Building a Friendly Environment for Renewable Energy Resources by Upgrading Primary Feeders from Normally Closed Loop to Mesh Arrangement

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Abstract- In this paper, the upgrades and expansions of primary feeders from normally closed loop to a mesh arrangement have been explored for building a friendly environment for renewable energy resources. First of all, the effects of the interconnection of distributed renewable energy resources (DER) on a meshed distribution network under normal and abnormal operation conditions were investigated. Then, the feasible connection schemes for addition of new feeders and the degree of improvement of voltage deviations along feeders under various operation conditions were analyzed and compared, followed by a concise discussion and conclusion. The research results are of value for building a friendly environment for DER to reduce CO_2 emissions and lessen power transmission and distribution losses.

Keywords- Distributed renewable energy resources (DER), primary feeder, normally closed loop, mesh arrangement, voltage deviations.

1. Introduction

In 1992, the first United Nations framework convention on climate change was adopted in New York. Following on from the Kyoto protocol in Japan in 1998 and the Durban conference in South Africa 2011, the energy crisis and greenhouse gas emissions have gained increased concern worldwide. Many energy policies and research and development projects focused on energy-saving and clean energy have been undertaken in recent years. In order to reduce energy losses, some studies have proposed the installation of energy storage system (ESSs) in distribution system [1, 2]. The ESS should be built near the load center to regulate the peak-loading demand and it would need to be rechargeable by wind turbines during off-peak periods. Due to this storage capacity, customer's demands can be easily met in an economical way at any time; moreover, peak loadings can be smoothly moved from the peak loading period to the off-peak loading period. And, line loss and voltage deviation can be greatly improved by application of the ESS as well [2].

On the other hand, the desire to reduce greenhouse gases has led to growing interest worldwide in increasing the penetration of renewable energy generation in the distribution system [3-6]. In Europe, the major part of the increasing number of DER will probably be wind powered. Wind energy is a type of clean energy, produces no air pollution, and therefore has rapidly become the most competitive energy resource among the renewable energy resources. As outlined in GWEC's Global Wind Report 2012 [3, 4], the GWEO Moderate scenario foresees that global wind energy capacity could reach more than 1,600 GW by the end of 2030. Wind power could produce about 4,300 TeraWatts hour (TWh) of electricity per year, which will supply 14.1-15.8% of global electricity demand by 2030. On the basis of the current electricity distribution, the average number to characterize the savings generated by wind power is 600 g CO_2/kWh. Wind power may eliminate as much as 4 billion tonnes of CO_2 per year by 2030.

With the large number of DER installed in the power networks, advantages such as the reduction of distribution network power loss and capacity release of transmission system, and improved system continuity and reliability can usually be obtained. However, operating DER in parallel with the power grid will alter the traditional system characteristic operating rules of the latter and poses new issues regarding power quality and safety. For a system with high penetration of DER, the system issues may include voltage variation, protection, loss, system restoration, and many others as summarized in [7, 8]. To regulate the connection of large-scale wind farms to utility systems, a grid interconnection code was proposed in [9]. Technical requirements such as active and reactive power regulation, wind farm behavior as grid disturbance, and operating limitation on voltage and frequency were involved.

As of now, many studies have investigated the allocation of DER corresponding to the specified local constraints and grid interconnection standards and codes [10, 11]. For solving the distribution system planning problems by implementing DER, some optimal models and algorithms have been presented in [11-16]. Using cost-benefit analysis, a new heuristic approach for optimal sizing and siting decisions for DER capacity were presented in [17]. In [18], an optimal method based on the mixed integer non-linear programming (MINLP) approach was used to find suitable locations and number of distributed renewable energy resources in a hybrid electricity market. In this article, real power price and real power loss sensitivity index are used to search for the better location for DER, and multiple objective functions which consist of the minimization of cost for conventional generation plants and distributed renewable energy resources and transmission line loss were applied. In [19], the continuous power flow calculation combined with the sensitivity analysis of bus voltage was presented.

