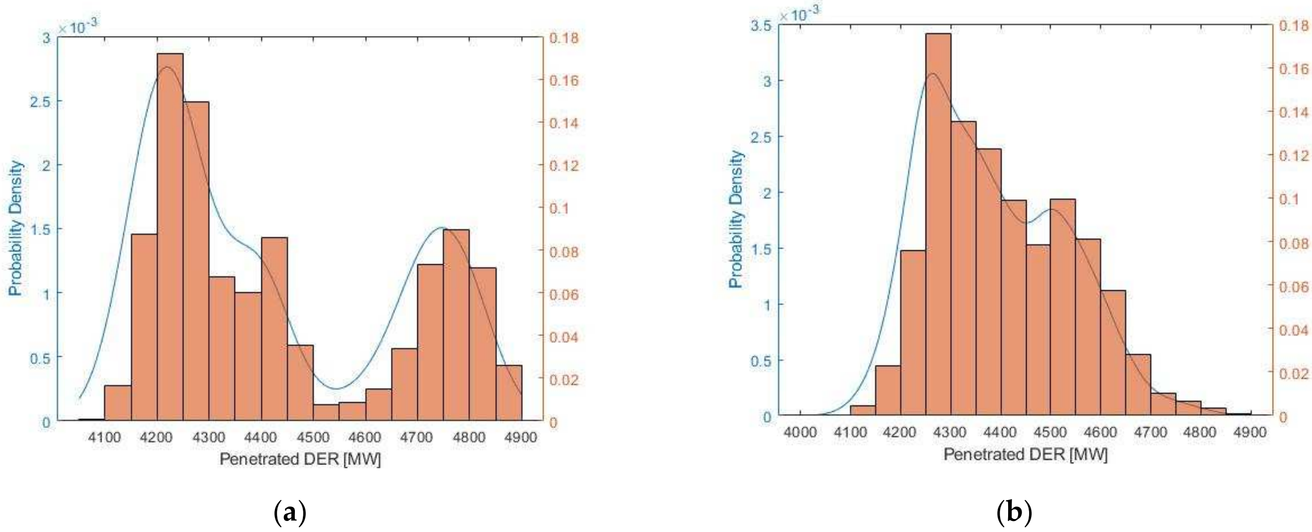


Figure 7. Simulation results of reinforced case: (**a**) P2P case; (**b**) Three-station case.

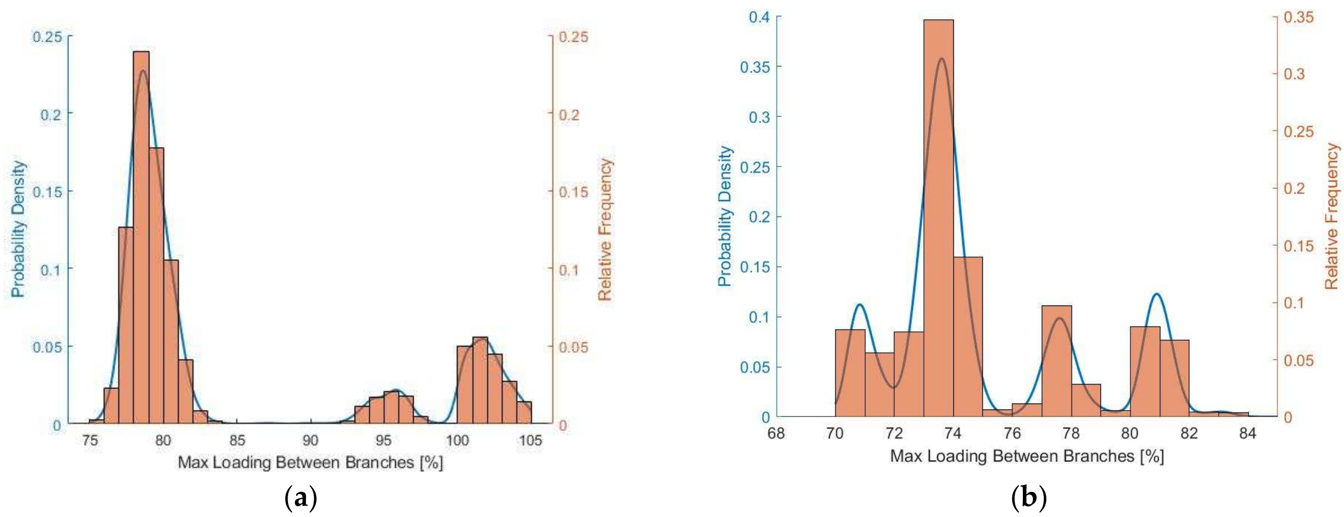


Figure 8. Results of maximum loading when hosting limits are reached: (**a**) P2P case; (**b**) Three-station case.

