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Characteristics of Various Single Wind-Power Distributed Generation Placements for Voltage Drop Improvement in a 22 kV Distribution System

Santipont Ananwattanaporn [1], Surakit Thongsuk [2], Praikanok Lertwanitrot [2], Suntiti Yoomak [1,*] and Issarachai Ngamroo [1]

[1] School of Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520, Thailand; san_ti_ton@hotmail.com (S.A.); issarachai.ng@kmitl.ac.th (I.N.)
[2] Faculty of Industrial Technology, Rajabhat Rajanagarindra University, Chachoengsao 24000, Thailand; surakit.tho@rru.ac.th (S.T.); prailkanok@gmail.com (P.L.)
* Correspondence: suntiti.yo@kmitl.ac.th

Abstract: A major challenge in distribution systems is the issue of voltage drop along the distribution line resulting from an increased load capacity connected to the utility. A significant voltage drop can affect the performance of a distribution system and cause quality issues for end users, impacting the system's long-term sustainability and reliability. Therefore, regulations have been set stating that the voltage level should not be more that 5% higher or lower than the rated voltage. Thus, in this study, we aimed to evaluate the voltage level characteristics of a 22 kV distribution system that replicates the actual distribution system in the Provincial Electricity Authority. A voltage improvement technique based on distributed generation placement was proposed. In addition, the distribution system characteristics with and without distributed generation placement were evaluated under fault conditions. The results indicate that distributed generation placement in the distribution system can improve the voltage level along the distribution line. However, the level of increase in voltage depends on the size of the load, the capacity of the distributed generation, and the location of the distributed generation system on the distribution line. Furthermore, placing a distributed generation system with a minimum capacity at the proposed location can improve the voltage within the utility's standard level. Thus, the installation of a distributed generation system in the distribution system is beneficial in terms of voltage improvement in the distribution system and provides the power system with a sustainable method to address the issue of voltage drop.

Keywords: distributed generation; distribution system; voltage drop; fault; wind power generation; renewable energy

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1. Introduction

Electricity has become one of the main components of people's quality of life in the modern age. Power systems that provide electricity to the population and industry primarily consist of generation, transmission, and distribution systems. A large proportion of the electricity generated in conventional power systems comes from large power plants located near resources and is transmitted through transmission lines before being distributed to customers via the distribution system. In general, the specifications of the equipment in distributed substations and other components in the distribution system are designed using specific load conditions during the design phase, with a margin for growth [1]. A substation is installed along the path to ensure that the voltage along the distribution line is at the rated value. The standard level of voltage deviation allowed for utilities is within 5% of the rated voltage level [2]. However, economic and population growth has led to a higher rate of urbanization and increased electrical demand. This has resulted in a rapid expansion of both the size and number of loads connected to the distribution system, becoming higher than the design margin. Therefore, the voltage level along the distribution line decreases by more than the allowable value [3]. In addition, electric vehicle chargers can further distort the load pattern of the distribution network and subsequently cause voltage variations [4]. The issue of voltage drop affects both the utility in terms of power quality and customer load connected to the distribution line, in which some equipment requires operation at the rated voltage level to achieve the desired efficiency [5].

A solution to address voltage drop along the distribution line for utilities is to use devices such as an automatic voltage regulator [6] and a high-voltage capacitor [7] or to use load management methodologies [8] to temporarily regulate the voltage level within the standard value. In the long term, the system may require the installation of a new substation along the distribution line with voltage issues or the expansion of the substation located at both ends of the distribution line to support load expansion. However, some constraints may affect the plan to install new substations, such as the acquisition of land, opposition by the local population, and the environmental impact. Furthermore, the expansion of the current substation may encounter entirely different issues, such as a limited available area for new equipment and a low margin for safety. Moreover, the results may not achieve the intended effect in terms of voltage level improvement.

Additional power generation requires a distribution system with an additional power source, which provides an ever-increasing load, instead of a substation. This small-scale power generation system from a renewable resource, which is located in the distribution system, is referred to as "distributed generation (DG)" [9]. In Thailand, the current centralized power system has been steady shifting toward a distributed system, with many privately owned independent power producers (IPPs), small power producers (SPPs), and very small power producers (VSPPs), due to constraints on public utilities regarding the construction of new power plants. This process is further accelerated by support from the government, providing benefits for the environment and energy security [10]. Thailand's Ministry of Energy has set out an Alternative Energy Development Plan (AEDP 2018) that aims to increase the proportion of renewable energy to 34% of the power generated [11]. This plan set a quota for each renewable energy source by 2036, wherein solar power represents the highest proportion, followed by biomass and wind power. However, the actual data on the interconnection of renewable sources showed that the quota for wind power is still to be achieved, with a capacity of 118 MW having been commissioned so far versus a 3000 MW target [12]. However, the solar power plants commissioned so far account for more than 50% of the quota. Thus, the presence of a DG system using wind power generation has significant potential for construction and commission in the Thailand distribution system.

Previous studies have demonstrated that the presence of a DG system in the network has several advantages for distribution systems [13], such as an improvement in voltage stability [14], power quality [15,16], power loss reduction [17–19], and reactive power compensation [20]. In terms of system reliability, research has shown that optimal DG placement can improve the System Average Interruption Frequency Index and the System Average Interruption Duration Index in a distribution system [21]. The power system's reliability can also be improved when the DG system is located in a suitable location, which can benefit the utility and the customer from an economic perspective [22,23]. The optimal DG placements proposed in previous studies can address the voltage drop issue due to power generation from the source being located near the end user [24]. DG placement is beneficial, especially in terms of improved voltage levels on the distribution line. However, the presence of a DG system significantly alters the system characteristics [25]. A simulation of a distribution system with DG placement showed that the presence of a DG system can shift the current flow, particularly under fault conditions [26,27]. As the number of DGs in a distribution system increases, the fault detection [28] and fault classification systems [29] must consider the current characteristics in cases with DG interconnections. In addition, the changes in the current characteristics also affect the coordination of conventional protection systems that do not support the presence of a DG system [30,31]. Previous studies have shown the potential of improving voltage levels in distribution systems by using interconnected DG systems on the line. However, the effect of DG placement on the distribution system's characteristics must be considered during operation to ensure the reliability of the power system.

Based on previous research, voltage improvements in distribution systems using high-voltage capacitor banks with placement locations based on 1/2 kVar and the 2/3 rule [32] have been proposed. The results indicated that, to improve the voltage to an acceptable level, a 12 MW capacitor bank must be installed. There is also a constraint on achieving this required size in terms of the installed location, the number of units, and other effects, which may not be suitable in some locations. Therefore, in this study, we aimed to assess the potential to use renewable energy as a sustainable method to address the voltage drop issue in a distribution system instead of the traditional method of installing a high-voltage capacitor bank. A simulation was performed using software to replicate a part of the Provincial Electricity Authority (PEA) 22 kV distribution system located in the northern section of the central region of Thailand. Wind power generation was selected as the DG system because of the area's wind potential and the possibility of future investments in this field. The system characteristics, in terms of voltage and current, were evaluated before and after the DG connection. Furthermore, a variety of DG sizes and placement locations were considered in the case studies. In addition, the impact of DG on system characteristics under both normal and fault conditions was assessed. This study aimed to evaluate both the potential of DG to improve the voltage level of the distribution system and its impact on system characteristics to provide information on the possibility of using renewable energy DG as a method to the support voltage level in the system with additional benefits for social and economic sustainability.

The contributions of this study can be summarized as follows:

- Electrical parameters and characteristics were evaluated using a model based on actual data from the PEA 22 kV distribution system in Thailand.
- The process of selecting DG size and placement location in the distribution system to address the voltage drop issue was presented.
- The impact of DG placement at the proposed location in terms of fault occurrence was evaluated to determine the system characteristics under fault conditions.
- This method provides a sustainable way to maintain voltage regulation in distribution systems with renewable energy.

The remainder of this paper is organized as follows: in Section 2, we describe the configuration of the distribution system with the proposed DG placement locations used in the case studies. The voltage improvement when the DG placement location is on the entire distribution line is described in Section 3. In Section 4, we assessed the voltage improvement in the case where the DG placement location is between the substation and the critical load. In Section 5, the impact of DG placement on the proposed placement location during fault occurrence is described. Finally, a discussion of the results and the study conclusions are presented in Section 6.

2. Research Methodologies and Configuration of the Distribution System

2.1. Research Methodologies

This research proposed a voltage improvement method based on DG placement on a 22 kV distribution system based on actual information from utilities using the Power Systems Computer-Aided Design (PSCAD) software to simulate the system. The software used in this research is PSCAD version 4.5, with the ability to simulate system characteristic under both steady-state and transient conditions. In order to evaluate the impact of DGs on the voltage improvement, the case study distribution system was constructed in the PSCAD software using a substation, cable, tower, and load data from the utility. After that, the simulation was performed to evaluate the characteristics of the system under normal conditions without the connection of DGs. Wind power generation was selected as a distributed generation system based on the assumption that the area has wind potential and the recent commission plan consists mainly of wind farm. Wind power generation was installed in the distribution system with the sizing varying from 3 to 8 MW to evaluate the voltage improvement level in each case. The placement of DG was also taken into consideration, being installed on the 1/2 line, the 1/3 line, or the 2/3 line. The comparison between the placement location was performed to find the most suitable location in terms of voltage improvement with the smallest power generation requirement. In addition, this study also examined the impact of DG on the distribution system in terms of the current characteristics under fault conditions, which may affect the performance of the protection system.

2.2. System Description

The 22 kV distribution system used in the case studies in this work is a part of the PEA distribution system. Two substations—Sukhothai (STA) and Sawankhalok (SWA)—are present on both sides of the main feeder, as shown in Figure 1. The detailed configuration of the distribution system is presented in Table 1. The data came from the PEA, grouping nearby loads into connected loads at the point of connection. The distance between each load was measured from one point of connection to another. This distribution line consisted of 9 group of connected loads with a total power of 40.87 MVA and average power factors lagging by 0.95. The details of each load are listed in Table 2. The load characteristics were as follows: the maximum demand load was observed for residential buildings and industrial plants, with load group 4 having the largest load and load group 9 having the smallest load, located 17.5 km and 33.5 km away from the STA substation, respectively.

Table 1. Data configuration parameters of the distribution system.

Parameter	Value Setting
1. System Voltage	23 kV
2. Boundary voltage	20.9–23.1 kV
3. Cable type	Space Aerial Cable
4. Conductor style	Solid core
5. Sizing cable	185 mm^2
6. Number conductor	3 conductors
7. Outer radius	0.00799 m.
8. DC Resistance	0.164 Ω
9. Total load of feeder	40.87 MVA

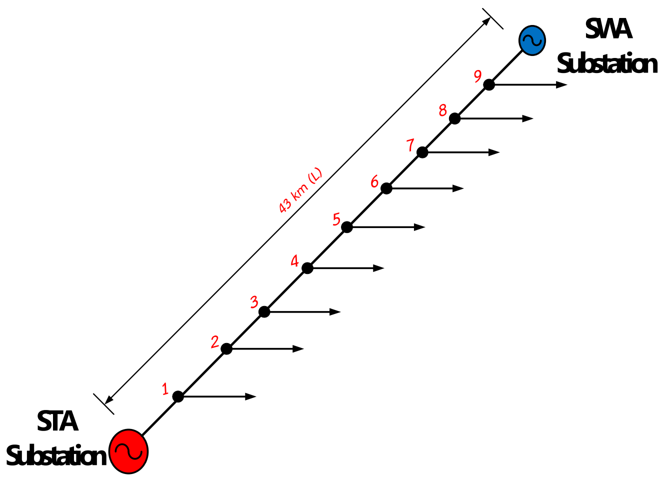

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Figure 1. *Cont.*

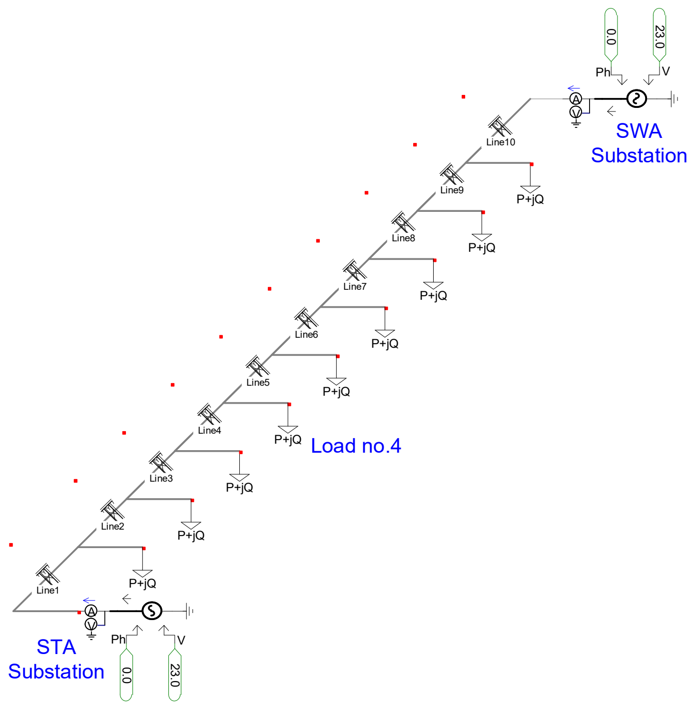

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Figure 1. Single-line diagram of a case without DG placement. (**a**) Single-line diagram. (**b**) PSCAD model.