This paper differs from the above studies mostly in research object. Much of the research above focused on the discussion of the planning, design, and operation of DER under a distribution system of conventional architecture, but the main object of this paper is to build a DER-friendly environment for installation of DER. In this way, the enhanced penetration of DER can not only reduce the CO_2 emission but also lessen losses in energy transmission. This paper is organized as follows. Section 2 introduces the scheme of a meshed distribution feeder and wind resources; Section 3 presents the interconnection rules for DER and the determination of maximum permissible DER capacity; In Section 4, the effects of DER interconnection on steady-state voltage deviation are investigated. In Section 5, a conclusion is drawn.

2. Meshed Distribution Network and Wind Energy Resource

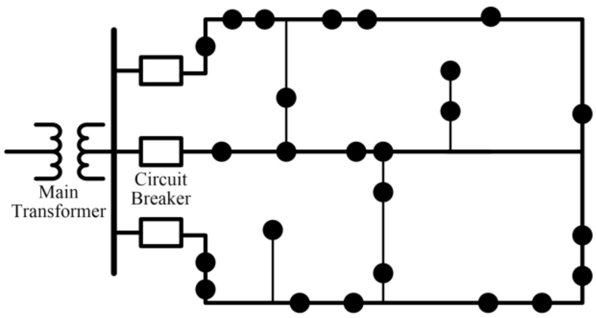

Fig. 1. Schematic diagram of a meshed distribution system

2.1. Meshed Distribution Network

A meshed distribution feeder arrangement provides more reliable and flexible service to its customers than does a radial feeder arrangement or closed loops whether loops are normally closed or opened. The schematic diagram of a meshed distribution network is shown in Fig. 1.

2.2. Wind Resources

Wind power is plentiful, renewable, widely distributed, clean, produces no greenhouse gas emissions during operation, and therefore has rapidly become the most competitive energy resource among the sustainable energy resources. Wind power generation may also lead to great social and economic benefits. With fixed profits, it is insensitive to many economic fluctuations. In order to investigate the overall economic benefits of wind power generation, the overall cost of electricity generation needs to be considered. Hence, the lifetimes, capital investment, maintenance, and operation costs of wind turbines should all be taken into consideration. Moreover, the average wind speed at wind farms is the key factor in siting and developing a wind power plant.

Besides wind velocity (m/s) and wind power density (W/m^2), the capacity factor (C.F.) is a key index to assess the performance of wind turbines. The capacity factor of a power plant is defined as the ratio of the net electricity generated, for the time considered, to the energy that could have been generated at continuous full-power operation during the same period, shown as (1).

Table 1. Estimated average full load hours and estimated average capacity factor for various countries

Country	Estimated Average Full Load Hours (h)	Estimated Average Capacity Factor (%)
United Kingdom	2,880	33
Taiwan	2,630	30
Denmark	2,250	26
P.R. China	2,100	24
USA	2,000	23
Germany	1,880	21
India	1,800	20

$$\text{C. F.} = \frac{\text{net electricity generated over a designated period of time T}}{\text{plant rating} \times \text{T}} \quad (1)$$

In general, the C.F. of a wind power plant depends on its external geographical conditions. According to the 2004 BTM Consult Report, the potential for wind power in Taiwan is ranked as second place in the world, shown as Table 1[20].

3. Interconnection Rules for DER and Determination of Maximum Permissible DER Capacity

3.1. Interconnection Rules for DER

Conventionally, utility electric power systems were not designed to accommodate active power generation at the distribution level. Thus, there are many concerns and obstacles to integrating distributed renewable energy resources with a distribution grid. A lot of rules or standards for interconnecting distributed renewable energy resources with an electric power network have been made. In general, they specify requirements relevant to performance, operation, testing, and safety considerations, and maintenance of distributed renewable energy resources as well. They include general requirements, response to power quality of grid, islanding, and many others. The key requirements of interest for interconnection codes for distributed renewable energy resources in Taiwan are outlined as follows.

1) The voltage deviation at the point of common coupling (PCC) should not be more than ±2.5% due to parallel operation of distributed renewable energy resources.
2) The voltage profile along a distribution feeder should be kept within ±5% of nominal voltage.
3) The wind power generators connected to high-voltage networks (> 600 V) should be equipped with the function of low voltage ride through (LVRT).

