Effects of Renewable Distributed Generation on the Operational Characteristics of Meshed Power Distribution Systems

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Abstract: - This paper analyzes the effects of renewable distributed generation on the operational characteristics of meshed power distribution systems. Meshed power distribution systems are more reliable than radial and closed-loop ones; however, their structures and operating conditions are more complex than the latter. Hence, operating these types of systems is not easy for power engineers, especially in the case of combining renewable distributed generation sources. This paper first develops the constant power model of a renewable distributed generation source, then constructs the network model of a medium-voltage meshed distribution system in the professional simulation software, Matlab/Simulink. The effects of renewable distributed generation sources on the operational characteristics of meshed distribution systems are evaluated in detail. The evaluation takes into account the generation capacity, connecting location, and operating power factor of renewable distributed generation sources. The results shown in this paper can contribute well to electrical utilities with meshed power distribution systems.

Key-Words: - Meshed power distribution system, Renewable distributed generation, Operational characteristics.

1 Introduction

Medium-voltage power distribution systems are the major electric power sources used by many customers. A power distribution system has several primary distribution feeders. The primary distribution feeders can be arranged in different ways, such as radial, closed-loop, or meshed type, as shown in Fig.1 to 3 [1-4]. Distribution feeders are arranged in different types, the system's cost and reliability are different, too. A meshed power distribution system is more reliable than radial and closed-loop ones because its distribution feeders are interconnected [5,6]. Hence, this kind of system is popular with critical customers such as hospitals, skyscrapers, and factories with sensitive facilities.

Although meshed power distribution systems are more reliable than radial and closed-loop ones, their structures are more complex. Operating these kinds of systems is not easy for power engineers. Moreover, more and more distributed generation (DG) sources using renewable energy, such as wind, solar, oxygen, and exhausted heat, combine distribution systems and operate them together [7-15]. Under this circumstance, the inherent operational characteristics of meshed power distribution systems is affected by the renewable DG sources and become more complex [16,17]. For this reason, understanding the effects of renewable DG sources on the operational characteristics of meshed power distribution systems before installing and operating a meshed power distribution system is very important for power engineers.

In this paper, the constant power model of renewable DG sources is developed first, and then the network model of a meshed power distribution system is constructed in the professional simulation software, Matlab/Simulink. The equivalent models of renewable DG sources and major elements in a meshed power distribution system are all represented with Simulink blocks. Computer simulation is performed to evaluate the effects of renewable DG sources on the operational characteristics of meshed power distribution systems. In considering the practical operating conditions of renewable DG sources, the evaluation takes into account the generation capacity, connecting location, and operating power factor of renewable DG sources. The results, including distribution feeder voltages, distribution feeder currents, short-circuit currents, and system losses, are all shown in this paper. They can be useful references for electrical utilities when renewable DG sources are included in their power distribution systems.