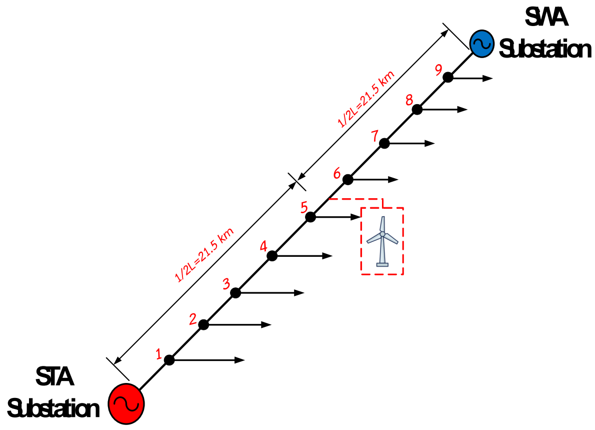
Table 2. Loads characteristics of the distribution system.

Load No.	Load Capacity (MVA)	Power Factor (p.f.)	Length (Load-Load) (km)
1	1.49	0.95	5.5
2	8.15	0.95	4.5
3	4.42	0.95	4.5
4	10.42	0.95	3.0
5	5.15	0.95	2.5
6	1.67	0.95	6.0
7	4.11	0.95	4.5
8	5.11	0.95	3.0
9	0.31	0.95	4.0
Total	40.87	-	43.0

Based on previous studies [27], we found that the voltage level on the distribution system from loads 2 to 7 decreased beyond the PEA threshold ranging between 23.1 kV and 20.9 kV. Thus, a DG system was installed to improve the voltage level along the distribution line to reach the standard level.

2.3. Distribution System with DG Placement

Based on previous research, the DG system was installed in the distribution system, as shown in Figure 2. Wind power generation was used as the DG system connected to the distribution in the point of connection. The detailed configuration parameters of the wind power generation system are listed in Table 3. As summarized in Table 3, the wind DG model comprised a synchronous wind turbine operating at a cut-in speed of 6 m/s with three blades and a rotor diameter of 87 m. The diagrams of the wind turbine model and its PSCAD counterpart are shown in Figure 2c. The turbine components consisted of a wind source, which could be used to control the input wind speed for the turbine. The data of wind speed on the turbine blades were then used as an input for the wind turbine governor. This value generated mechanical torque for the synchronous machine with AC exciters that generated voltage and current. Finally, the output power flowed through the power transformer to the distribution grid.



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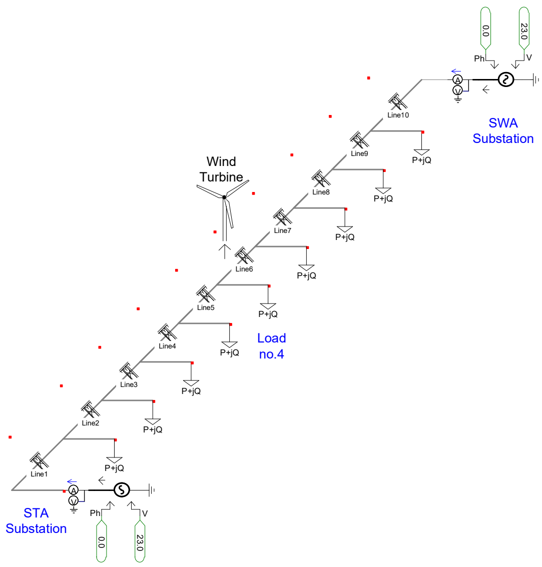

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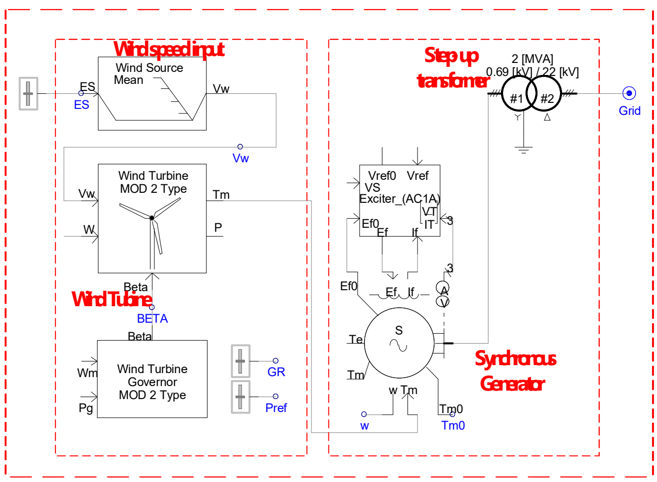

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Figure 2. Single-line diagram of a case with DG placement. (**a**) Single-line diagram. (**b**) PSCAD model. (**c**) Wind power generation model on PSCAD.

Table 3. Wind turbine generation model-type setting in the PSCAD program.

Item	Descriptions	Specifications
1	Turbine model type	GHFD87-2000/II
2	Manufacturer	Geoho
3	Rated power	2 MW
4	Rotor diameter	87 m
5	Blade quantity	3 blades
6	Wind speed	7–13 m/s
7	Generator type	Synchronous
8	Rated power	2 MVA
9	Rated voltage	690 V
10	Rated current	1840 A

Previous studies [27] have shown that installing a DG system with a capacity of 3 MW at the midpoint of the distribution line (1/2 along the feeder) can increase the voltage level to that recommended by the PEA, as shown in Figure 3. However, there may be constraints on the installation of a 3 MW DG system at the middle point of the transmission line in real-world scenarios owing to the limitations caused by the location, grid connections, and land acquisition. Thus, a discussion regarding the assessment of the potential for 3 MW DG placement at other locations along the distribution line with respect to voltage improvement is presented in the next section.

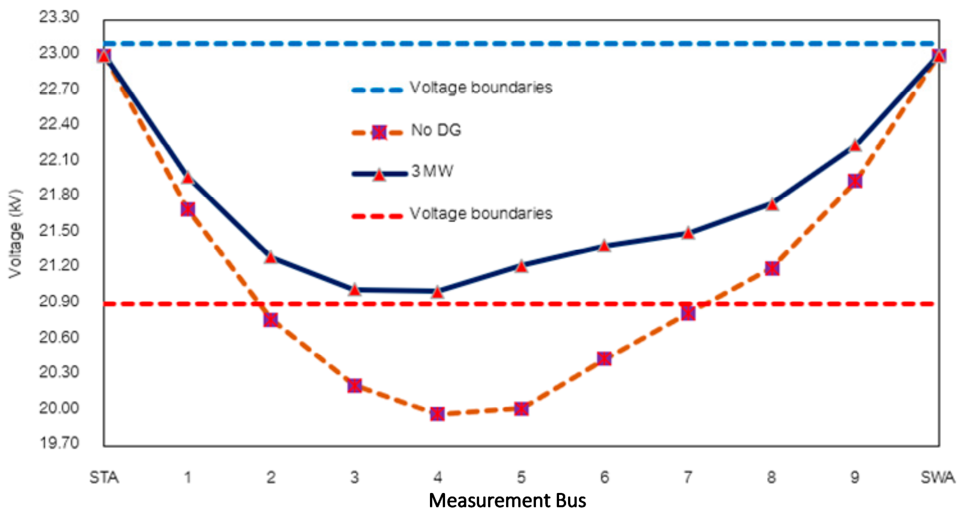


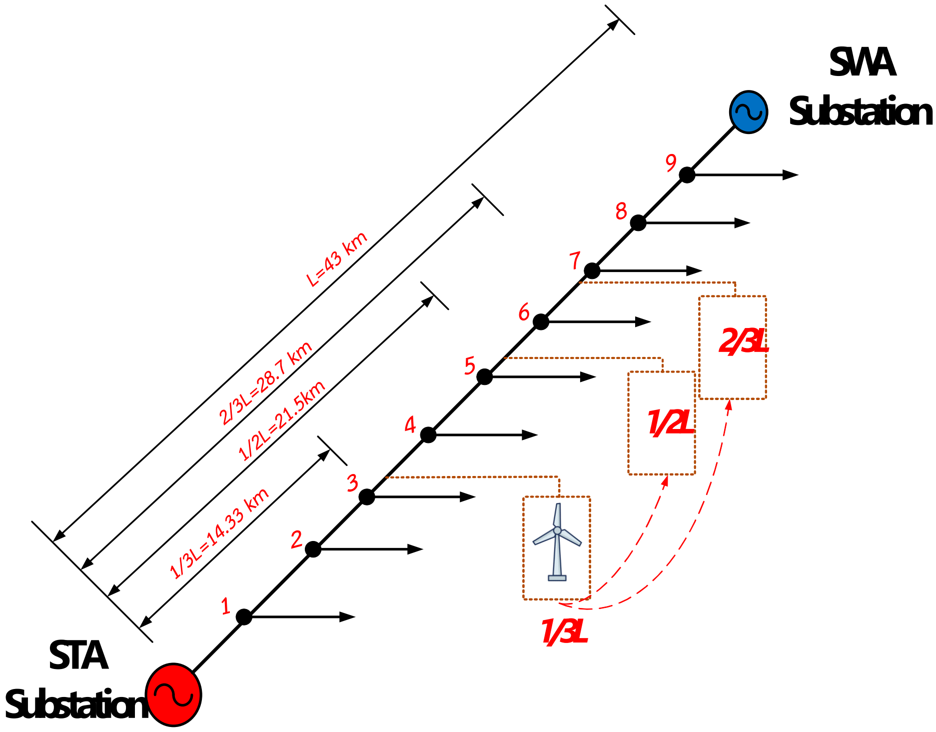
Figure 3. Voltage profile at the middle point with a 3 MV DG system.

3. Single DG Placement along the Length of the Distribution Line

In this section, the performance of the 3 MW DG system at specified positions (1/3, 1/2, and 2/3) along the length of the distribution line is described. A schematic of DG placement is shown in Figure 4. As shown in this figure, the length of the distribution line between the STA and SWA substations was 43 km. Therefore, the DG was located at 14.33 km, 21.5 km, and 28.7 km along the length of the distribution line in the cases of the 1/3, 1/2, and 2/3 placements, respectively. The simulation results of the three case studies are presented in Table 4 and Figure 5.

As summarized in Table 4, in the case of 1/3 placement along the distribution line, the 3 MV DG placement improved the voltage level at all loads according to the PEA standard. In the case of 1/2 placement, the voltage level at all loads was increased to reach the PEA standard, as reported in a previous study [27]. Finally, in the case of 2/3 placement, the voltage level at loads 3–5 was lower than the PEA standard.

These results indicate that 3 MW DG placement at any location along the distribution line cannot achieve voltage improvement within the PEA regulation. Thus, the DG capacity was varied to determine the capacity level that can improve the voltage at each placement location.



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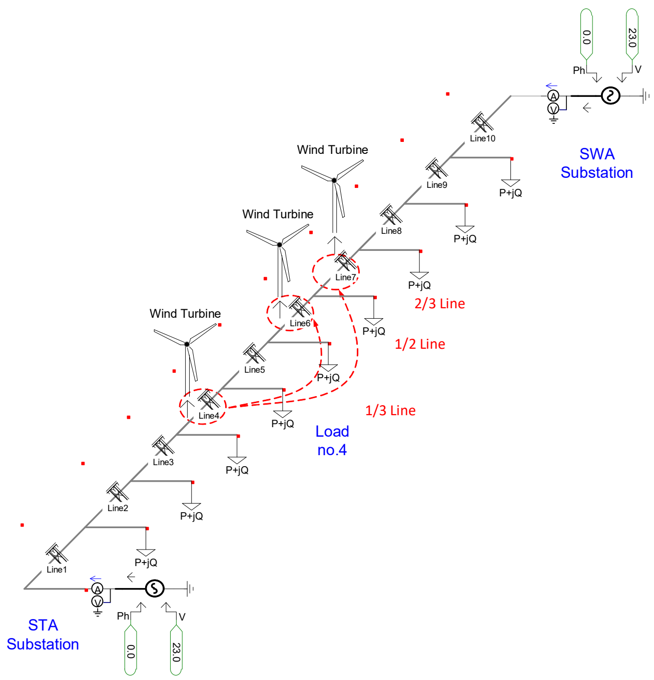

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Figure 4. Various DG positions along the length of the distribution feeder. (**a**) Single-line diagram. (**b**) The PSCAD model.

Table 4. Voltage simulation results of placing a single 3 MV DG system along the length of the distribution feeder.