3.2. Determination of Maximum Permissible DER Capacity

For the most part, (2) and (3) are used to assess steady-state voltage deviations due to DER interconnections with distribution networks.

$$d\% = \frac{R \cdot P_\phi + X \cdot Q_\phi}{\left|V_{DER(w/o)}\right|^2} \times 100\% \quad (2)$$

where $d\%$ denotes the steady-state voltage deviation as a percentage of the nominal voltage; $V_{DER(w/o)}$ is the nominal line-to-line voltage (in kV) without DER output; R and X represent the equivalent resistance and inductive reactance at the DER-connected point respectively (in Ohms); P_ϕ and Q_ϕ stand for the maximum active and reactive power produced by DER (in MW and Mvar) respectively.

$$d\% = \frac{S_{DER}}{S_{S.C.}} \cos(\phi + \theta) \times 100\% \quad (3)$$

where $S_{S.C.}$ is the network short circuit capacity at the point of DER interconnection; S_{DER} stands for the rated apparent power of DER at 1-min. time interval; and ϕ and θ represent the phase angle of driving-point impedance of the grid and the phase angle between the output voltage and current of DER, respectively. The short-circuit capacity and driving-point impedance angle of the grid are the parameters that describe the strength and characteristics of the grid at the point of DER interconnection. Therefore,

$$P_{DER} = \frac{d \times S_{S.C.}}{\cos(\phi + \theta)} \times \cos\theta \quad (4)$$

where P_{DER} is the maximum permissible DER capacity at the interconnection point under the given conditions.

4. Effects of DER Interconnection on the Steady-State Voltage Deviation

In this section, the effects of the size of additional feeders on the operation of DER interconnection are investigated. Based on the normally closed-loop primary feeders, the feasible schemes for addition of new feeders for upgrading primary feeders from normally closed loop to a mesh arrangement are explored. To build a proper meshed distribution system for the interconnection of DER, the effects of the interconnection of DER on the steady-state voltage deviation and maximum permissible DER capacity should be taken into account. In this paper, all computer programs were developed using the MATLAB R2006a software package and were run on a Windows XP-based PC with AMD Athlon 64 processor 3200+.

4.1. Parameters for Sample Systems

Two distribution systems with meshed feeders, shown in Figs. 2 and 3, were adopted as sample systems to investigate the effect of additional feeders on the operation of DER interconnections. With a Type I meshed arrangement, new feeder from bus A1 to bus B3 through bus C3 is located in the vicinity of the secondary sides of substation transformers, as shown in Fig. 2. With a Type II meshed arrangement, new feeder from bus A5 to bus B7 through bus C3 is located in the vicinity of the middle of the place between two feeders, as shown in Fig. 3. The parameters of sample systems listed below are used as a basic scenario:

1) The short-circuit capacity at the primary side of the substation transformer is 7500 MVA.
2) The rated capacity and percent impedance of the substation transformer are 60 MVA and 15.78%, respectively. The rated voltage of the substation transformer is 161-22.8 kV.
3) The main feeder conductors are 25kV, 500 MCM XLPE underground cables. The lengths of Feeder A and Feeder B, and Feeder C and Feeder D are 10 km and 5 km, respectively.

4) There are 30 load tapped-off points (load points for short) in the two sample systems. The interval between two adjacent load points is 1 km. The load of each load point is 300 kVA, operated at a power factor of 0.85 lagging.

4.2. Normal Operation Conditions

In this paper, the results for the effects of the size of additional feeders on the operation of DER interconnection are obtained by modifying the corresponding system parameters of the sample system and performing a series of power flow analyses. The modified parameters of the sample systems are listed as follows:

1) The rated capacity of DER is 5 MVA. The DER are operated at power factors of 0.85 lagging, 1.0 and 0.95 leading, respectively.
2) The new additional feeder conductors are 336, 477 and 795 MCM AAC overhead lines, or 500 MCM XLPE underground cables.
3) The total load of other feeders supplied by the same substation transformer is represented as a lumped load of 16.5 MW. The power factor of this lumped load is assumed to be corrected to unity.