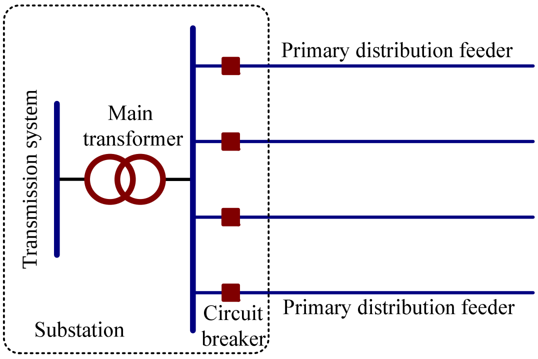

Fig.1 Distribution feeders in radial arrangement

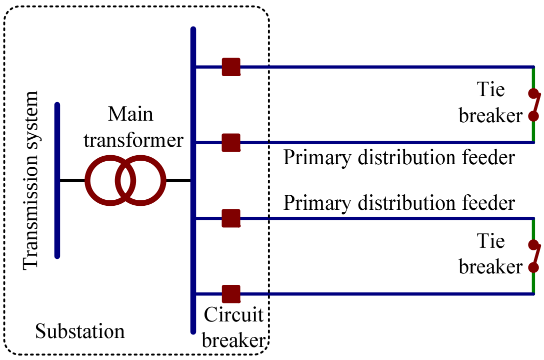

Fig.2 Distribution feeders in closed-loop arrangement

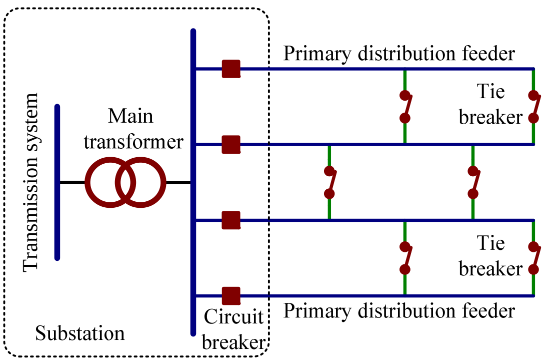

Fig.3 Distribution feeders in meshed arrangement

2 Description of the Sample System

The configuration of the sample system is shown in Fig. 4. The main transformer supplies power to three primary distribution feeders, namely, sample feeder FD_1, FD_2, and FD_3 via circuit breakers CB_1, CB_2, and CB_3, respectively. The three distribution feeders are interconnected to each other by three tie lines and three tie breakers, TB_1, TB_2, and TB_3. These tie breakers are normally closed. Hence, the sample system has a meshed configuration.

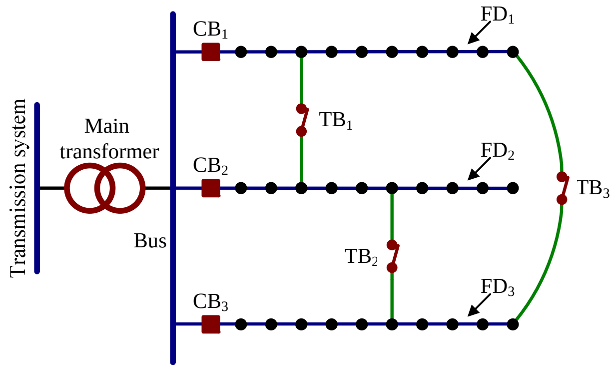

Fig.4 Configuration of the sample system

The rating of the MAIN TRANSFORMER in the sample system is set at 60 MVA, 161/22.8 kV. The short-circuit capacity on the high-voltage side of the MAIN TRANSFORMER is 7500 MVA. The distribution feeders in the sample system have the same length of 5 km and cut area of 500 MCM. The loads in each distribution feeder are all distributed equally. The total loads of the distribution feeders FD_1, FD_2, and FD_3, are 6MVA, 1MVA, and 6MVA, respectively. Each dot on these feeders represents a tapped-off load point, which includes a disconnecting switch, a distribution transformer, and a lumped load with a 0.8 lagging power factor. All dots are at intervals of 0.5 km.

The DG sources are not shown in the sample system because the number and connection locations of DG sources depend on the needs of related studies. They are addressed in the following sections.

3 Modeling of the Sample System

In constructing the network model of the sample system, the equivalent models of the elements in the sample system are first developed. The simulation tool adopted in this paper is Matlab/Simulink. Simulink offers a lot of power element models such as sources, transformers, branches, and breakers [18,19], which are suitable for this paper. Hence, only the equivalent models of DG source and load need to be developed.

Fig.5 shows the equivalent model of a DG source or a load developed by this paper. This equivalent model comprises one dynamic load block and two gain blocks of Simulink. The dynamic load block can make the equivalent model operate under constant power condition. The gain blocks can make the equivalent model provide or absorb power. If the parameters of the two gain blocks are negative, the equivalent model acts as a DG source. Inversely, if the parameters of the two gain blocks are positive, the equivalent model acts as a load.

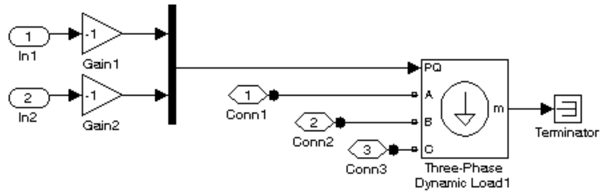

Fig.5 Equivalent model of a load/DG source

Combining the developed DG source/load models and the models offered by Simulink according to the structure of the sample system, the network model of the sample system can be constructed easily in Simulink. Fig.6 shows the schematic diagram of the equivalent model of the sample system. In this figure, the source block, transformer block, and series of RLC branch blocks represent the equivalent model of the transmission system, main transformer, and distribution feeders in the sample system, respectively. The breaker blocks represent the circuit breakers, tie breakers, and disconnecting switches.