DG Locations	PEA Std.	Without DG	1/3 Line	1/2 Line	2/3 Line
STA	20.900	23.000	23.000	23.000	23.000
Load 1	20.900	21.705	22.243	22.103	21.922
Load 2	20.900	20.766	21.601	21.484	21.146
Load 3	20.900	20.213	21.325	21.276	20.764
Load 4	20.900	19.967	20.953	21.283	20.651
Load 5	20.900	20.017	20.910	21.551	20.812
Load 6	20.900	20.433	21.068	21.732	21.511
Load 7	20.900	20.821	21.277	21.756	21.746
Load 8	20.900	21.203	21.555	21.903	21.904
Load9	20.900	21.939	22.142	22.339	22.344
SWA	20.900	23.000	23.000	23.000	23.000

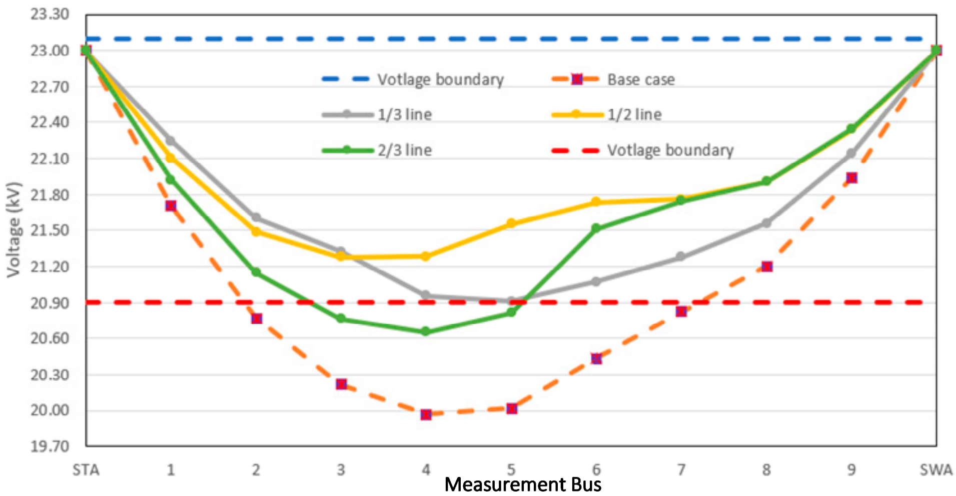


Figure 5. Voltage profile of the 3 MW DG system at various positions.

Based on the results shown in Figure 5, the DG capacity for the 1/3 and 2/3 placements along the distribution line ranged from 2 MW to 8 MW. The obtained results are displayed in Figures 6 and 7 for the 1/3 and 2/3 placements, respectively.

By considering the results shown in Figure 6 and Table 5, a DG capacity of 4 MW or higher can increase the voltage level to the PEA regulation in the case of the 1/3 placement. The reason for increasing the DG capacity is that the placement unit is located far away from load 5 (up to 6 km). This result differs from that observed in the case of the 1/2 placement, wherein the DG system was located near loads 4 and 5, with a distance of less than 3 km between the loads. In the case of the 2/3 placement, as shown in Figure 7 and Table 6, 5 MW is the lowest DG capacity that can improve the voltage of all individual loads to a level higher than the lower voltage boundaries. This is because the DG system is located far away from the load (>8 km), which leads to a reduction in voltage. Thus, a larger DG capacity is required to improve the voltage level of long-distance loads.

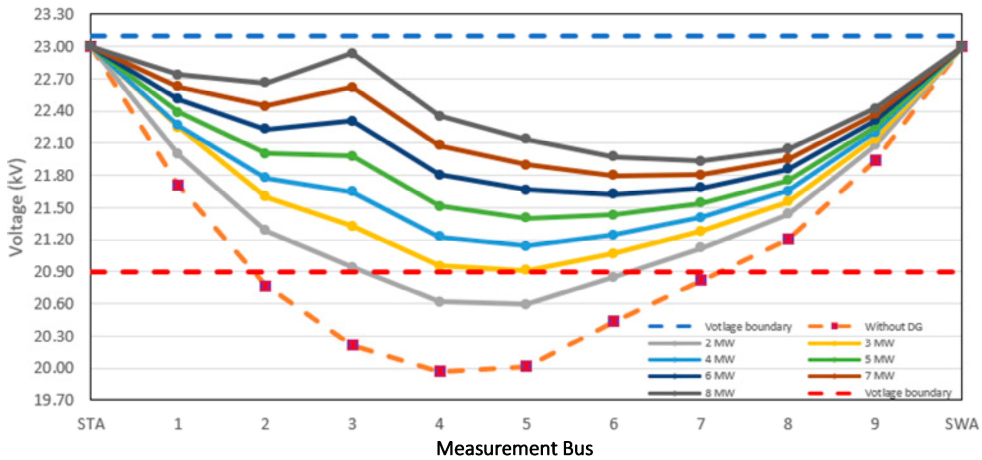


Figure 6. Voltage profiles of nine loads with various DG capacities at 1/3 placement.

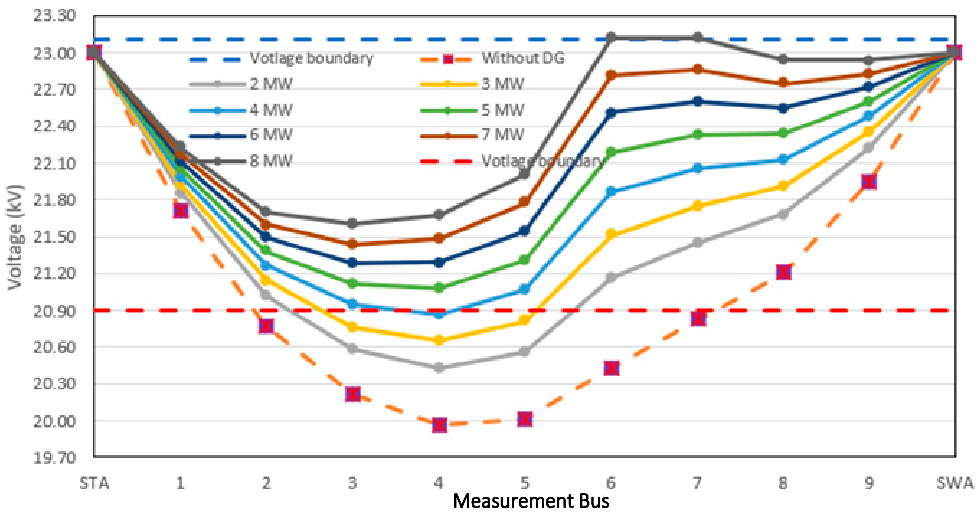


Figure 7. Voltage profiles of nine loads with various DG capacities at the 2/3 placement.

Table 5. Voltage simulation results at the 1/3 placement.

Locations	Without DG	2 MW	3 MW	4 MW	5 MW	6 MW	7 MW	8 MW
STA	23.000	23.000	23.000	23.000	23.000	23.000	23.000	23.000
1	21.705	21.997	22.243	22.262	22.385	22.509	22.622	22.736219
2	20.766	21.283	21.601	21.772	22.000	22.228	22.444	22.660486
3	20.213	20.941	21.325	21.646	21.975	22.304	22.618	22.932569
4	19.967	20.612	20.953	21.224	21.513	21.802	22.075	22.349410
5	20.017	20.590	20.910	21.141	21.401	21.660	21.897	22.133517
6	20.433	20.845	21.068	21.244	21.431	21.619	21.795	21.971349
7	20.821	21.122	21.277	21.407	21.543	21.679	21.804	21.928803
8	21.203	21.436	21.555	21.651	21.753	21.854	21.948	22.042515
9	21.939	22.074	22.142	22.196	22.254	22.312	22.367	22.422310
SWA	23.000	23.000	23.000	23.000	23.000	23.000	23.000	23.000

Based on the above discussion, we infer that voltage improvement depends on the DG placement location by considering the load with the lowest voltage level as the terminal of the line. The distances for DG placement, namely 1/2, 1/3, and 2/3, were reconsidered based on the distance from the substation to the critical load, which is discussed in the next section.

Table 6. Voltage Simulation Results at the 2/3 placement.

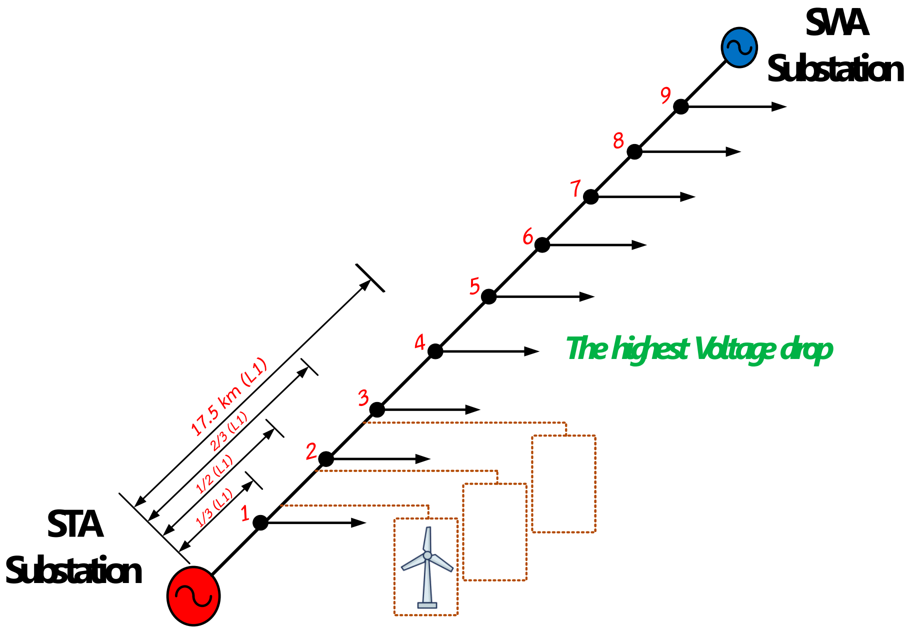
Locations	Without DG	2 MW	3 MW	4 MW	5 MW	6 MW	7 MW	8 MW
STA	23.000	23.000	23.000	23.000	23.000	23.000	23.000	23.000
1	21.705	21.856	21.922	21.988	22.048	22.109	22.164	22.219574
2	20.766	21.025	21.146	21.266	21.379	21.492	21.595	21.698174
3	20.213	20.583	20.764	20.944	21.111	21.279	21.438	21.597143
4	19.967	20.431	20.651	20.870	21.079	21.288	21.481	21.674618
5	20.017	20.557	20.812	21.066	21.304	21.543	21.771	22.000575
6	20.433	21.163	21.511	21.859	22.184	22.510	22.812	23.114537
7	20.821	21.447	21.746	22.045	22.322	22.599	22.860	23.120848
8	21.203	21.682	21.904	22.125	22.334	22.542	22.742	22.942699
9	21.939	22.215	22.344	22.472	22.593	22.713	22.825	22.937549
SWA	23.000	23.000	23.000	23.000	23.000	23.000	23.000	23.000

4. Single DG Placement between the Substation and the Critical Load

In this section, by assuming the critical load to be load 4, the DG system was placed at each position of 1/3, 1/2, and 2/3 between the substation and the critical load (Figure 8). Figure 8 shows that the distribution system has two substations. Therefore, the case study was divided into two parts: from the STA substation to the critical load and from the SWA substation to the critical load.

4.1. Voltage Drop Improvement in the Case of DG Placement between the STA Substation and the Critical Load

The DG system was placed at three locations between the STA substation and the critical load: 5.8 km (in the case of 1/3), 8.75 km (in the case of 1/2), and 11.67 km. (in the case of 2/3) from the STA substation (Figure 8). The results obtained from all locations in the case of DG placement between the STA substation and the critical load are listed in Table 7. By considering the voltage level of the critical load presented in Table 7, the voltage level at the 2/3 placement (11.67 km) was higher than that at the other placements. However, the voltage level in the case of the 1/2 and 1/3 placements was still lower than the PEA standard, whereas the voltage level at the 2/3 placement reached the PEA standard. This is because the 2/3 placement was closer to the critical load than the 1/3 and 1/2 placements. However, the voltage level of load 4 exceeded the PEA standard, whereas the voltage level of load 5 at the 2/3 placement was slightly lower than the PEA standard because the DG placement was more than 8 km away from load 5. Furthermore, we found that the obtained voltage level at all loads in the case of the 2/3 placement was lower than that in the case of the 1/3 placement along the distribution line because the DG position in the case of the 2/3 placement was located far away from the critical load. However, not all DG placement locations between the STA substation and the critical load can improve the voltage level to reach the PEA standard, as shown in Figure 9. To overcome this problem, the DG capacity should be increased by more than 3 MW at these locations to achieve voltage improvement. Hence, DG capacities between 2 and 8 MW were simulated to verify whether increasing the DG capacity can improve the voltage level. The results are presented in Tables 8–10 and Figures 10–12.