Figure 8 shows the probabilistic distribution diagram of the maximum loading among the branches when the hosting limit is reached for each reinforcement case. Although there was no significant difference in the hosting capacity, the loading was low in the case determined by the proposed operation method and location search method for the multi-station case. This means that in the case of a multi-station, the degree of freedom of selection is increased. As the power flow controllability is improved, the loading of overall existing lines is also improved.

Compared to the existing research methods, the proposed methodology not only carried out the transmission level hosting limit evaluation, which was mainly conducted only in the distributions system [17–19] but also considered the peculiarities of only the large-scale transmission network [20], e.g., generation system aspect. This method has the advantage of convenience being applicable to various scenarios. This study also shows that the HVDC-related strategy through an optimization problem is applicable to the proposed strategy and the simulation results confirmed that the strategy is effective in increasing the hosting capacity improvement. Moreover, it can be utilized in multi-station HVDC plans that will become dominant in future power grids.

4. Conclusions

In this paper, a method for estimating the overall large-scale transmission system hosting capacity using probabilistic approaches has been developed. Furthermore, a hosting limit improving method using an HVDC system and optimization technique has also been developed. The simulation results of several scenarios have been presented, and the results validated the proposed methods. Additionally, the results of proposed hosting limit evaluation showed improved performance by reflecting the characteristics to be considered in the transmission system, such as change in the power generation system, including the case for the entire system, beyond the estimation of the hosting capacity, which was limited within the distribution system. In addition, an optimal location search method for HVDC to improve the probabilistic hosting capacity estimated through this method was presented, and the simulation results for the cases of the P2P and multiple stations were shown. Compared to the base case, hosting capacity can be increased by about 30% when the HVDC system is optimally operated. When using more stations, it was confirmed that the loading problem was free compared to P2P case.

From these results, the proposed operation strategy could effectively increase the hosting capacity of the entire system, and through regional integration scenarios, it was possible to determine the strategy for reinforcing the transmission system or integrate new DERs to increase the capacity. Furthermore, by introducing additional constraints, such as critical inertia and reserve management, constraints could be included in the proposed methodology to estimate the hosting capacity reflecting dynamic evaluation. Section 3 allows us to draw the conclusion that to maximize the improvement of power flow controllability, the support of reactive power must be accompanied. Future work will focus on the reactive power aspect to strengthen the methodology, and conduct research on the adverse effects of introducing large-scale renewable energy on large-power system dynamic characteristics, e.g., the flexible operation of large-scale offshore wind farm MTDC systems for improving hosting capacity.

Author Contributions: Conceptualization, software, and writing—original draft preparation, D.L.; methodology and validation, D.L. and J.L.; writing—review and editing, D.L. and J.L.; supervision, G.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government (MOTIE) (No. 20191210301890) and the Basic Research program through the National Research Foundation of Korea (NRF) funded by the MSIT (No. 2020R1A4A1019405).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

In this section, the results of the validity of the sensitivity-based analysis used in the proposed methodology are presented. The results of the analysis of the change in power flow in the system branches due to the change in the operating point of the P2P HVDC case are presented in Table A1 and Figure A1.

Table A1 presents the information on the reactance of all lines, including the two-winding transformer and the sensitivity analysis results for the change in the operating point with a positive sign when a unit MW injection occurred. The P2P stations are located on buses 6 and 19. Here, the reactance value is P.U.-based, and the sensitivity is in MW. Table A2 lists the power generation and load in the system.

Figure A1 shows that compared to the base case, the theoretical value and the line load during actual HVDC operation are consistent. In addition, Figure A2 shows the change in the reactive power flow owing to the change in the HVDC operating point. Based on this result, the voltage is changed when the HVDC operating is changed for line loading control, and the flow of the reactive power is changed to solve the voltage variation. To alleviate the adverse effect on the line loading from this varying reactive power flow, the voltage-related problem could be solved at the regional scale. Thus, the effectiveness of the proposed operational strategy can improve the performance. These results are also valid for the number of increased multi-terminal station cases.