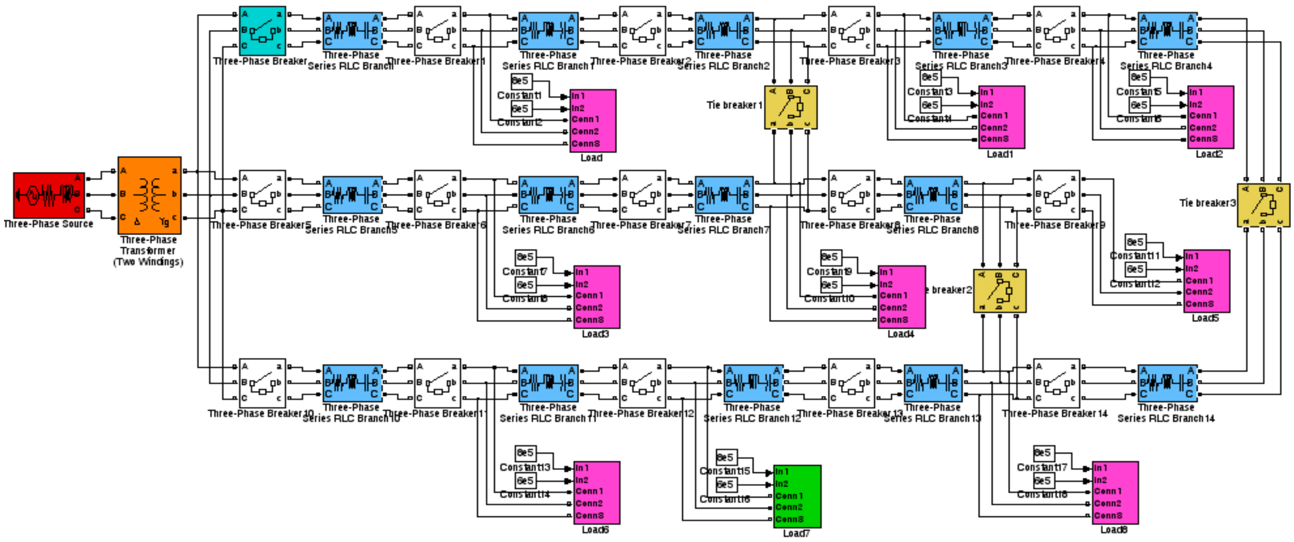

Fig.6 A part of the equivalent model of the sample system

4 Description of the Operating Rules

In Taiwan, the rules for DG interconnection in distribution systems have been established. Understanding the rules is very important in evaluating the effects of DG sources on the operation of power systems. The rules in Taiwan for the interconnection of DG sources in a distribution system are summarized as follows:

1. The voltage deviation at the point of common coupling (PCC) should not exceed ±2.5% while the DG source is interconnected to the PCC.
2. The voltage profile along a distribution feeder should be kept within ±5% of the nominal voltage.
3. The maximum current that flows in a distribution feeder should not exceed 300 A.
4. The maximum short-circuit current that flows in a distribution feeder should not exceed 10 kA.
5. The generation capacity of a DG source should not exceed 10 MVA.
6. The operating power factor of a DG source should be kept within 0.85 lagging and 0.95 leading.

5 Analysis of Simulation Results

5.1 Feeder Voltages

Fig. 7 shows the configuration of the sample system when a DG source connected with the end of the sample feeder FD_1, FD_2, or FD_3. The DG source is named the sample DG source. Its generation capacity and operating power factor were 10 MVA and 1.0, respectively. Fig.8 to 10 show the voltage profiles of the sample feeders FD_1, FD_2, and FD_3, respectively. The simulation results indicate that the interconnection of the sample DG sources made the sample feeder voltages go up. However, the sample feeder voltages did not exceed the upper limits because the sample DG sources only supplied active power to the sample system.

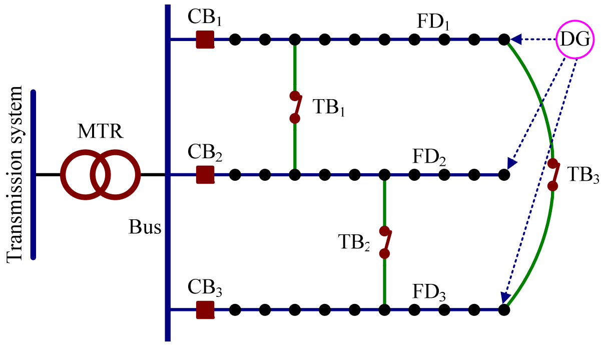

Fig. 7 Configuration of the sample system when a DG source connected with the end of the sample feeder FD_1, FD_2, or FD_3