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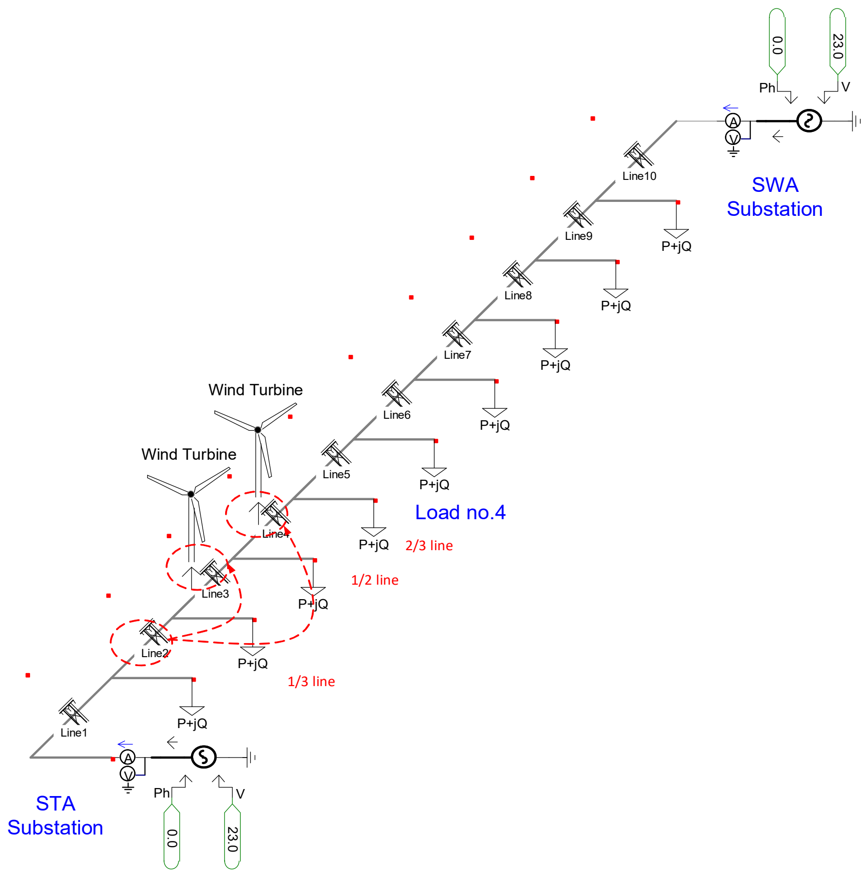

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Figure 8. Various DG placements between the STA substation and the critical load. (**a**) Single-line diagram. (**b**) PSCAD model.

Table 7. Voltage simulation results of placing a single 3 MV DG system between the STA substation and the critical load.

DG Locations	PEA Std.	Without DG	1/3 Line	1/2 Line	2/3 Line
STA	20.900	23.000	23.000	23.000	23.000
Load 1	20.900	21.705	22.485	22.358	22.225
Load 2	20.900	20.766	21.420	21.752	21.573
Load 3	20.900	20.213	20.752	21.038	21.324
Load 4	20.900	19.967	20.445	20.697	20.946
Load 5	20.900	20.017	20.444	20.662	20.892
Load 6	20.900	20.433	20.740	20.902	21.065
Load 7	20.900	20.821	21.048	21.160	21.277
Load 8	20.900	21.203	21.373	21.457	21.545
Load9	20.900	21.939	22.037	22.085	22.136
SWA	20.900	23.000	23.000	23.000	23.000

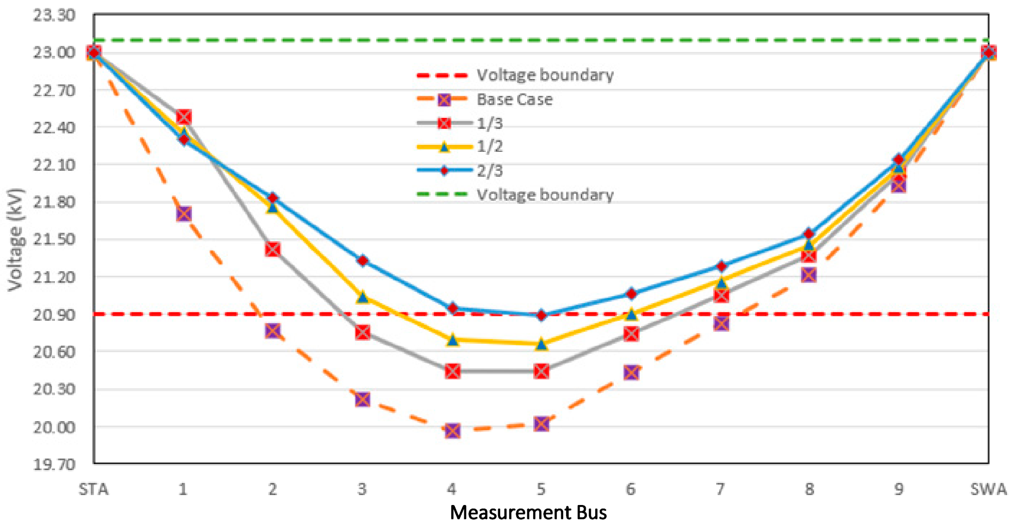


Figure 9. RMS voltage profile after a 3 MW capacity in various placements between the STA substation and the critical load.

Table 8. Obtained voltage results at the 1/3 placement between the STA substation and the critical load by increasing the DG capacity from 2 MW to 8 MW.

Locations	Without DG	2 MW	3 MW	4 MW	5 MW	6 MW	7 MW	8 MW
STA	23.000	23.000	23.000	23.000	23.000	23.000	23.000	23.000
1	21.705	22.118	22.311	22.505	22.692	22.880	23.060	23.241
2	20.766	21.109	21.273	21.437	21.595	21.753	21.906	22.059
3	20.213	20.492	20.629	20.766	20.898	21.031	21.158	21.286
4	19.967	20.219	20.339	20.458	20.574	20.690	20.802	20.913
5	20.017	20.242	20.349	20.456	20.559	20.663	20.762	20.862
6	20.433	20.594	20.672	20.750	20.825	20.900	20.972	21.044
7	20.821	20.944	21.000	21.056	21.110	21.164	21.216	21.268
8	21.203	21.295	21.337	21.379	21.420	21.461	21.500	21.539
9	21.939	21.992	22.016	22.041	22.064	22.087	22.110	22.132
SWA	23.000	23.000	23.000	23.000	23.000	23.000	23.000	23.000

Table 9. Obtained voltage results at the 1/2 placement between the STA substation and the critical load by increasing the DG capacity from 2 MW to 8 MW.

Locations	Without DG	2 MW	3 MW	4 MW	5 MW	6 MW	7 MW	8 MW
STA	23.000	23.000	23.000	23.000	23.000	23.000	23.000	23.000
1	21.706	22.095	22.240	22.384	22.539	22.694	22.840	22.985
2	20.767	21.291	21.539	21.788	22.021	22.254	22.480	22.705
3	20.213	20.645	20.852	21.059	21.257	21.454	21.635	21.816
4	19.967	20.350	20.550	20.750	20.900	21.049	21.221	21.392
5	20.017	20.360	20.551	20.743	20.865	20.986	21.139	21.291
6	20.434	20.680	20.798	20.915	21.029	21.143	21.245	21.347
7	20.821	21.003	21.088	21.172	21.252	21.332	21.410	21.488
8	21.203	21.339	21.403	21.466	21.528	21.589	21.646	21.703
9	21.939	22.018	22.055	22.091	22.126	22.162	22.194	22.227
SWA	23.000	23.000	23.000	23.000	23.000	23.000	23.000	23.000

Table 10. Obtained voltage results at the 2/3 placement between the STA substation and the critical load by increasing the DG capacity from 2 MW to 8 MW.

Locations	Without DG	2 MW	3 MW	4 MW	5 MW	6 MW	7 MW	8 MW
STA	23.000	23.000	23.000	23.000	23.000	23.000	23.000	23.000
1	21.706	22.150	22.225	22.374	22.453	22.592	22.725	22.857
2	20.767	21.566	21.573	21.980	22.127	22.382	22.618	22.854
3	20.213	21.044	21.324	21.477	21.630	21.901	22.155	22.409
4	19.967	20.701	20.946	21.079	21.213	21.448	21.662	21.876
5	20.017	20.674	20.892	21.011	21.130	21.339	21.535	21.730
6	20.434	20.905	21.065	21.152	21.240	21.392	21.532	21.672
7	20.821	21.162	21.278	21.342	21.407	21.514	21.615	21.716
8	21.203	21.460	21.546	21.594	21.642	21.721	21.800	21.878
9	21.939	22.087	22.136	22.164	22.192	22.238	22.283	22.328
SWA	23.000	23.000	23.000	23.000	23.000	23.000	23.000	23.000

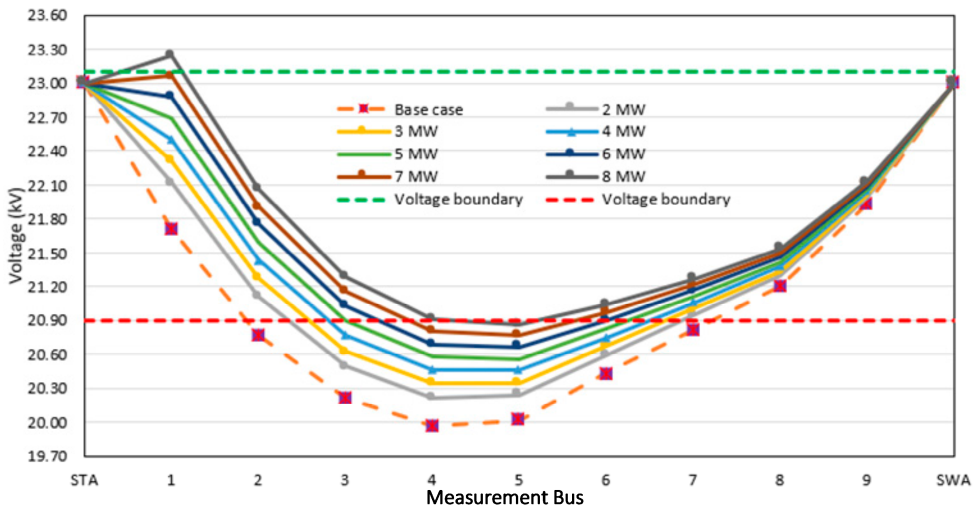


Figure 10. Voltage profiles at various DG capacities in the case of the 1/3 placement from the STA substation.

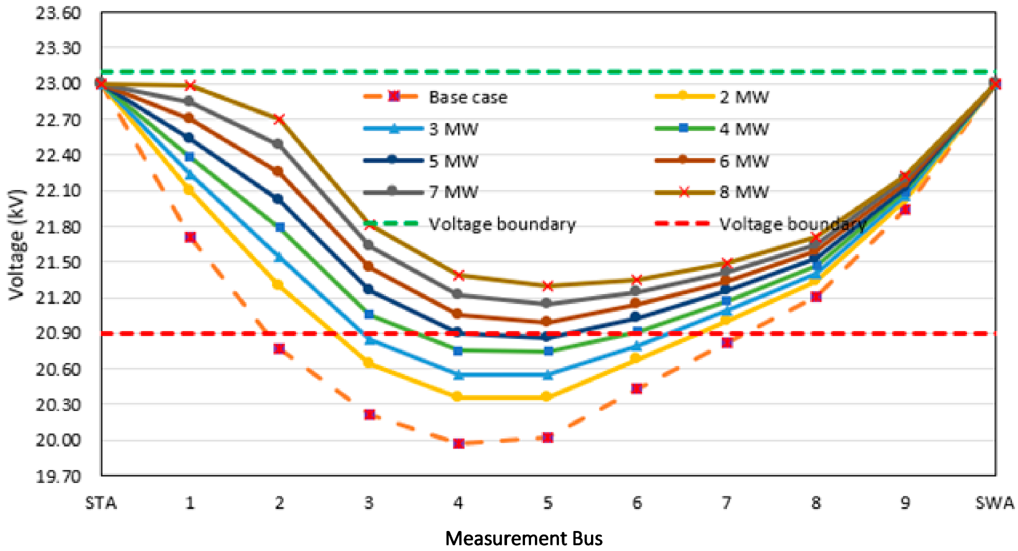


Figure 11. Voltage profiles at various DG capacities in the case of 1/2 placement from the STA substation.

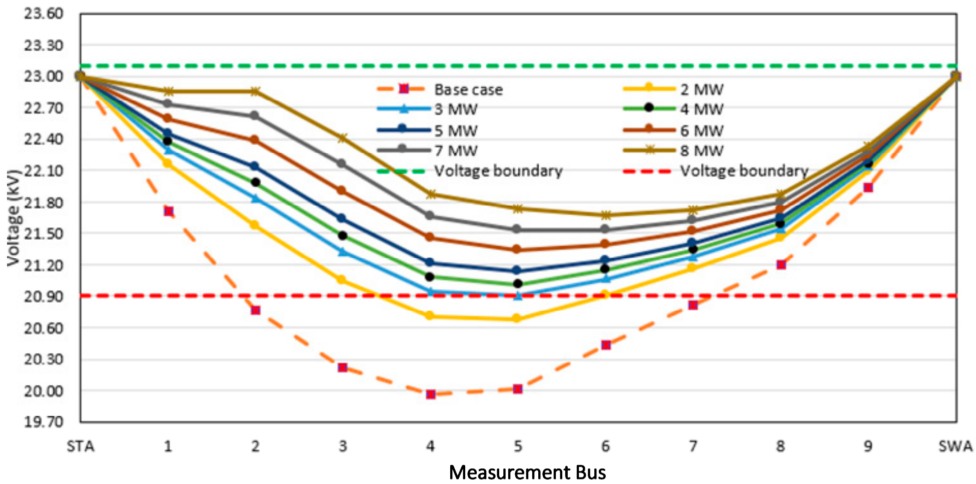


Figure 12. Voltage profile of the 2/3 DG placement from the STA substation.