Table A1. Sensitivity Analysis Results.

Branch Index (*l*, *k*)	Reactance and Sensitivity	Branch Index (*l*, *k*)	Reactance and Sensitivity	Branch Index (*l*, *k*)	Reactance and Sensitivity	Branch Index (*l*, *k*)	Reactance and Sensitivity
1 (1, 2)	0.0411 −0.10836	13 (6, 11)	0.0082 −0.38154	25 (15, 16)	0.0094 −0.54407	37 (22, 35, Tr)	0.0143 0
2 (1, 39)	0.025 0.10836	14 (6, 31, Tr)	0.025 0	26 (16, 17)	0.0089 0.45593	38 (23, 24)	0.035 0
3 (2, 3)	0.0151 −0.0039	15 (7, 8)	0.0046 −0.10223	27 (16, 19)	0.0195 −1	39 (23, 36, Tr)	0.0272 0
4 (2, 25)	0.0086 −0.10446	16 (8, 9)	0.0363 −0.10836	28 (16, 21)	0.0135 0	40 (25, 26)	0.0323 −0.10446
5 (2, 30, Tr)	0.0181 0	17 (9, 39)	0.025 −0.10836	29 (16, 24)	0.0059 0	41 (25, 37, Tr)	0.0232 0
6 (3, 4)	0.02129 0.34757	18 (10, 11)	0.0043 0.34722	30 (17, 18)	0.0082 0.35146	42 (26, 27)	0.0147 −0.10446
7 (3, 18)	0.0133 −0.35146	19 (10, 13)	0.0043 −0.34722	31 (17, 27)	0.0173 0.10446	43 (26, 28)	0.0474 0
8 (4, 5)	0.0128 0.5101	20 (10, 32, Tr)	0.0 20	32 (19, 20)	0.0138 0	44 (26, 29)	0.0625 0
9 (4, 14)	0.0129 −0.16254	21 (11, 12, Tr)	0.0435 −0.03432	33 (19, 33, Tr)	0.0142 0	45 (28, 29)	0.0151 0
10 (5, 6)	0.0026 0.51623	22 (12, 13, Tr)	0.0435 −0.03432	34 (20, 34, Tr)	0.018 0	46 (29, 38, Tr)	0.0156 0
11 (5, 8)	0.0112 −0.00613	23 (13, 14)	0.0101 −0.38154	35 (21, 22)	0.014 0		
12 (6, 7)	0.0092 −0.10223	24 (14, 15)	0.0217 −0.54407	36 (22, 23)	0.0096 0		