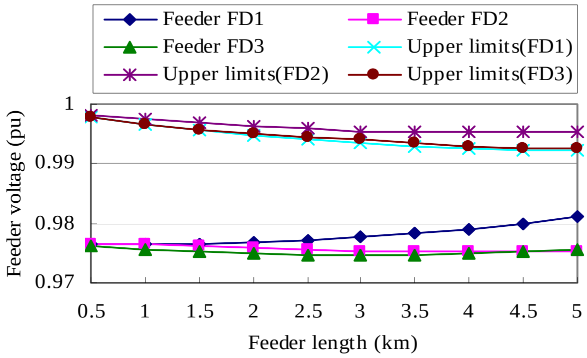

Fig.8 Voltage profiles of the sample feeders when the sample DG source connected with sample feeder FD_1 and operated with a 1.0 power factor

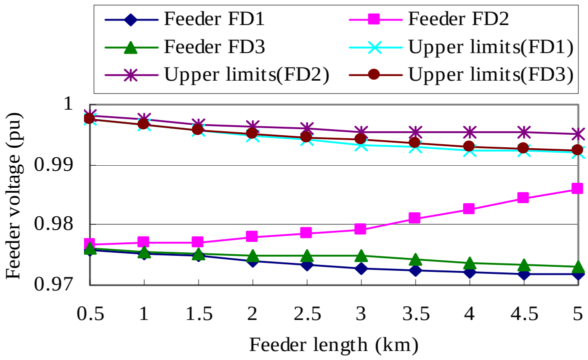

Fig.9 Voltage profiles of the sample feeders when the sample DG source connected with sample feeder FD_2 and operated with a 1.0 power factor

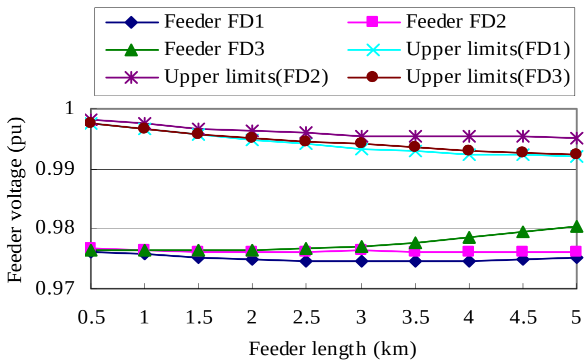

Fig.10 Voltage profiles of the sample feeders when the sample DG source connected with sample feeder FD_3 and operated with a 1.0 power factor

Fig. 11 to 13 show the voltage profiles of the sample feeders FD_1, FD_2, and FD_3, respectively, while the operating power factor of the sample DG source was 0.85 lagging.. The simulation results indicate that the interconnection of the sample DG sources not only made the sample feeder voltages go up, but also made them exceed the upper limits. This is because the sample DG source generated a lot of reactive power into the sample system.

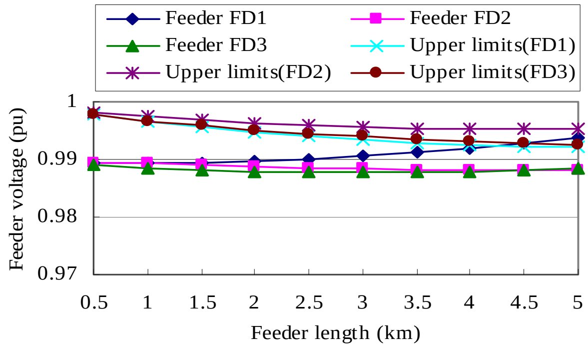

Fig.11 Voltage profiles of the sample feeders when the sample DG source connected with sample feeder FD_1 and operated with a 0.85 lagging power factor

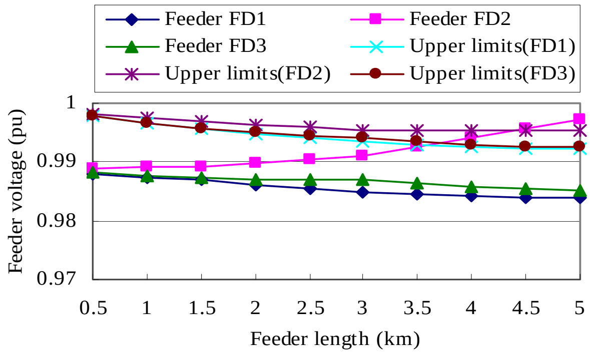

Fig.12 Voltage profiles of the sample feeders when the sample DG source connected with sample feeder FD_2 and operated with a 0.85 lagging power factor