The DG capacity was increased from 2 MW to 8 MW at the 1/3 placement between the STA substation and the critical load, as shown in Table 8 and Figure 10. By considering the voltage level of the critical load presented in Table 8, only the 8 MW DG system improved the voltage level to the PEA standard, indicating that the DG placement location and capacity directly impact the voltage level. However, when considering load 5, the voltage level did not reach the PEA standard. We found that, compared with the voltage level in the case of the 3 MW DG system at the 2/3 placement along the distribution line, the voltage level at the critical load was significantly higher in the case of the 8 MW DG system at the 2/3 placement along the distribution line because the 8 MW DG system was located closer to the critical load and load 5.

Next, the DG capacity was varied between 2 and 8 MW at the 1/2 placement between the STA substation and the critical load (Table 9 and Figure 11). In the case where the critical voltage level reached the PEA standard at a 6 MW capacity, the voltage level can be improved by using other loads. Similarly, the voltage level at the critical load was higher than that in the case of the 3 MW DG system at the 2/3 placement along the distribution line because the DG capacity directly impacts the voltage level at all loads. However, by comparing the voltage level in the case of the 8 MW DG system at the 1/3 placement between the STA substation and the critical load, we found that the voltage level in the case of the 8 MW DG system was better than that in the case of the DG system at all other loads.

Furthermore, the obtained voltage result is shown in Table 10, and Figure 12 indicates the 2/3 placement between the STA substation and the critical load, which shows that the critical load voltage follows the PEA standard when applying the DG at a capacity of 4 MW can improve the voltage level at all loads. By comparing the DG capacity, the capacity is derived if the DG placement moves close to the critical load location according to the 1/3, 1/2, and 2/3 placements.

In the case of the 8 MW DG system at the 1/3 placement, the critical load voltage reached the PEA standard, except for load 5, wherein the voltage was lower than the PEA threshold. Next, when DG capacities were compared, we found that the use of a 4 MW DG system at the 2/3 placement increased the voltage level to the PEA standard. By contrast, a 6 MW DG system was used at the 1/2 placement to increase the voltage level for all loads. We found that the DG capacity would be smaller when the distance between the critical loads is small. Moreover, the minimal DG capacity to be applied at the 2/3 placement is 4 MW because the DG system is placed near the critical load in the case of the 1/3 and 1/2 placements between the STA substation and the critical load. In the next section, the effect of DG placement between the SWA substation and the critical load is described.

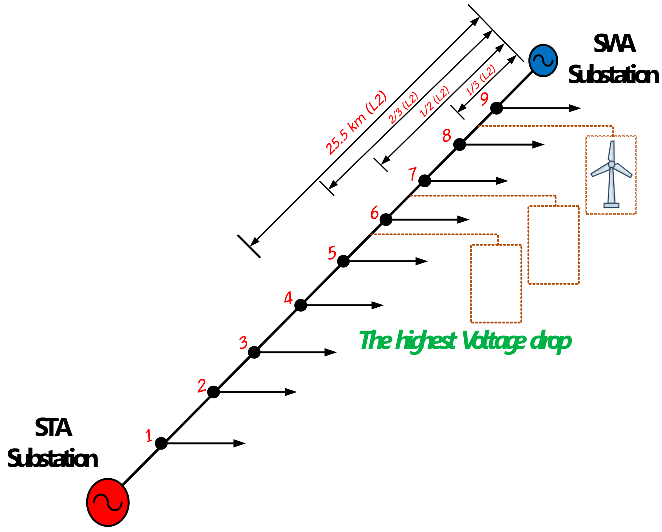
4.2. Voltage Drop Improvement in the Case of DG Placement between the SWA Substation and the Critical Load

In the previous section, we described the effect of DG when placed between the STA substation and the critical load. In this section, we investigated the effect of DG when placed between the SWA substation and the critical load. Cases 1/3, 1/2, and 2/3 were located 8.5, 12.5, and 17 km from the SWA substation, respectively, as shown in Figure 13.

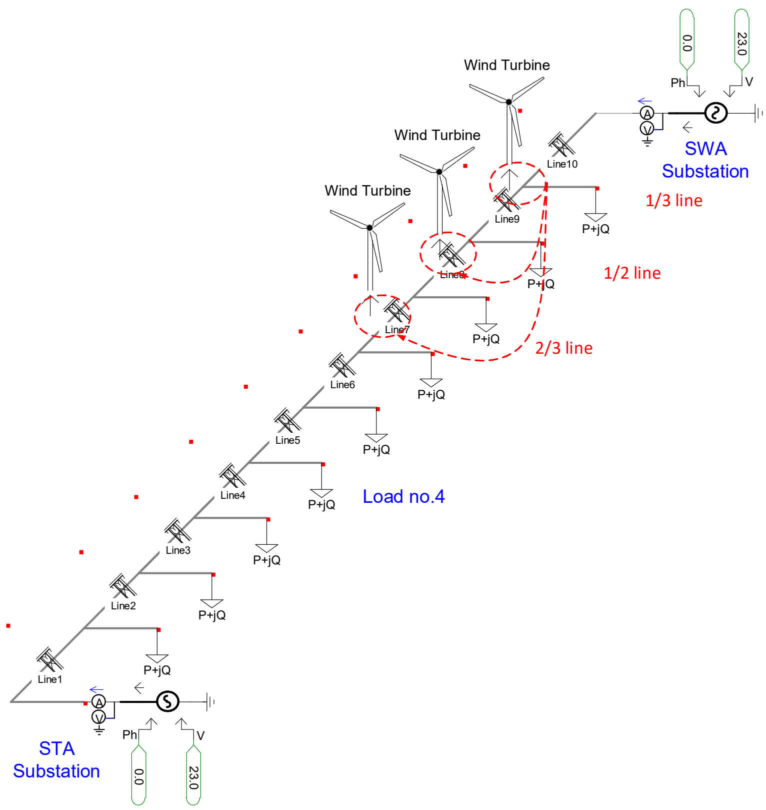
The voltage results of 3 MV DG placement between the SWA and the critical load and those without DG placement were compared; the results are presented in Table 11. The results indicated that only the voltage level obtained in the case of the 2/3 placement from the SWA substation was within the PEA standard. In addition, when compared with the 2/3 DG placement on the STA substation side (Table 7), we observed that the DG in the case of the 2/3 placement from the STA substation was located closer to the critical load than that in the case of the 2/3 placement from the SWA substation; however, the voltage level at load 5 was still lower than the voltage threshold. This characteristic indicates that the load density may affect voltage improvement because the STA side has a higher load density than the SWA side. When considering the other two cases, the voltage level of loads 3–5 in the case of 1/2 DG placement was higher than that in the case of the 1/3 DG placement; however, in both cases, the voltage level was still lower than the PEA standard, as shown in Figure 14. This demonstrates that the load density as well as the distance between the DG and the critical load play an important role in voltage improvement.

Table 11. Voltage simulation results of placing a single 3 MV DG system between the SWA substation and the critical load.

DG Locations	PEA Std.	Without DG	1/3 Line	1/2 Line	2/3 Line
STA	20.900	23.000	23.000	23.000	23.000
Load 1	20.900	21.706	21.882	21.929	22.045
Load 2	20.900	20.767	21.073	21.160	21.307
Load 3	20.900	20.213	20.659	20.790	20.994
Load 4	20.900	19.967	20.524	20.677	20.942
Load 5	20.900	20.017	20.665	20.851	21.154
Load 6	20.900	20.434	21.308	21.039	21.973
Load 7	20.900	20.821	21.879	22.121	21.944
Load 8	20.900	21.203	22.381	22.118	22.036
Load9	20.900	21.939	22.616	22.504	22.417
SWA	20.900	23.000	23.000	23.000	23.000



(**a**)



(**b**)

Figure 13. Various DG placements between the SWA substation and the critical load. (**a**) Single-line diagram. (**b**) PSCAD model.

To improve the voltage levels at the 1/3 and 1/2 placements, the DG capacity was varied from 2 to 8 MW, and the results are presented in Tables 12 and 13, respectively. In the case without DG placement, the voltage level was less than the PEA standard at loads 2–7, as shown in Figure 15. When the DG capacity was increased from 2 MW to 8 MW, the voltage level at all loads increased with the DG capacity; at a DG capacity of 7 MW, the voltage level at all loads was within the PEA standard. This indicated a mismatch between the distance and the DG capacity. For clarity, when the case of the 1/2 placement was considered (Table 13 and Figure 16), the DG capacity was also varied from 2 MW to 8 MW. When the DG capacity was increased to 5 MW, the obtained voltage levels at all loads were within the PEA standard. The results from all of the simulated cases indicated that three factors affect the voltage improvement level: the load density, the distance between the DG and the critical load, and the DG capacity.

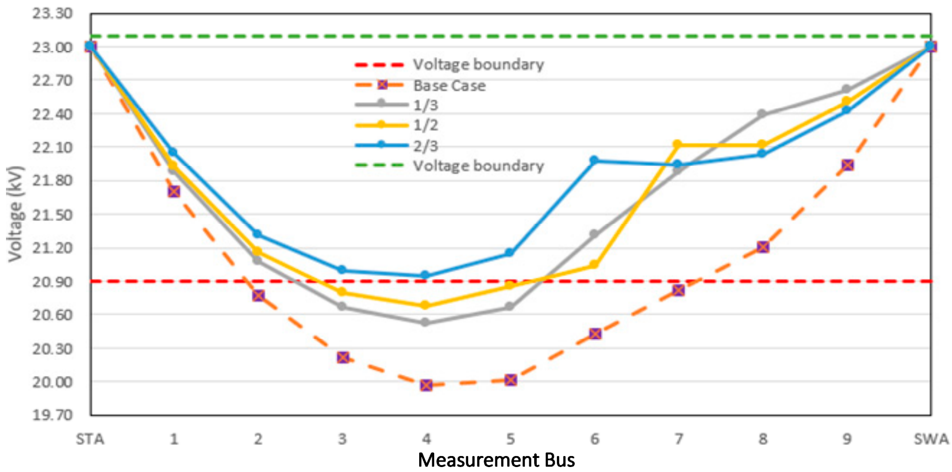


Figure 14. RMS voltage profiles of various 3 MV DG placements between the SWA substation and the critical load.

Table 12. Obtained voltage results at the 1/3 placement between the SWA substation and the critical load by increasing the DG Capacity from 2 MW to 8 MW.

Locations	Without DG	2 MW	3 MW	4 MW	5 MW	6 MW	7 MW	8 MW
STA	23.000	23.000	23.000	23.000	23.000	23.000	23.000	23.000
1	21.706	21.806	21.848	21.889	21.928	21.968	22.005	22.042
2	20.767	20.932	21.008	21.085	21.157	21.230	21.298	21.367
3	20.213	20.448	20.561	20.675	20.782	20.890	20.991	21.093
4	19.967	20.264	20.402	20.541	20.673	20.805	20.929	21.054
5	20.017	20.361	20.523	20.685	20.838	20.992	21.137	21.283
6	20.434	20.894	21.114	21.333	21.542	21.750	21.947	22.144
7	20.821	21.381	21.645	21.909	22.159	22.410	22.647	22.885
8	21.203	21.825	22.119	22.414	22.694	22.974	23.238	23.503
9	21.939	22.298	22.467	22.637	22.798	22.959	23.112	23.264
SWA	23.000	23.000	23.000	23.000	23.000	23.000	23.000	23.000

Table 13. Obtained voltage results at the 1/2 placement between the SWA Substation and the critical load by increasing the DG Capacity from 2 MW to 8 MW.