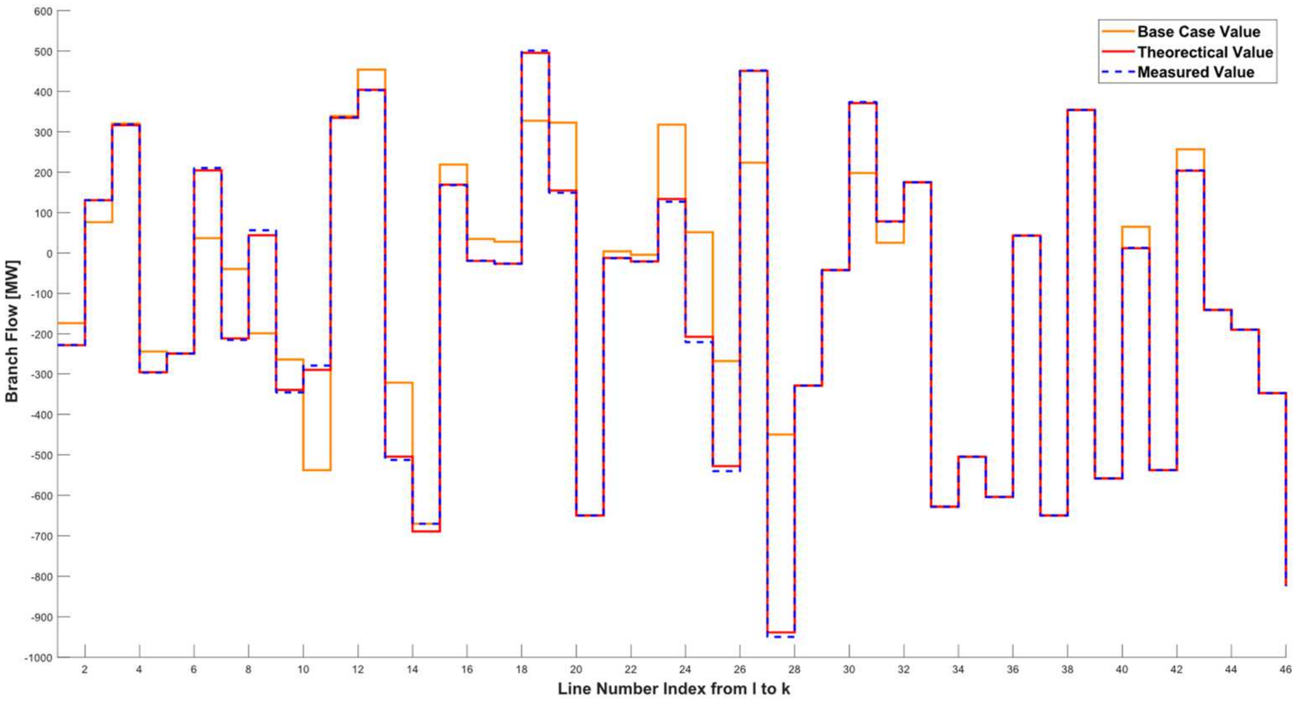


Figure A1. Sensitivity-based analysis and measured MW flow data comparison.

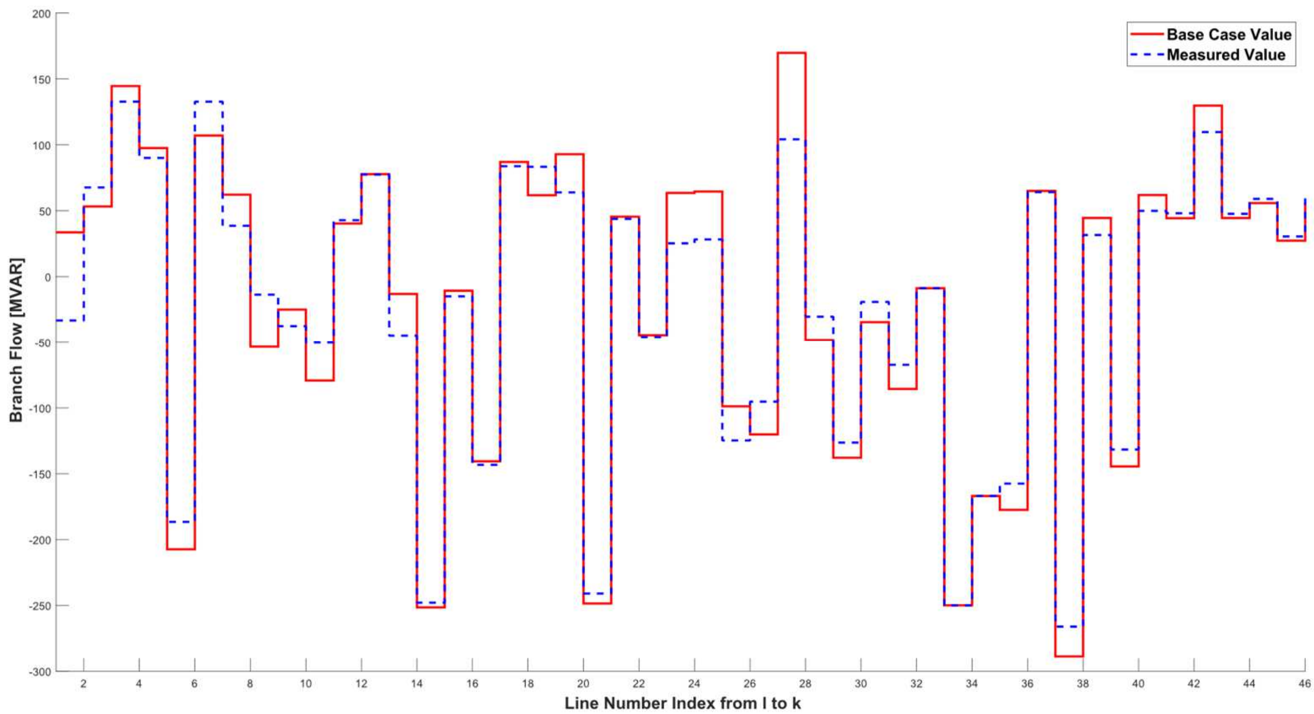


Figure A2. Sensitivity-based analysis and measured MVAR flow data comparison.