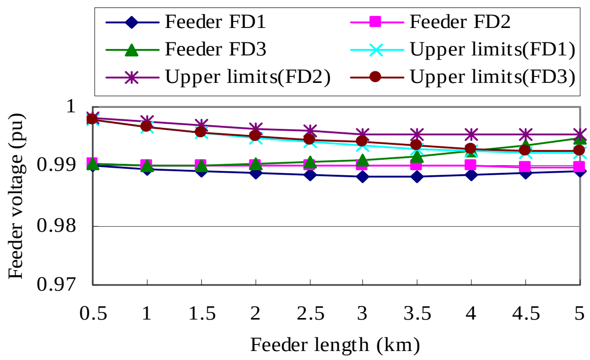

Fig.13 Voltage profiles of the sample feeders when the sample DG source connected with sample feeder FD_3 and operated with a 0.85 lagging power factor

A meshed distribution system has good robustness owing to the interconnection of distribution feeders.

The effects of DG sources on feeder voltages are usually within an allowable limit. However, the configuration of meshed distribution systems may change because of faults. When configuration changes, the system's robustness may become weak, and the effects of DG sources on feeder voltages may become serious.

Fig.14 shows the configuration of the sample system when breakers opened. Fig. 15 shows the configuration of the sample system when breakers CB_3 and TB_2 opened at the same time. The sample DG source was connected to the front of sample feeder FD_3 and had a distance of 500 m from the sample main transformer. Its generation capacity and power factor were as stated above.

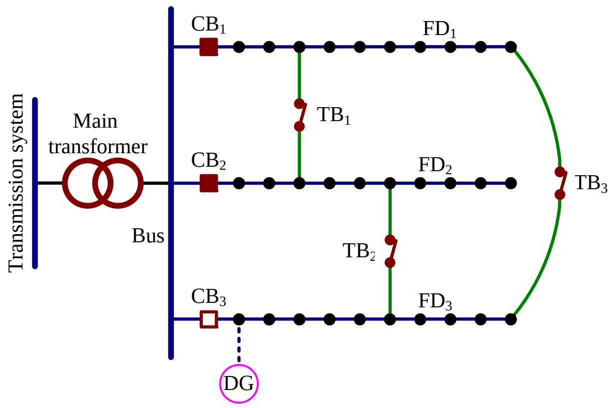

Fig.14 Configuration of the sample system when the sample DG source was connected to the front of sample feeder FD_3 and breaker CB_3 was opened

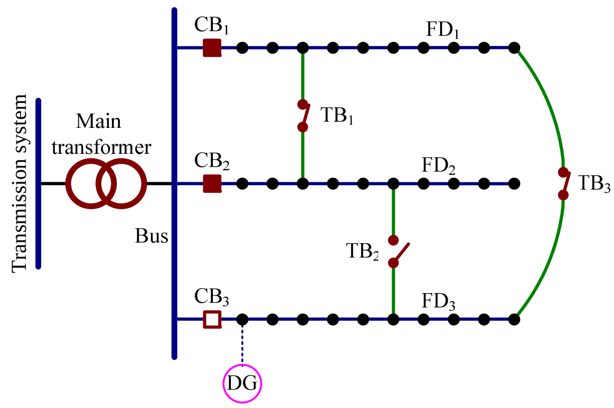

Fig.15 Configuration of the sample system when the sample DG source was connected to the front of sample feeder FD_3 and breakers CB_3 and TB_2 were opened

Fig.16 and 17 show the voltage profiles of the sample feeders when the configuration of the sample system changed. Figure 16 shows that the voltages of sample feeder FD_3 went up, but did not exceed the upper limit. In this operating condition, circuit breaker CB_3 opened because of a fault, but the tie breakers remained closed. Because only circuit breaker CB_3 opened, the sample system still retained its meshed configuration and had good robustness. Hence, the effects of the sample DG source on the sample feeder voltages were not very significant. Figure17 shows that the sample feeder voltages went up significantly and exceeded the upper limit. This was because tie breaker TB_2 opened as well during the fault. Under this circumstance, sample feeder FD_3 was interconnected with sample feeder FD_1 via tie breaker TB_1 and became a long radial feeder. Hence, the effects of the sample DG source on the sample feeder voltages became very significant.