To mitigate the impact of the interconnection of DER on the voltage deviations along a feeder, upgrading primary feeder from normally closed loop to a mesh arrangement is a good measure. The DER are assumed to be connected to Buses A1, A5 and A10, respectively. The comparisons of the effects of the two types of meshed arrangements on the voltage deviation are shown in Fig. 4 to Fig. 6. When DER are connected in the vicinity of the secondary side of substation transformer (A1), the interconnection of DER has a slight effect on the voltage deviations due to high short-circuit capacity. In contrast, when DER are connected in the vicinity of the middles or ends of the feeder, the interconnection of DER has a significant effect on the voltage deviations due to low short-circuit capacity.

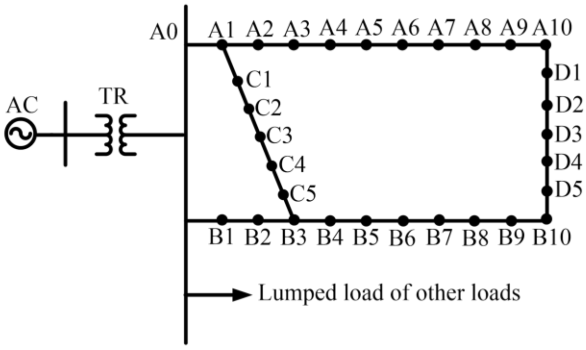

Fig. 2. Schematic diagram of a meshed distribution system (Type I).

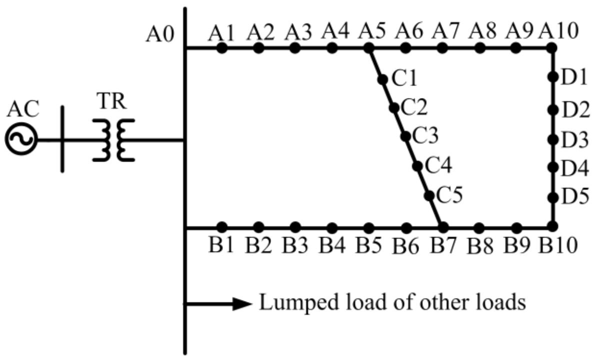

Fig. 3. Schematic diagram of a meshed distribution system (Type II).

4.3. Abnormal Operation Conditions

In this section, the effects of the interconnection of DER on the steady-state voltage deviation along feeders under abnormal operation conditions are investigated. The abnormal operation conditions denote that after a fault occurs on the sample feeder, the fault is detected and isolated by protection relays, and the system structure is reconfigured.

In general, a closed-loop arrangement may become one

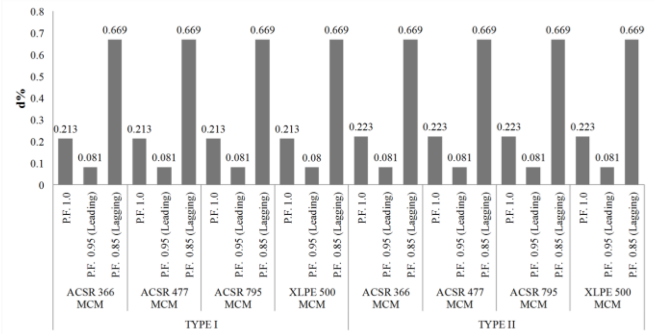

Fig. 4. Steady-state voltage deviations while DER are connected to Bus A1 under normal operation conditions.

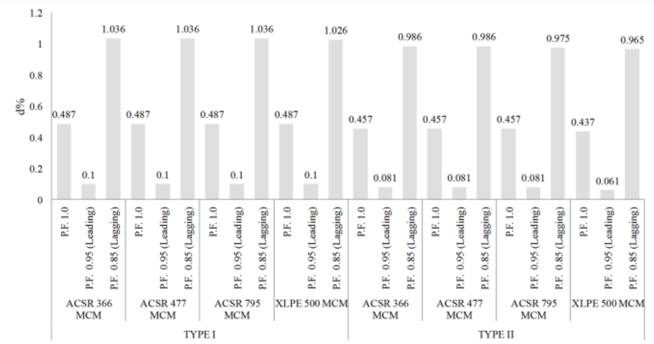

Fig. 5. Steady-state voltage deviations while DER are connected to Bus A5 under normal operation conditions.