Table A2. Test System Data.

BUS	P Gen	P Load	Q Gen	Q Load	Bus	P Gen	P Load	Q Gen	Q Load
1		97.6000		44.2000	21		274.0000		115.0000
2		0.0000		0.0000	22		0.0000		0.0000
3		322.0000		2.4000	23		247.5000		84.6000
4		500.0000		184.0000	24		308.6000		−92.2000
5		0.0000		0.0000	25		224.0000		47.2000
6		0.0000		0.0000	26		139.0000		17.0000
7		233.8000		84.0000	27		281.0000		75.5000
8		522.0000		176.6000	28		206.0000		27.6000
9		6.5000		−66.6000	29		283.5000		26.9000
10		0.0000		0.0000	30	250.0000	0.0000	232.4171	0.0000
11		0.0000		0.0000	31	681.4871	9.2000	252.9522	4.6000
12		8.5300		88.0000	32	650.0000	0.0000	246.5658	0.0000
13		0.0000		0.0000	33	632.0000	0.0000	250.0000	0.0000
14		0.0000		0.0000	34	508.0000	0.0000	167.0000	0.0000
15		320.0000		153.0000	35	650.0000	0.0000	285.7561	0.0000
16		329.0000		32.3000	36	560.0000	0.0000	142.7507	0.0000
17		0.0000		0.0000	37	540.0000	0.0000	69.8833	0.0000
18		158.0000		30.0000	38	830.0000	0.0000	141.7562	0.0000
19		0.0000		0.0000	39	1000.0000	1104.0000	111.8836	250.0000
20		680.0000		103.0000					

References

1. IPCC. *Global Warming of 1.5 °C*; IPCC: Incheon, Korea, 2021.
2. IEA. *Global Energy Review 2020*; IEA: Paris, France, 2020.
3. Julia, M.; Shun, H.H.; Pengweil, D.; Nitika, M.; Rochie, G. Operational security. *IEEE PES Mag.* **2021**, *19*, 20–29.
4. Abbas, A.S.; El-Sehiemy, R.A.; Abou El-Ela, A.; Ali, E.S.; Mahomoud, K.; Lehtonen, M.; Darwish, M.M.F. Optimal Harmonic Mitigation in Distribution Systems with Inverter Based Distributed Generation. *Appl. Sci.* **2021**, *11*, 774. [CrossRef]
5. Bendary, A.F.; Abdelaziz, A.Y.; Ismail, M.M.; Mahmoud, K.; Lehtonen, M.; Darwish, M.M.F. Proposed ANFIS Based Approach for Fault Tracking, Detection, Clearing and Rearrangement for Photovoltaic System. *Sensors* **2021**, *21*, 2269. [CrossRef] [PubMed]
6. Ali, E.S.; El-Sehiemy, R.A.; El-Ela, A.; Adel, A.; Mahmoud, K.; Lehtonen, M.; Darwish, M.M. An Effective Bi-Stage Method for Renewable Energy Sources Integration into Unbalanced Distribution Systems Considering Uncertainty. *Processes* **2021**, *9*, 471. [CrossRef]
7. Emara, D.; Ezzat, M.; Abdelaziz, A.Y.; Mahomoud, K.; Lehtonen, M.; Darwish, M.M.F. Novel Control Strategy for Enhancing Microgrid Operation Connected to Photovoltaic Generation and Energy Storage Systems. *Electronics* **2021**, *10*, 1261. [CrossRef]
8. Ziyad, M.S.; Bodgan, S.B.; Atia, R.A.A. Photovoltaic module-site matching based on the capacity factors. *IEEE Trans. Energy Convers.* **1995**, *10*, 326–332.
9. Daniel, V.; Jose, L.P.; Andres, F. Probabilistic Load Flow Including Wind Power Generation. *IEEE Trans. Power Syst.* **2011**, *26*, 1659–1667.
10. Tomonori, S.; Takayuki, I.; Masakazu, K.; Yuzuru, U.; Jun-ichi, I. Spatiotemporally multiresolutional optimization toward supply-demand-storage balancing under PV prediction uncertainty. *IEEE Trans. Smart Grid.* **2015**, *6*, 853–865.
11. Mahrous, E.; Walid, A.O.; Said, F.M.; Hossam, E.A.T. Allocation of FACTS devices using a probabilistic multi-objective approach incorporating various sources of uncertainty and dynamic line rating. *IEEE Access.* **2020**, *8*, 167647–167664.
12. Mojtaba, M.; Turaj, A. Hybrid AC/DC Transmission Expansion Planning Considering HVAC to HVDC conversion under renewable penetration. *IEEE Trans. Power Syst.* **2021**, *36*, 579–591.
13. Alexandre, M.; David, P.; Alexandre, S.; Enzo, S. Reliable renewable generation and transmission expansion planning: Co-optimizing system's resources for meeting renewable targets. *IEEE Trans. Power Syst.* **2017**, *32*, 3246–3257.
14. Bo, Z.; Jianhua, Z.; Xu, Y.; Jianhui, W.; Jun, D.; Yuying, Z. Integrated planning for transition to low-carbon distribution system with renewable energy generation and demand response. *IEEE Trans. Power Syst.* **2014**, *29*, 1153–1165.
15. Hossain, M.I.; Abido, M.A. Active Power Control of PV-Battery Connected MMC-HVDC System for FRT Support. *Appl. Sci.* **2020**, *10*, 7186. [CrossRef]