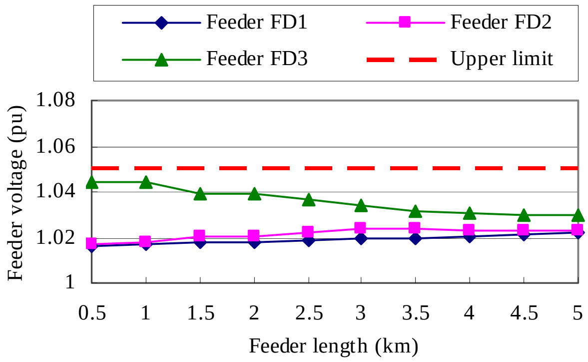

Fig.16 Voltage profiles of the sample feeders when the sample DG source was connected to the front of sample feeder FD_3 and breaker CB_3 was opened

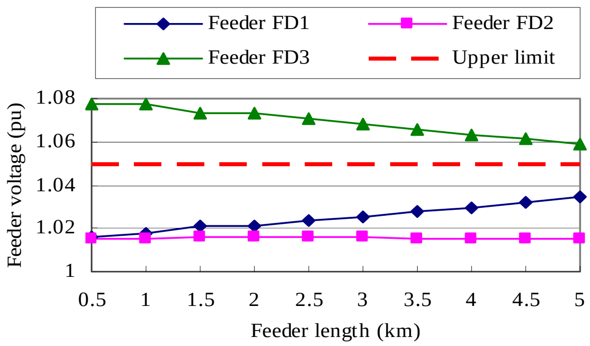

Fig.17 Voltage profiles of the sample feeders when the sample DG source was connected to the front of sample feeder FD_3 and breakers CB_3 and TB_2 were opened

5.2 Feeder Currents

Fig. 18 to 20 show the magnitude of the sample feeders' currents when the sample DG source was connected with the ends of sample feeders FD_1, FD_2, and FD_3, respectively. The generation capacity and power factor of the sample DG source were 10 MVA and 1.0, respectively. The configuration of the sample system is shown in Fig. 7. The simulation results indicate that the magnitude of sample feeder currents did not exceed the feeder's thermal limit. This is because only one DG source was interconnected with the sample system and its generation capacity did not exceed the limit of 10 MVA.

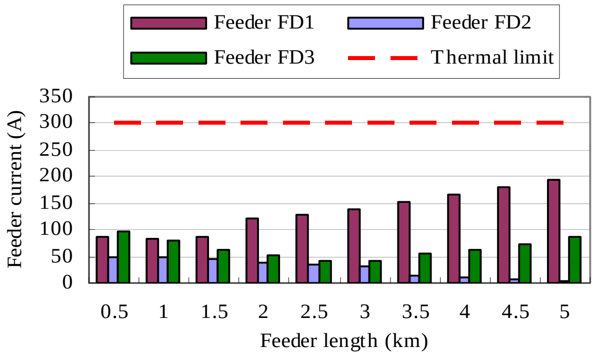

Fig.18 Magnitude of the sample feeder currents when the sample DG source connected with sample feeder FD_1 and operated with a 1.0 power factor

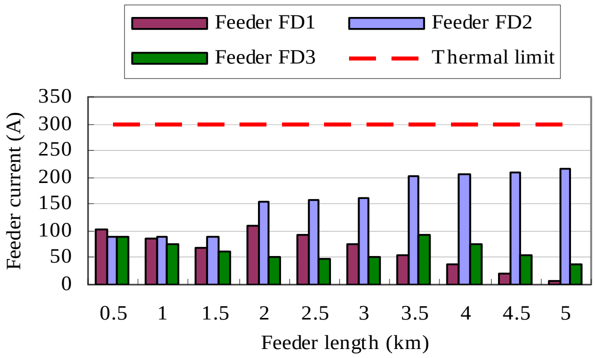

Fig.19 Magnitude of the sample feeder currents when the sample DG source connected with sample feeder FD_2 and operated with a 1.0 power factor

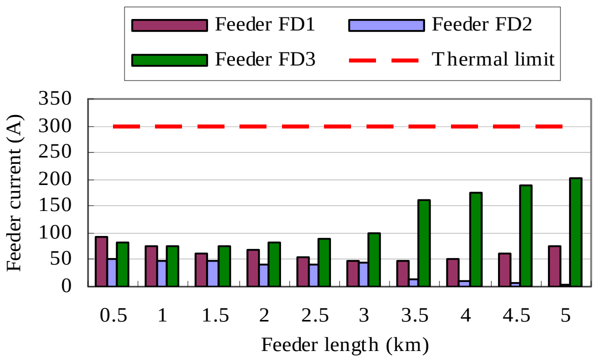

Fig.20 Magnitude of the sample feeder currents when the sample DG source connected with sample feeder FD_3 and operated with a 1.0 power factor

However, a meshed distribution system may be operated with two or more DG sources at the same time. If the DG sources had a big generation capacity and were connected to the same distribution feeder, the feeder currents might exceed their thermal limit. Fig.21 and 22 show the configuration of the sample system and the magnitude of the sample feeders' currents, respectively, when two sample DG sources were connected with sample feeder FD_3 at the same time. The two sample DG sources had the same generation capacity of 10 MVA and power factor of 1.0. One was connected to the end of sample feeder FD_3, and the other was connected 3 km from the front of sample feeder FD_3. The simulation results indicate that currents in some segments of sample feeder FD_3 exceeded the feeder's thermal limit of 300 A owing to the accumulation of the currents generated by the two sample DG sources.