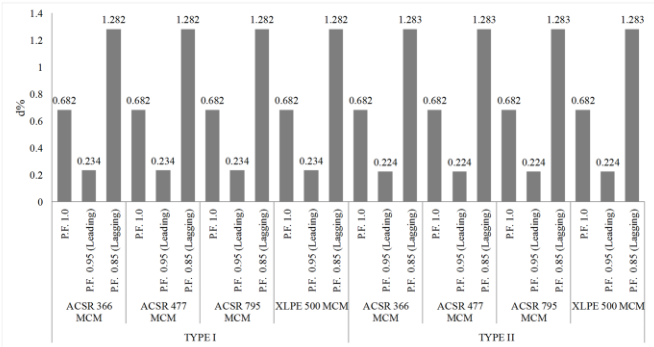

Fig. 6. Steady-state voltage deviations while DER are connected to Bus A10 under normal operation conditions.

or two radial feeders after a fault occurs. Therefore, the short-circuit capacity will reduce noticeably. In contrast, a meshed arrangement system can provide high quality and reliable service after a fault is isolated. In this section, two meshed arrangement systems, shown in Fig. 2 and Fig. 3 are adopted as sample systems to investigate the effect of additional feeders on the operation of DER interconnections under abnormal operation conditions. Type I meshed arrangement is adopted in Case #1, Case #3 and Case #5, and Type II meshed arrangement is adopted in Case #2, Case #4 and Case #6. The simulation scenarios are shown in Table 2.

Table 2. Simulation scenarios and loading conditions under abnormal operation conditions

Case No.	Fault Location	Distribution of Discrete Loads
Case #1	Between A0 and A1	1. Uniformly distributed loads. 2. The load at each load point is 250 kVA. 3. Lumped load of other feeders supplied by the same substation transformer is 16.5 MVA. 4. The utilization factor (F_u) of the substation transformer is 0.4.
Case #2	Between A5 and A6	
Case #3	Between D2 and D3	
Case #4	Between A0 and A1	
Case #5	Between A5 and A6	
Case #6	Between D2 and D3	

In the six abnormal operation conditions mentioned above, the maximum permissible DER capacities are quite different. In various abnormal operation conditions, the

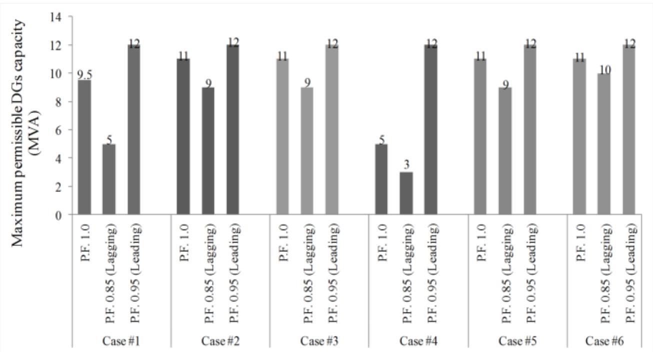

Fig. 7. Maximum permissible DER capacities at Bus A1 under abnormal operation conditions.

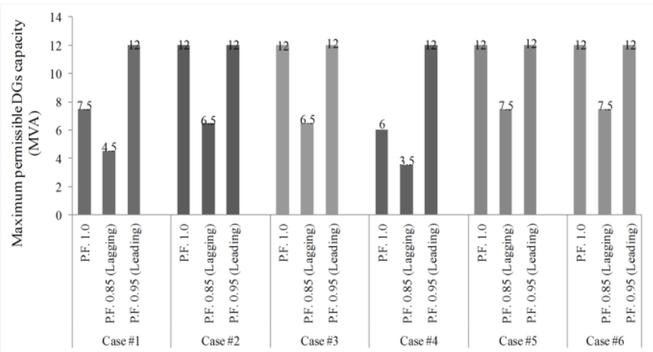

Fig. 8. Maximum permissible DER capacities at Bus A5 under abnormal operation conditions.