Locations	Without DG	2 MW	3 MW	4 MW	5 MW	6 MW	7 MW	8 MW
STA	23.000	23.000	23.000	23.000	23.000	23.000	23.000	23.000
1	21.706	21.833	21.886	21.939	21.988	22.036	22.085	22.133
2	20.767	20.981	21.079	21.178	21.268	21.358	21.444	21.530
3	20.213	20.520	20.667	20.814	20.950	21.087	21.219	21.351
4	19.967	20.348	20.527	20.705	20.906	21.027	21.193	21.360
5	20.017	20.485	20.682	20.879	21.065	21.251	21.443	21.635
6	20.434	21.023	21.312	21.601	21.861	22.120	22.369	22.618
7	20.821	21.517	21.842	22.167	22.475	22.783	23.069	23.355
8	21.203	21.727	21.973	22.218	22.454	22.690	22.909	23.128
9	21.939	22.241	22.384	22.528	22.660	22.792	22.916	23.040
SWA	23.000	23.000	23.000	23.000	23.000	23.000	23.000	23.000

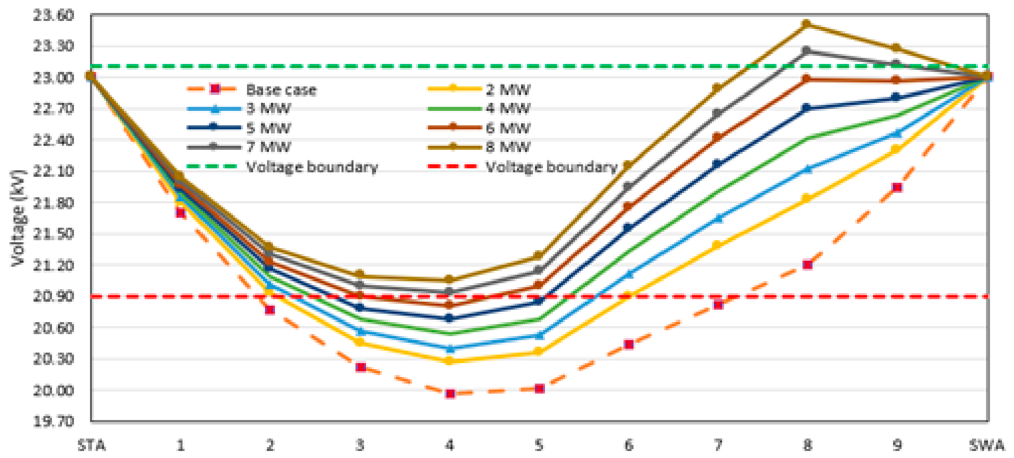


Figure 15. Voltage profile improvement when the DG capacity is increased from 2 MW to 8 MW in the case of the 1/3 placement from the SWA substation.

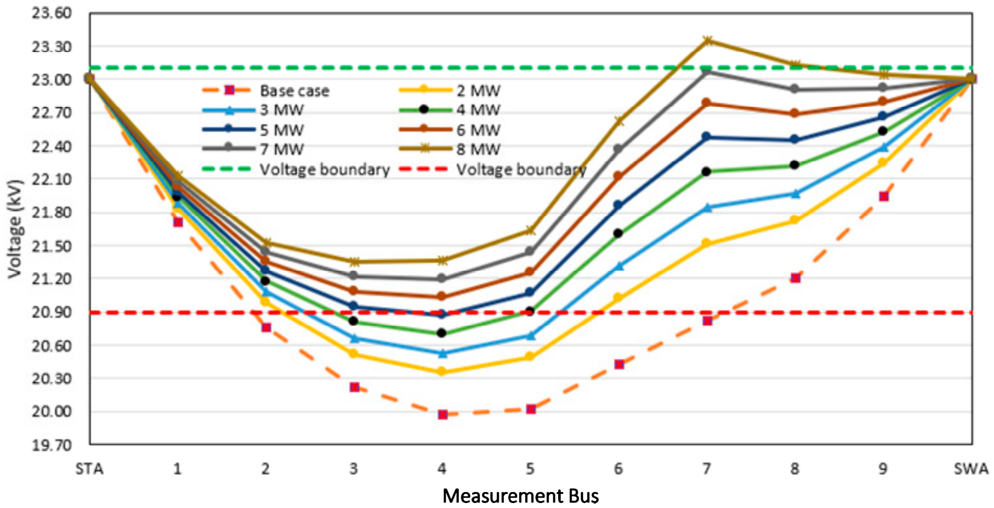
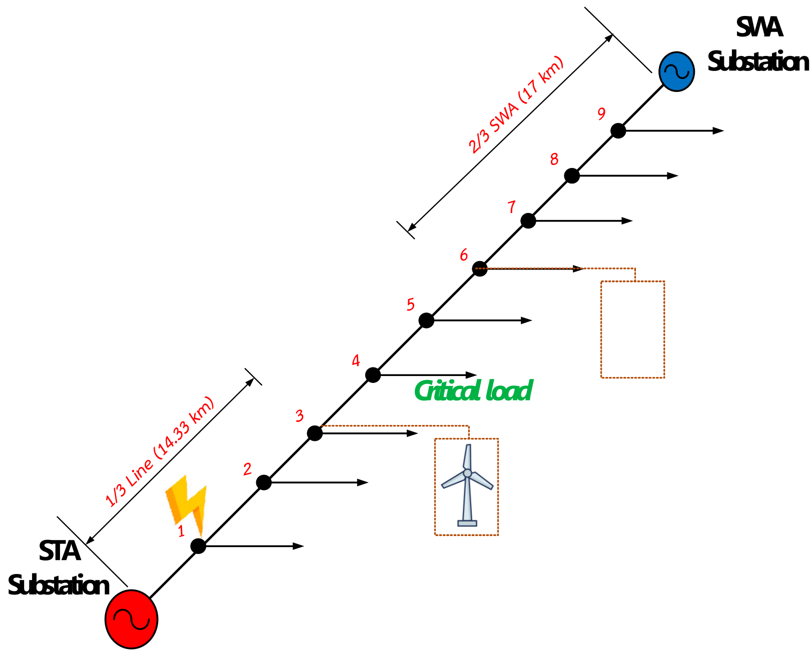


Figure 16. Voltage profile improvement when the DG capacity is increased from 2 MW to 8 MW in the case of the 1/2 placement from the SWA substation.

Furthermore, in the previous sections, the distribution system was described under normal conditions, which was shown in terms of voltage drop improvement. For this reason, the 3 MW DG capacity of the 1/3 distribution line (from Section III) and 2/3 placement from the SWA substation (from Subsection B in Section IV) was investigated under two fault conditions.

5. Single DG Placement under Fault Occurrence

Herein, the three-phase and single-line-to-ground faults occurring in the 22 kV distribution system with a 3 MV DG 3 were investigated (Figure 17). The results obtained in the case of the 1/3 placement along the distribution line and the 2/3 placement from the SWA substation under normal and fault conditions were considered, as shown in Figures 18–20. Six case studies were developed based on the fault location on the distribution lines: locations L1, L2, L3, L4, L5, and L6 at 5.5 km, 10 km, 17.5 km, 21.5 km, 33.5 km, and 37.5 km, respectively, as measured from the STA substation. A summary of the results obtained from various fault locations in the case of single-line-to-ground and three-phase faults is presented in Tables 14 and 15, respectively.



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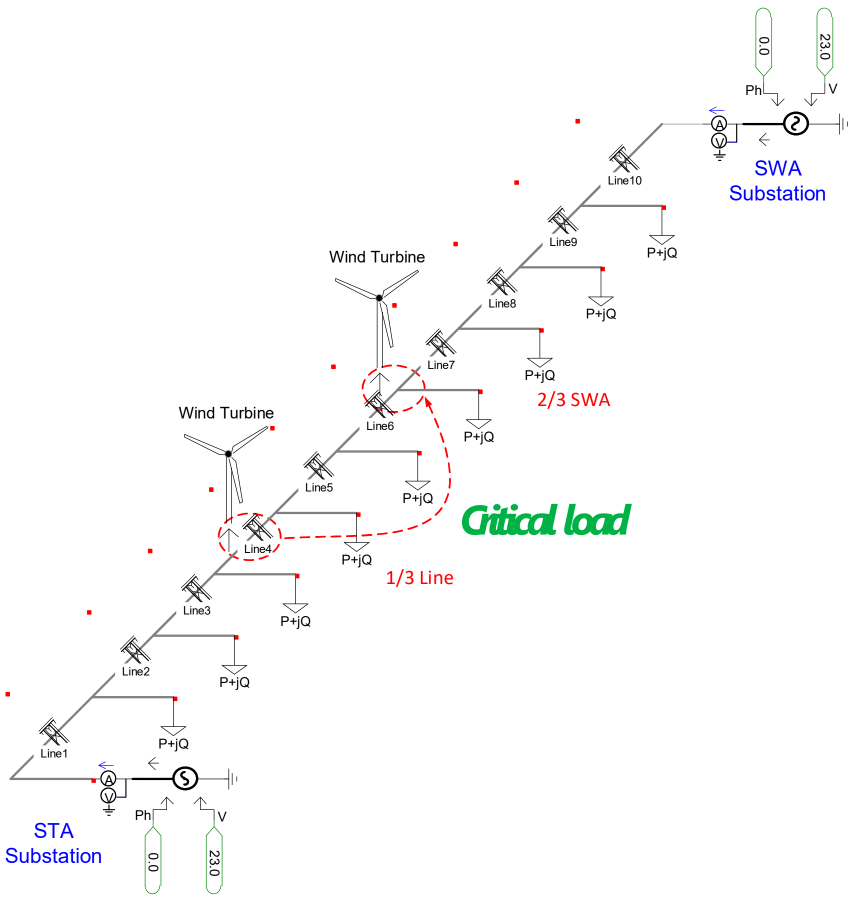
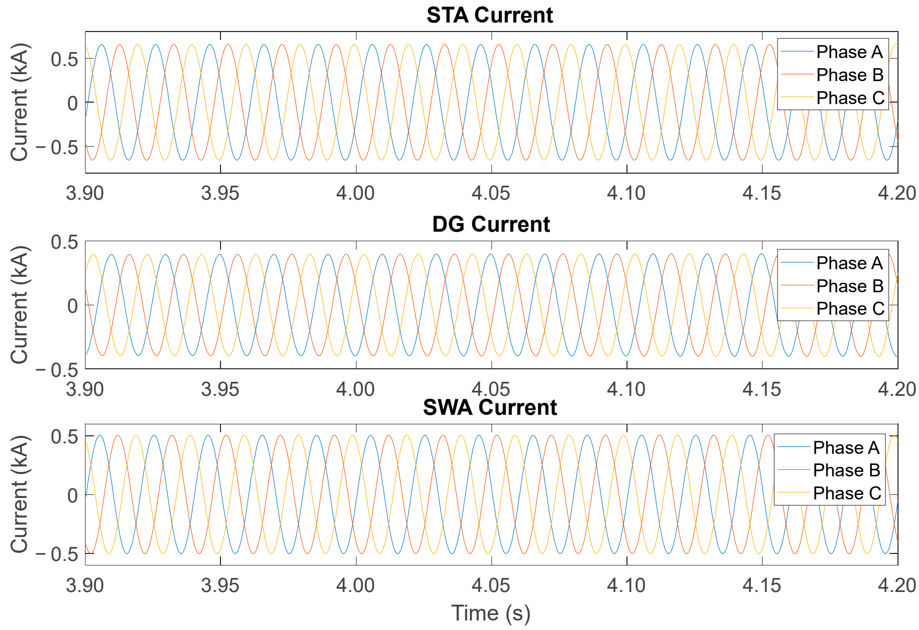


(**b**)

Figure 17. Single DG placement on the distribution line under fault occurrence. (**a**) Single-line diagram. (**b**) PSCAD model.