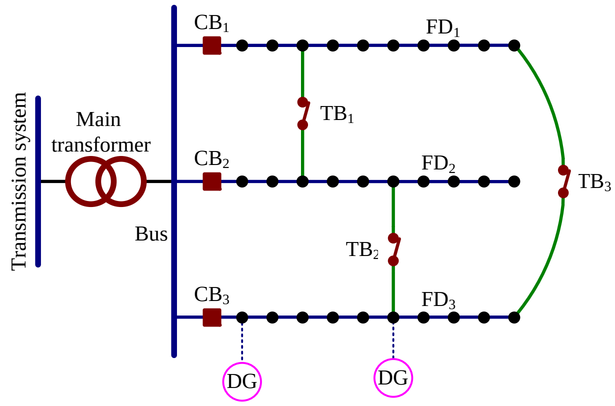

Fig.21 Configuration of the sample system when two sample DG sources connected with the sample feeder FD_3

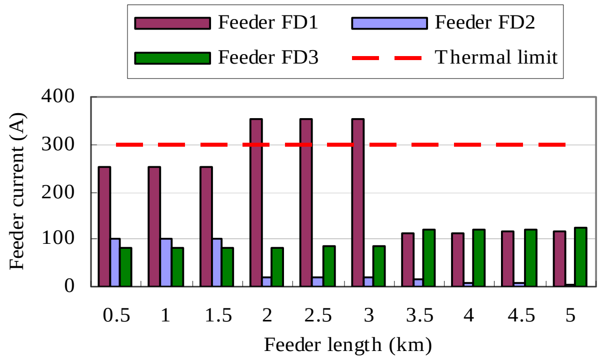

Fig.22 Magnitude of the sample feeders when two sample DG sources connected with the sample feeder FD_3 and operated with a 1.0 power factor

5.3 Short-circuit Currents

Fig. 23 shows the directions of short-circuit currents in a meshed power distribution system when a short-circuit fault occurs on a distribution feeder. This figure indicates that the flow of short-circuit currents in a meshed distribution system is more complex than radial and close-loop distribution systems, but the short-circuit current at the fault place is still completely contributed from the main transformer in substation.

Fig.24 shows the magnitude of the sample feeders' short-circuit currents when a three-phase short-circuit fault occurred on the sample feeders. In this simulation scenario no DG source was connected to the sample system. The simulation results indicate that the short-circuit currents of the sample feeders did not exceed the short-circuit current limit of 10 kA.

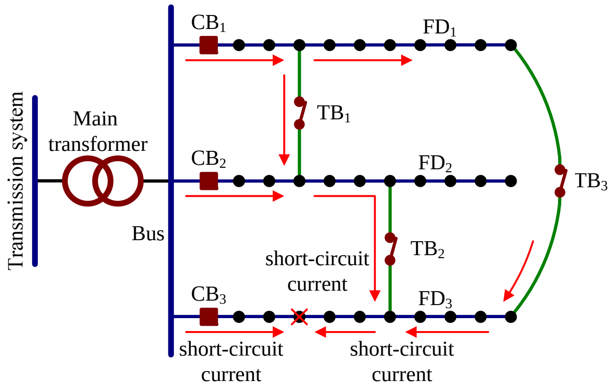

Fig. 23 Directions of short-circuit currents in a meshed power distribution system when a short-circuit fault occurs on a distribution feeder

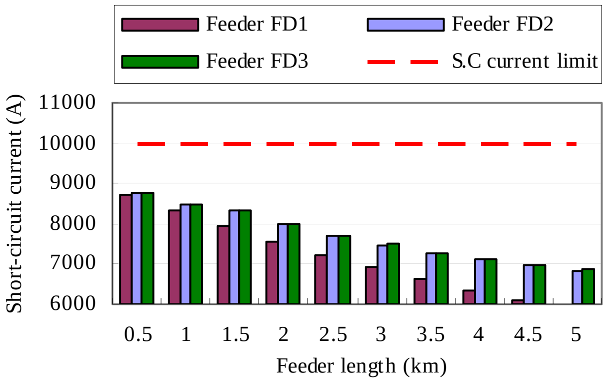

Fig.24 Magnitude of the sample feeders' short-circuit currents when a three-phase short-circuit fault occurred along the sample feeders in order

Fig. 25 shows the contribution of short-circuit currents at a fault place when a meshed distribution system interconnects with a DG source and a short-circuit fault on it.