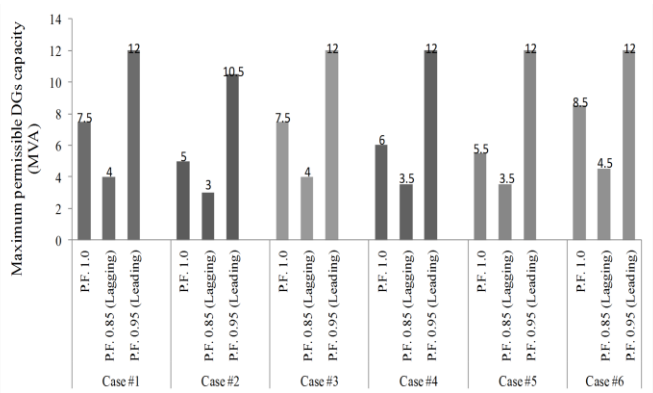

Fig. 9. Maximum permissible capacities at Bus A10 under abnormal operation conditions.

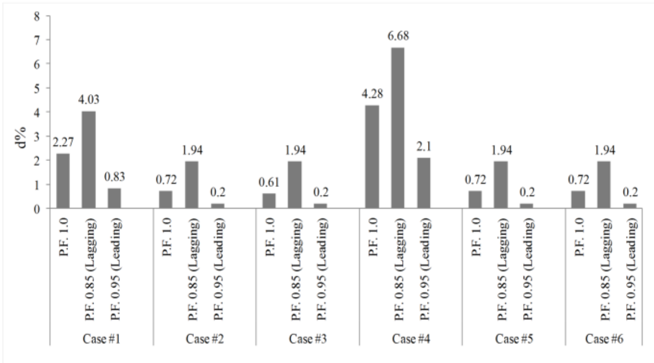

Fig. 10. Steady-state voltage deviations along the sample system while DER are connected to Bus A1 under abnormal operation conditions.

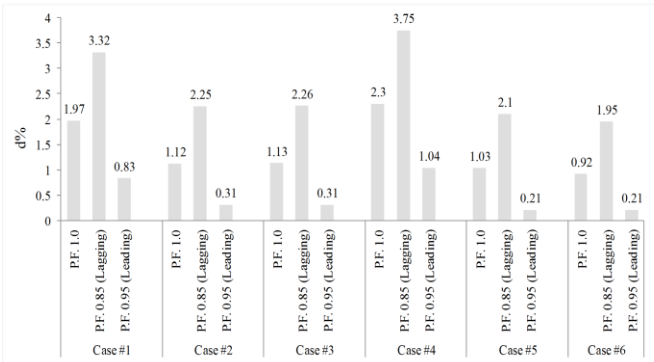

Fig. 11. Steady-state voltage deviations along the sample system while DER are connected to Bus A5 under abnormal operation conditions

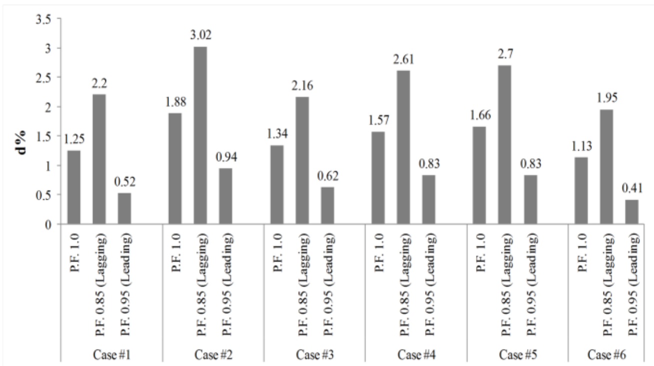

Fig. 12. Steady-state voltage deviations along the sample system while DER are connected to Bus A10 under abnormal operation conditions.

evaluation results of maximum permissible DER capacities are shown in Fig. 7 to Fig. 9, respectively. The interconnected DER operated at the power factor of 0.85 lagging may have a significant effect on the steady-state voltage deviation of the feeders to which they are connected.

The average value of maximum permissible DER capacities under abnormal operation conditions is set as a default value for each load point. The average maximum permissible DER capacities are 5.95 MW in Bus A1, 5.1 MW in Bus A5 and 3.18 MW in Bus A10. Then, using the average maximum permissible DER capacities mentioned above, the effects of the interconnection of DER on the voltage deviation under abnormal operation conditions are investigated. The analysis results are shown in Fig. 10 to Fig. 12.