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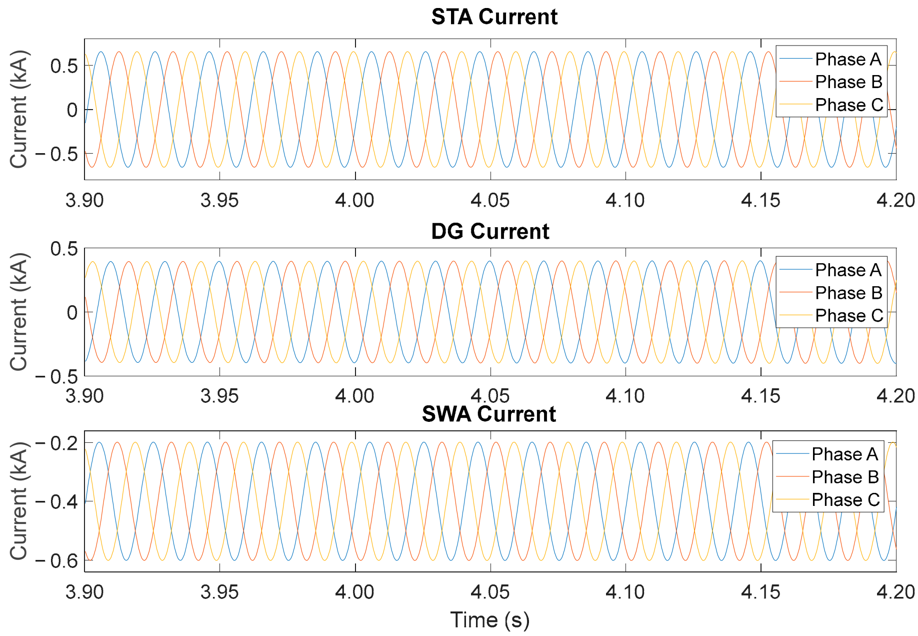
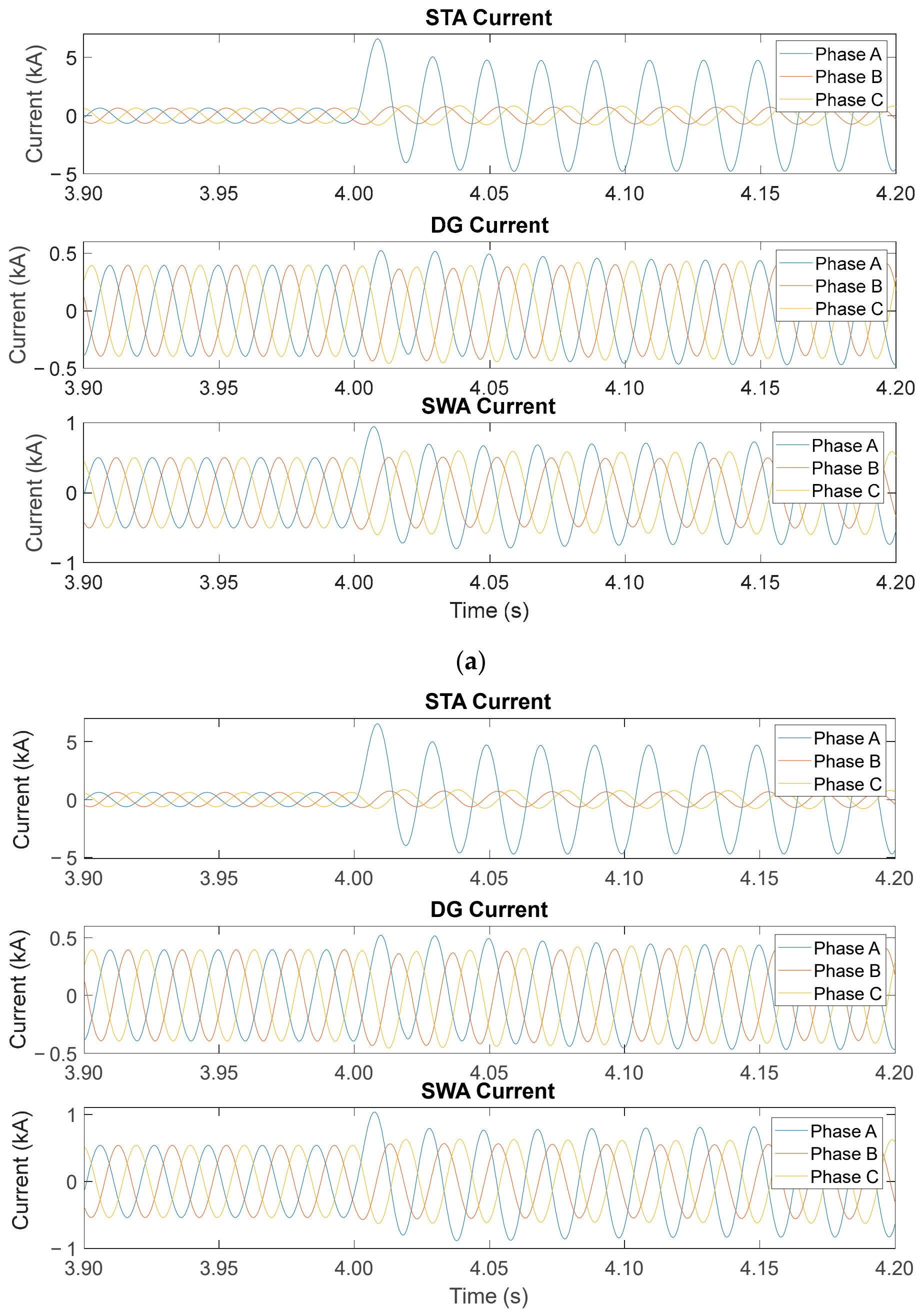


(**b**)

Figure 18. Current waveform in the normal condition. (**a**) The 2/3 placement from the SWA substation. (**b**) The 1/3 placement along the distribution line.

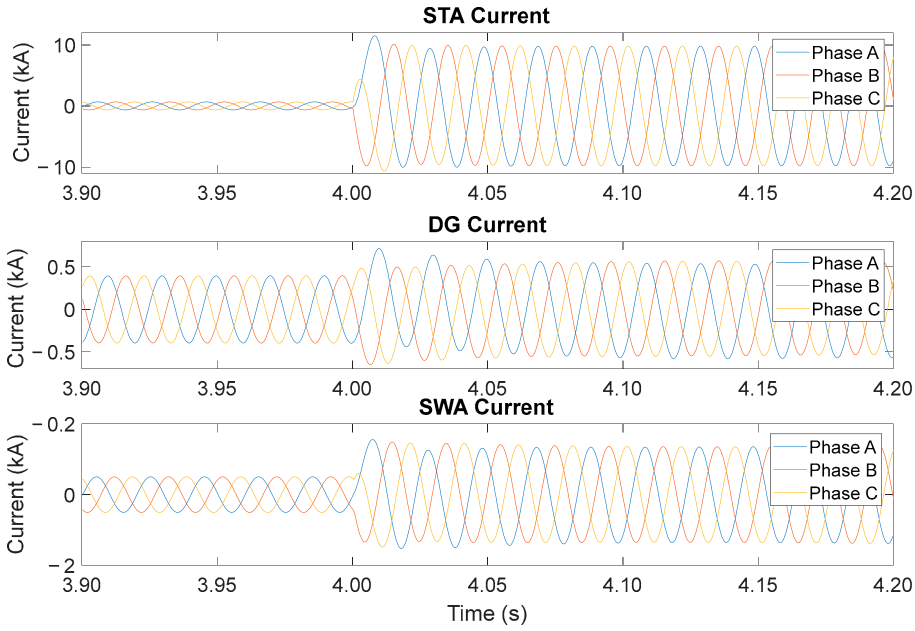
Figure 18 shows that, under normal conditions, the current level is slightly changed by DG installation. The current from the substation near the DG system was slightly reduced, whereas the load current near the DG system was slightly increased. When a single line-to-ground fault occurred at L1 (5.5 km), the fault current during the transient state at both the substations and the DG system in the case of the 1/3 placement along the distribution line was higher than in the case of the 2/3 placement from the SWA substation, as shown in Figure 19. By considering the current RMS value during fault occurrence, as presented in Tables 14 and 15, we found that the current level in the case of the 1/3 placement was slightly higher than that in the case of the 2/3 placement from the SWA substation between loads 1 and 4, whereas the current level in the case of the 2/3 placement from the SWA substation between loads 5 and 9 was slightly higher than that in the case of the 1/3 placement. This is attributed to the effect of the DG position on the current level of each load when the unit located near the load can provide a current to the load during fault conditions while limiting the current flow from the substation. To verify this assumption, a three-phase fault was simulated, as shown in Figure 20. The obtained current waveform displayed characteristics similar to those of a single line-to-ground fault. However, the current level was significantly higher owing to the severity of the three-phase fault.



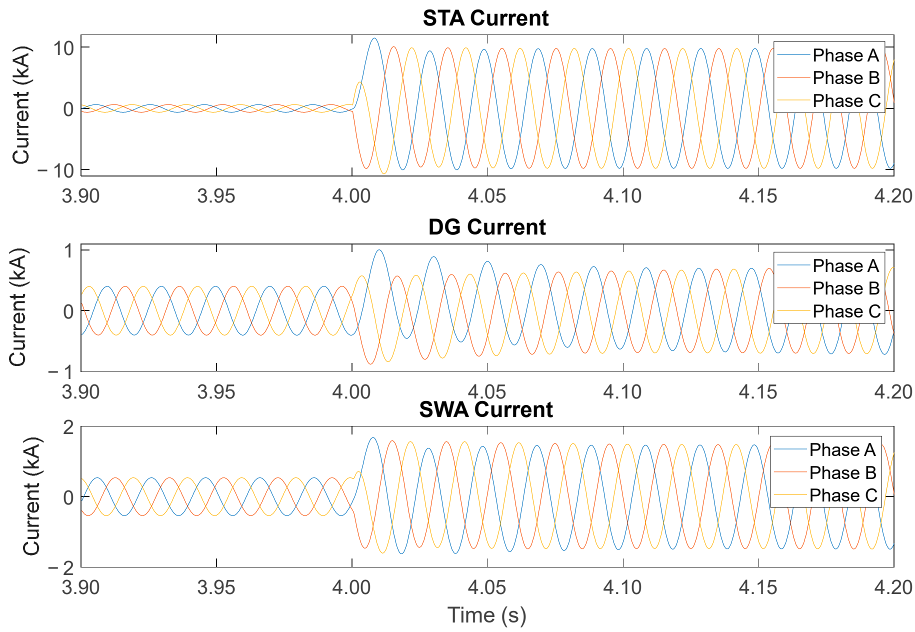
(**a**)

(**b**)

Figure 19. Current waveform in the case where the single-line-to-ground fault occurs at 5.5 km from the STA substation. (**a**) The 2/3 placement from the SWA substation. (**b**) The 1/3 placement along the distribution line.



(**a**)



(**b**)

Figure 20. Current waveform in the case where the three-phase fault occurs at 5.5 km from the STA substation. (**a**) The 2/3 placement from the SWA substation. (**b**) The 1/3 placement along the distribution line.

In the case of the 2/3 placement from the SWA substation (Table 14), when the fault location differed from the STA substation to the SWA substation, the results showed that the current level on each load on the STA substation side increased as the location of the fault moved further away, from L1 to L6, whereas the current level at the STA substation significantly decreased as the current flowed from SWA substation to the fault location. However, opposite trends were observed as the current on each load on the SWA substation side decreased, whereas the current level at the SWA substation was significantly increased because the current flowed to the fault location instead of the load.

Table 14. Current characteristics at various fault locations with the 3 MW DG system at the 2/3 placement from the SWA substation.

Fault Locations (Measured from STA Substation)	Fault Types	Load Locations (kA)										
		STA (S1)	**Load No. 1**	**Load No. 2**	**Load No. 3**	**Load No. 4**	**Load No. 5**	**Load No. 6**	**Load No. 7**	**Load No. 8**	**Load No. 9**	**SWA (S2)**
3 MW (Normal condition)		0.468	0.036	0.189	0.101	0.238	0.119	0.040	0.098	0.123	0.008	0.363
L1, or	1Φ	3.368	3.859	0.048	0.038	0.114	0.066	0.028	0.078	0.104	0.007	0.521
5.5 km	3Φ	6.914	7.929	0.040	0.028	0.088	0.053	0.025	0.072	0.098	0.007	0.988
L2, or	1Φ	1.987	0.019	2.613	0.027	0.083	0.052	0.025	0.072	0.099	0.007	0.598
10 km	3Φ	3.812	0.017	5.016	0.023	0.065	0.043	0.023	0.068	0.094	0.007	1.096
L3, or	1Φ	1.234	0.026	0.092	0.032	2.100	0.031	0.017	0.058	0.086	0.006	0.755
17.5 km	3Φ	2.215	0.026	0.087	0.032	3.824	0.034	0.016	0.056	0.083	0.006	1.425
L4, or	1Φ	1.012	0.028	0.115	0.040	0.065	0.041	0.012	0.047	0.076	0.006	0.916
21.5 km	3Φ	1.842	0.027	0.106	0.035	0.048	0.036	0.010	0.044	0.072	0.006	1.775
L5, or	1Φ	0.716	0.032	0.150	0.069	0.141	0.061	0.012	0.026	0.054	0.004	1.867
33.5 km	3Φ	1.264	0.031	0.138	0.061	0.119	0.050	0.010	0.027	0.046	0.004	3.813
L6, or	1Φ	0.650	0.033	0.157	0.075	0.159	0.071	0.017	0.029	0.031	3.815	3.255
37.5 km	3Φ	1.135	0.031	0.146	0.067	0.139	0.062	0.015	0.025	0.031	8.039	6.906

Table 15. Current characteristics at various fault locations with the 3 MW DG system at the 1/3 placement from the SWA substation.