16. Li, Z.; Wei, Z.; Zhan, R.; Li, Y.; Tang, Y.; Zhang, X.-P. Frequency Support Control Method for Interconnected Power Systems Using VSC-MTDC. *IEEE Trans. Power Syst.* **2021**, *36*, 2304–2313. [CrossRef]
17. Jesus, V.; Nikos, H.; Lisandro, J.; Marco, R.; Andreas, A.; Brnoit, B. The IGREENGrid project: Increasing hosting capacity in distribution grids. *IEEE PES Mag.* **2017**, *15*, 30–40.
18. Sherif, M.; Shady, H.; Almoataz, Y.; Ahmed, F. State-of-the-art of hosting capacity in modern power systems with distributed generation. *Renew. Energy* **2018**, *130*, 1002–1020.
19. Mohammad, S.; Jin, M.; Diwei, Z.; Shabir, A.; Hesamoddin, M. Probabilistic assessment of hosting capacity in radial distribution systems. *IEEE Trans. Sust. Energy* **2018**, *9*, 1935–1947.
20. Phylicia, C.; Eduardo, C.; Bjorn, V.; Jake, G. Transmission hosting capacity of distributed energy resources. *IEEE Trans. Sust. Energy* **2021**, *12*, 794–801.
21. Math, H.; Sarah, K. Hosting capacity of the power grid for renewable electricity production and new large consumption equipment. *Energies* **2017**, *10*, 1325.
22. Vishnuvardhan, T.; Janmejaya, P.; Anubha, A.; Manohar, S.; Sankighatta, G. Protection challenges under bulk penetration of renewable energy resources in power systems: A review. *CSEE J. Power Energy Syst.* **2017**, *3*, 365–379.
23. Nicola, V.; Stefanos, D.; Pierre, P.; Gabriela, H.; Joachim, H. Dynamic reserve and transmission capacity allocation in wind dominated power systems. *IEEE Trans. Power Syst.* **2021**, *36*, 3017–3028.
24. Jon, S.; Alan, R.; Damian, F.; Paul, S.; Alan, M. Studying the maximum instantaneous non-synchronous generation in an island system-frequency stability challenges in Ireland. *IEEE Trans. Power Syst.* **2014**, *29*, 2943–2951.
25. Gonzalez-Torres, J.C.; Costan, V.; Damm, G.; Benchaib, A.; Lamnabhi-Lagarrigue, F. Dynamic control of embedded HVDC to contribute to transient stability enhancement. In Proceedings of the Cigre 2020 e-Session, Paris, France, 24 August–3 September 2020; p. C2-141.
26. Mohsen, R.; Amin, K.; Gabiela, H. Comprehensive power transfer distribution factor model for large-scale transmission expansion planning. *IET Gener. Transm. Distrib.* **2016**, *10*, 2981–2989.
27. Zimmerman, R.D.; Murillo-Sánchez, C.E.; Thomas, R.J. Matpower: Steady-State Operations, Planning and Analysis Tools for Power System Research and Education. *IEEE Trans. Power Syst.* **2011**, *26*, 12–19. [CrossRef]