The simulation results show that when DER are operated at the average maximum permissible DER capacity, the steady-state voltage deviations due to DER may be larger than the specified steady-state voltage variation limitations of ±2.5%. In the next section, some network upgrading strategies are employed to restrain the impact of the interconnection of DER on the voltage deviations.

4.4. Network Upgrading Strategies

In this section, the addition of a new feeder is used to increase the system strength and improve voltage deviations along feeders. The feasible connection schemes and the degree of improvement of voltage deviations under various operation conditions are shown in Table 3 to Table 5. As mentioned previously, the evaluation results show that the maximum voltage deviations may occur in the vicinity of the fronts of feeders when DER are operated with a lagging power factor. As shown in Table 3 to Table 5, the feasible connection schemes for the addition of new feeders can be classified as follows: (1) one tie-point is located in the vicinity of the connected point of DER and (2) another tie-point is located at the point with high short-circuit capacity. Therefore, the short-circuit capacity of the connected points of DER can be strengthened considerably. The impact of the interconnection of DER on the voltage deviations can be restrained within the specified steady-state voltage variation limitations of ±2.5%.

The analysis results are summarized as follows:

1) Whenever 336, 477 and 795 MCM AAC overhead lines, and 500 MCM XLPE underground cables are adopted as the new additional feeder conductors for upgrading primary feeders, the size of additional feeders has only a slight effect on the steady-state voltage deviations caused by the interconnection of DER.
2) The distribution of discrete loads has a small effect on the steady-state voltage deviations along the feeders caused by the interconnection of DER. In contrast, the operating power factor and interconnection location of DER have significant effects on the steady-state voltage deviations along the feeders.
3) When upgrading primary feeders from normally closed loop to a mesh arrangement, the effect of the distribution of discrete loads on the steady-state voltage deviations along the feeders can be mitigated.
4) The short-circuit capacity of meshed feeders is larger than that of normally closed-loop feeders. The effect of the interconnection of DER on the meshed feeders is smaller than that on normally closed-loop feeders.
5) In meshed feeder arrangements, the maximum permissible DER capacity is restrained by the maximum continuous operation current of feeders under normal operation conditions. That is, the maximum permissible DER capacity is not restrained by the steady-state voltage deviations due to DER.

5. Conclusion

In this paper, the effects of the interconnection of DER on a meshed distribution system were investigated. To suppress the impact of the interconnection of DER on the distribution systems, upgrading primary feeders from normally closed loop to a mesh arrangement is an effective

Table 3. Feasible connection schemes for addition of new feeders while DER are connected to Bus A1

Case No.	DER Capacity	Connection Schemes	*d*%	
			Before	After
Case #1	5.95MW (P.F.0.85lagging)	A2－B1	4.03%	2%
		A3－B1		2.5%
Case #4	5.95MW (P.F.0.85lagging)	A2－B1	6.68%	2%
		A3－B1		2.5%
	5.95MW (P.F. 1.0)	A2－(B2~B10)	4.28%	0.81%～2.5%
		A3－(B1~B8)		1.4%～2.5%
		A4－(B1~B7)		1.6%～2.5%

Table 4. Feasible connection schemes for addition of new feeders while DER are connected to Bus A5

Case No.	DER Capacity	Connection Schemes	*d*%	
			Before	After
Case #1	5.1MW (P.F. 0.85 lagging)	A4－(B1~B2)	3.32%	2.3%~2.5%
		A5－(B1~B3)		2.2%~2.5%
		A6－(B1~B2)		2.3%~2.5%
		A7－B1		2.3%
		A8－B1		2.4%
Case #4	5.1MW (P.F. 0.85 lagging)	A1－B1	3.75%	2.5%
		A2－B1		2.4%
		A3－(B1~B2)		2.3%~2.5%
		A4－(B1~B2)		2.3%~2.5%
		A5－(B1~B2)		2.2%~2.4%
		A6－B1		2.3%
		A7－(B1~B2)		2.4%
		A8－B1		2.5%

action. The advantages of the addition of new feeders include

Table 5. Feasible connection schemes for addition of new feeders while DER are connected to Bus A10