Fault Locations (Measured from STA Substation)	Fault Types	Load Locations (kA)										
		STA (S1)	**Load No. 1**	**Load No. 2**	**Load No. 3**	**Load No. 4**	**Load No. 5**	**Load No. 6**	**Load No. 7**	**Load No. 8**	**Load No. 9**	**SWA (S2)**
3 MW (Normal condition)		0.468	0.036	0.189	0.101	0.238	0.119	0.040	0.098	0.123	0.008	0.363
L1, or	1Φ	3.368	3.859	0.048	0.038	0.114	0.066	0.028	0.078	0.104	0.007	0.521
5.5 km	3Φ	6.914	7.929	0.040	0.028	0.088	0.053	0.025	0.072	0.098	0.007	0.988
L2, or	1Φ	1.987	0.019	2.613	0.027	0.083	0.052	0.025	0.072	0.099	0.007	0.598
10 km	3Φ	3.812	0.017	5.016	0.023	0.065	0.043	0.023	0.068	0.094	0.007	1.096
L3, or	1Φ	1.234	0.026	0.092	0.032	2.100	0.031	0.017	0.058	0.086	0.006	0.755
17.5 km	3Φ	2.215	0.026	0.087	0.032	3.824	0.034	0.016	0.056	0.083	0.006	1.425
L4, or	1Φ	1.012	0.028	0.115	0.040	0.065	0.041	0.012	0.047	0.076	0.006	0.916
21.5 km	3Φ	1.842	0.027	0.106	0.035	0.048	0.036	0.010	0.044	0.072	0.006	1.775
L5, or	1Φ	0.716	0.032	0.150	0.069	0.141	0.061	0.012	0.026	0.054	0.004	1.867
33.5 km	3Φ	1.264	0.031	0.138	0.061	0.119	0.050	0.010	0.027	0.046	0.004	3.813
L6, or	1Φ	0.650	0.033	0.157	0.075	0.159	0.071	0.017	0.029	0.031	3.815	3.255
37.5 km	3Φ	1.135	0.031	0.146	0.067	0.139	0.062	0.015	0.025	0.031	8.039	6.906

In the case of 1/3 placement along the distribution line (Table 15), a similar trend was observed in the current characteristics, wherein the current level on each load increased and that on the STA substation significantly decreased as the fault location moved away, from L1 to L6. However, compared with that observed in the case of the 2/3 placement, a slight difference in the current level was noted in the case of the 1/3 placement owing to the location of the DG system. In the 1/3 case, the DG was located on the substation side of the STA. Thus, the current from the DG flowed to the fault location instead of flowing from the substation and the load resulted in a slight decrease in the STA substation current and an increase in the current load. However, in the case of the 2/3 placement from the SWA substation, the DG system was located at the other end of the distribution line near the SWA substation. Therefore, the current flowed from the DG to the fault location when the fault location moved near the SWA substation, resulting in a reduction in the substation current.

The results from the simulated three-phase fault for both the 1/3 placement along the distribution line and the 2/3 placement between the SWA substation and the critical load showed similar trends to the single-line-to-ground fault, with significantly higher current levels resulting from the severity of the three-phase fault. In summary, the different placement locations of similar-capacity DG systems on the distribution line have a limited impact on the current level obtained from both the load and substation buses. Thus, although the presence of DG can alter the current characteristics, the placement location does not have a significant impact on the current level.

6. Conclusions

In this study, we proposed a method to improve the voltage drop issue on the distribution line by placing the DG system at various positions along the distribution line, from both the STA and SWA substations to the critical load. The distribution system of Thailand, which is a part of the PEA, was selected as a case study, and the PEA standard [33] was used as a reference. Furthermore, a study on fault occurrence was conducted to evaluate its effect on the current characteristics of the distribution system under both normal and fault conditions. The simulation results demonstrated that DG placement along the distribution line can improve the voltage level at all loads. When a DG with a capacity of 3 MV is considered, 1/3 DG placement along the distribution line and 2/3 DG placement between the SWA substation and the critical load were found to increase the voltage level to the PEA standard. However, in cases of other DG positions, the voltage level can be improved to the PEA standard level by increasing the DG capacity. Based on these results, the three factors that affect voltage level improvement were found to be the load density, DG placement location, and DG capacity. Therefore, the voltage level can be improved by installing a DG with a minimal capacity near the critical load.

Regarding the effect of fault conditions on the system current characteristics, single-line-to-ground and three-phase faults, which are the most commonly occurring and severe faults, were selected. The fault location varied along the distribution line. The simulation results showed that DG placement in the distribution system can affect the current level at both the substation and load by providing current to the fault location instead of the substation, and the current level from the substation can be decreased. By providing current to the load when the fault location was farther away, DG increased the current level on the load bus. This can affect conventional protection systems, which rely on setting the current level, leading to maloperation. However, the reliability of the distribution system with DG can be improved due to the presence of another generator in case an interruption occurs. Thus, DG can also be part of a system that provides reliability and stability to the network.

The DG placement in distribution systems can provide benefits in terms of voltage improvement with high load densities. To achieve the desired improvement level, an optimal DG capacity and placement location must be selected to obtain the full benefit. In addition, the alteration of current characteristics in the presence of DG must be considered to operate distribution systems efficiently and reliably. However, the economic perspective is an important point to consider in order to determine the feasibility of using DG as a voltage improvement technique compared to another methodologies. In future studies, the application of multiple DGs for voltage improvement and various types of loads on distribution systems, such as electric charging stations, will be considered in a simulation environment to evaluate the performance under a complex load pattern. In addition, the laboratory level distribution line and simulator may be used to verify signals from real-world scenarios with an evaluation of economic feasibility for implementation in actual distribution grids.

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References

1. Khator, S.K.; Leung, L.C. Power distribution planning: A review of models and issues. *IEEE Trans. Power Syst.* **1997**, *12*, 1151–1159. [CrossRef]
2. *IEEE Std 141-1993*; IEEE Recommended Practice for Electric Power Distribution for Industrial Plants. IEEE: New York, NY, USA, 1994.
3. Osahenvemwen, O.A.; Omorogiuwa, O. Parametric Modeling of Voltage Drop in Power Distribution Networks. *Int. J. Tech. Res. Appl.* **2015**, *3*, 356–359.
4. Hasan, K.N.; Muttaqi, K.M.; Borboa, P.; Scira, J.; Zhang, Z.; Leishman, M. Distribution network voltage analysis with data-driven electric vehicle load profiles. *Sustain. Energy Grids Netw.* **2023**, *36*, 101216. [CrossRef]
5. Nunoo, S.; Attachie, J.C.; Duah, F.N. An Investigation into the Causes and Effects of Voltage Drops on an 11 kV Feeder. *Can. J. Electr. Electron. Eng.* **2012**, *3*, 40–47.
6. Priyank, S.; Rabab, H.; Vineet, J.N.; Venkatesh, V.; Anuradha, M.A.; Anurag, K.S. Voltage regulation in distribution grids A survey. *Annu. Rev. Control* **2023**, *55*, 165–181.
7. AlAhmad, O.; AlDahmi, M. Voltage Profile Improvement Analysis of 11 kV Feeders Using Capacitor Banks. In Proceedings of the 2021 International Conference on Electrotechnical Complexes and Systems (ICOECS), Ufa, Russia, 16–18 November 2021; pp. 83–87.
8. Hakim, M.F.; Saputra, M.; Ananto, R.A.; Harijanto, P.S.; Santoso, A.H. Voltage Improvement on the Feeder Using the Load Breaking Method. *Int. J. Electr. Eng. Appl. Sci.* **2023**, *6*, 1–7.
9. Mehigan, L.; Deane, J.P.; Gallachóir, B.P.Ó.; Bertsch, V. A review of the role of distributed generation (DG) in future electricity systems. *Energy* **2018**, *163*, 822–836. [CrossRef]
10. Razmjoo; Gakenia, K.L.; Vaziri, R.M.A.; Marzband, M.; Davarpanah, A.; Denai, M.A. Technical analysis investigating energy sustainability utilizing reliable renewable energy sources to reduce CO_2 emissions in a high potential area. *Renew. Energy* **2021**, *164*, 46–57. [CrossRef]
11. Ministry of Energy. *Alternative Energy Development Plan 2018–2037 (AEDP 2018)*; Ministry of Energy: Bangkok, Thailand, 2020.
12. Ministry of Energy. *Power Development Plan (PDP 2018 Revision 1)*; Ministry of Energy: Bangkok, Thailand, 2019.
13. Chu, D.I.; Samuel, G.; Emmanuel, T.; Eric, E. Distributed Generation and Renewable Energy Integration into the Grid Prerequisites, Push Factors, Practical Options, Issues and Merits. *Energies* **2021**, *14*, 5375. [CrossRef]
14. Song, Y.; Zheng, Y.; Liu, T.; Lei, S.; Hill, D.J. A New Formulation of Distribution Network Reconfiguration for Reducing the Voltage Volatility Induced by Distributed Generation. *IEEE Trans. Power Syst.* **2020**, *35*, 496–507. [CrossRef]
15. Bajaj, M.; Singh, A.K.; Alowaidi, M.; Sharma, N.K.; Sharma, S.K.; Mishra, S. Power Quality Assessment of Distorted Distribution Networks Incorporating Renewable Distributed Generation Systems Based on the Analytic Hierarchy Process. *IEEE Access* **2020**, *8*, 145713–145737. [CrossRef]
16. Robi, K.; Ardiansyah, N.; Arnawan, H.; Muzamir, I.; Muskan, G.; Shrikant, V.B. The Effect of Distributed Generator Injection with Different Number of Unit Power Quality in the Electric Power System. *J. Renew. Energy Electr. Comput. Eng.* **2021**, *1*, 71–78.
17. Mohammad-Ali, H.; Farzaneh, B. Optimal planning of distributed generation and battery energy storage systems simultaneously in distribution networks for loss reduction and reliability improvement. *J. Energy Storage* **2022**, *46*, 101216.
18. Chiradeja, P.; Ngaopitakkul, A. The impacts of electrical power losses due to distributed generation integration to distribution system. In Proceedings of the 2013 International Conference on Electrical Machines and Systems (ICEMS), Busan, Republic of Korea, 26–29 October 2013; pp. 1330–1333.
19. Niazi, Y.; Golshan, M.E.H.; Alhelou, H.H. Combined Firm and Renewable Distributed Generation and Reactive Power Planning. *IEEE Access* **2021**, *9*, 133735–133745. [CrossRef]
20. Aguila, T.; Lopez, G.; Isaac, I.; Gonzalez, J.W. Optimal reactive power compensation in electrical distribution systems with distributed resources. *Heliyon* **2018**, *4*, e00746. [CrossRef]
21. Chiradeja, P.; Ngaopitakkul, A. The impact of capacity and location of multidistributed generator integrated in the distribution system on electrical line losses, reliability, and interruption cost. *Environ. Prog. Sustain. Energy* **2015**, *34*, 1763–1773. [CrossRef]
22. Prakash, R.; Lokeshgupta, B.; Sivasubramani, S.; Kobaku, T.; Agarwal, V. Optimal DG Planning Incorporating Energy Management for an Economical and Resilient Smart Distribution System. *IEEE Trans. Ind. Appl.* **2024**, *60*, 1890–1901. [CrossRef]
23. Karngala, K.; Singh, C. Reliability Assessment Framework for the Distribution System Including Distributed Energy Resources. *IEEE Trans. Sustain. Energy* **2021**, *12*, 1539–1548. [CrossRef]

24. Muqthiar, S.; Padma, L.M.; Visali, N. Enhancement of Voltage Profile in the Distribution system by Reconfiguring with DG placement using Equilibrium Optimizer. *Alex. Eng. J.* **2022**, *61*, 4081–4093.
25. Hasibuan; Dani, F.; Asran; Nrartha, I.M.A. Simulation and Analysis of Distributed Generation Installation on a 20 kV Distribution System Using ETAP 19.0. *Bull. Comput. Sci. Electr. Eng.* **2022**, *3*, 18–29.
26. Yousaf, M.; Muttaqi, K.M.; Sutanto, D. An Investigative Analysis of the Protection Performance of Unbalanced Distribution Networks with Higher Concentration of Distributed Energy Resources. *IEEE Trans. Ind. Appl.* **2022**, *58*, 1771–1782. [CrossRef]
27. Ngamroo; Kotesakha, W.; Yoomak, S.; Ngaopitakkul, A. Characteristic Evaluation of Wind Power Distributed Generation Sizing in Distribution System. *Sustainability* **2023**, *15*, 5581. [CrossRef]
28. Hongchun, S.; Yaqi, D.; Pulin, C.; Tingyi, D.J.H.; Guangxue, W. A novel fault location scheme for transmission lines connected to wind farm based on variational iteration method. *IET Gener. Transm. Distrib.* **2022**, *16*, 3748–3759.
29. Patcharoen, T.; Ngaopitakkul, A. Fault classifications in distribution systems consisting of wind power as distributed generation using discrete wavelet transforms. *Sustainability* **2019**, *11*, 7209. [CrossRef]
30. Lim, S.-H.; Park, M.-K. Analysis on Protection Coordination of OCRs Using Voltage Components for the Application of SFCL in a Power Distribution System with DG. *IEEE Trans. Appl. Supercond.* **2021**, *31*, 5602106. [CrossRef]
31. Jin, W.; Zhang, S.; Li, J.; Feng, M.; Feng, S.; Lu, Y. A Novel Differential Protection Scheme for Distribution Lines under Weak Synchronization Conditions Considering DG Characteristics. *IEEE Access* **2023**, *11*, 86561–86574. [CrossRef]
32. Surakit, T.; Atthapol, N.; Wikorn, K.; Monthon, L.; Chaichan, P.; Suntiti, Y. An approach for voltage drop improvement in 22 kV PEA distribution system based on high voltage capacitor placement. *Energy Rep.* **2023**, *9*, 48–54.
33. Manual Book: "Control and Operation of the Power Distribution Procedure for the Power Distribution Commander Center of Thailand". PEA Command Center, May 2016.