Case No.	DER Capacity	Connection Schemes	d% Before	d% After
Case #2	3.187MW (P.F.0.85 lagging)	A1—(B7~B10)	3.02%	2.5%~2.2%
		A2—(B8~B10)		2.5%~2.2%
		A3—(B8~B10)		2.5%~2.3%
		A4—(B9~B10)		2.5%~2.4%
		A5—(B9~B10)		2.5%~2.4%
		A6—(B1~B9)		1.6%~2.5%
		A7—(B1~B9)		1.6%~2.5%
		A8—(B1~B9)		1.5%~2.5%
		A9—(B1~B9)		1.4%~2.5%
		A1—(D1~D5)		1.5%~2.1%
		A2—(D1~D5)		1.6%~2.1%
		A3—(D1~D5)		1.6%~2.5%
		A4—(D1~D5)		1.6%~2.2%
		A5—(D1~D5)		1.8%~2.2%
		D1—(B1~B10)		1.5%~1.8%
		D2—(B1~B8)		1.6%~2.5%
		D3—(B1~B7)		1.9%~2.5%
		D4—(B1~B6)		2%~2.5%
		D5—(B1~B5)		2.1%~2.5%
		D1—(B1~B10)		1.5%~1.8%
		D2—(B1~B8)		1.6%~2.5%
		D3—(B1~B7)		1.9%~2.5%
		D4—(B1~B6)		2%~2.5%
		D5—(B1~B5)		2.1%~2.5%
Case #4	3.187MW (P.F. 0.85 lagging)	A1—(B1~B10)	2.61%	2%~2.4%
		A2—(B1~B8)		1.9%~2.5%
		A3—(B1~B8)		1.9%~2.5%
		A4—(B1~B7)		1.8%~2.5%
		A5—(B1~B8)		1.8%~2.5%
		A6—(B1~B8)		1.4%~2.5%
		A7—(B1~B8)		1.6%~2.5%
		A8—(B1~B10)		1.5%~2.4%
		A9—(B1~B10)		1.1%~2.4%
		A1—(D1~D4)		2.5%
		A2—(D1~D4)		2.5%
		A3—(D1~D4)		2.5%
		A4—(D1~D3)		2.5%
		A5—(D1~D4)		2.5%
		A6—D1		2.5%
		A7—(D1~D5)		2.5%
		A8—(D1~D5)		2.5%
		A9—(D2~D5)		2.5%
		D1—(B1~B9)		1.1%~2.3%
		D2—(B1~B9)		1.3%~2.3%
		D3—(B1~B9)		1.3%~2.4%
		D4—(B1~B9)		1.3%~2.4%
		D5—(B1~B9)		1.5%~2.5%
Case #5	3.187MW (P.F. 0.85 lagging)	A1—(B5~B10)	2.7%	2.5%~1.9%
		A2—(B6~B10)		2.5%~1.9%
		A3—(B7~B10)		2.5%~2.1%
		A4—(B7~B10)		2.5%~2.2%
		A5—(B8~B10)		2.5%~2.2%
		A6—(B1~B10)		1.3%~2.2%
		A7—(B1~B10)		1.3%~2.2%
		A8—(B1~B10)		1.1%~2.2%
		A9—(B1~B10)		1%~2%
		A1—(D1~D5)		1%~1.7%
		A2—(D1~D5)		1.3%~1.7%
		A3—(D1~D5)		1.3%~2%
		A4—(D1~D5)		1.4%~2%
		A5—(D1~D5)		1.4%~2%
		A6—(D4~D5)		2.5%~2.3%
		A7—(D4~D5)		2.5%~2.3%
		A8—(D2~D5)		2.4%~2.3%
		A9—(D2~D5)		2.5%~2%
		D1—(B1~B10)		1%~2.1%
		D2—(B1~B10)		1.2%~2.2%
		D3—(B1~B10)		1.8%~2.3%
		D4—(B1~B10)		1.6%~2.4%

improving the voltage profile along feeders, reducing the system power losses and maximizing the possible installed capacity of DER. The feasible connection schemes for addition of new feeders and the degree of improvement of voltage deviations along feeders under various operation conditions were analyzed and compared. The outcomes are of value to the upgrades and expansions of primary distribution systems to build a friendly environment for DER and the implementation of sustainable development of renewable energy.

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