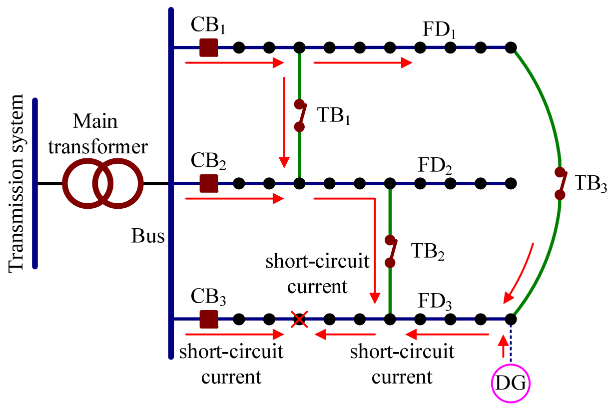

Fig. 25 Contribution of short-circuit currents at a fault place when a meshed distribution system interconnects with a DG source and a short-circuit fault on it

Fig.26 to 28 shows the magnitude of the sample feeders' short-circuit currents when the sample DG source was connected with the sample feeder FD_1, FD_2, or FD_3, respectively. The generation capacity of the sample DG source was 10 MVA. The simulation results indicate that the short-circuit currents in front of the sample feeders exceeded the short-circuit current limit because of the contribution of the sample DG source. It means the DG sources may increase the short-circuit current level of the meshed distribution system which is connected by it and endanger the system's security.

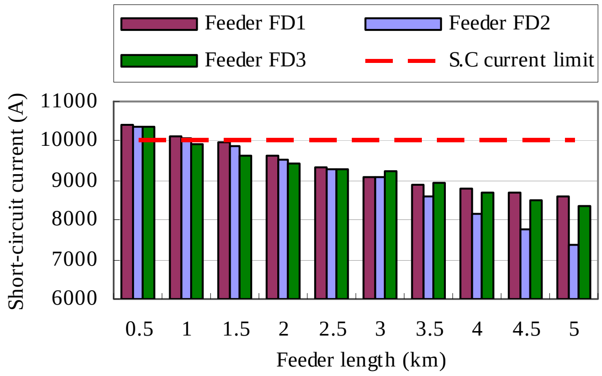

Fig.26 Magnitude of the sample feeders' short-circuit currents when a three-phase short-circuit fault occurred along the sample feeders in order and the sample DG source connected with the end of the sample feeder FD_1

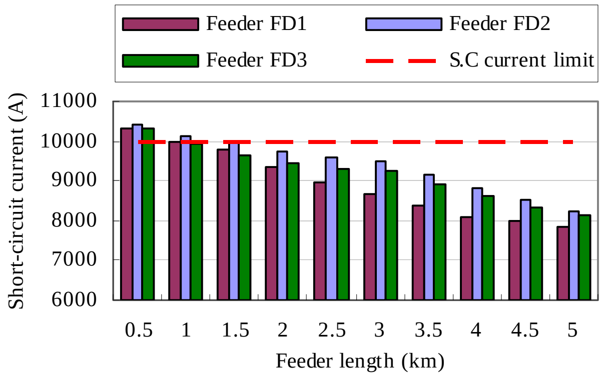

Fig.27 Magnitude of the sample feeders' short-circuit currents when a three-phase short-circuit fault occurred along the sample feeders in order and the sample DG source connected with the end of the sample feeder FD_2

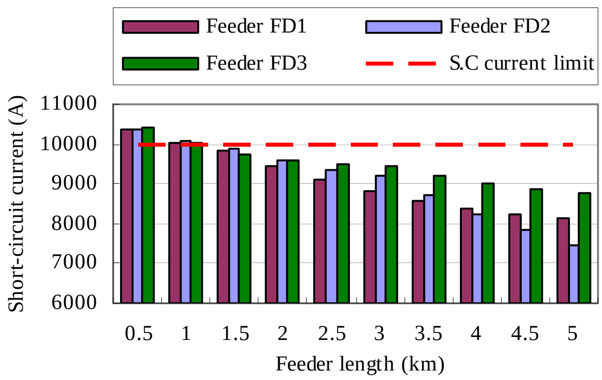

Fig.28 Magnitude of the sample feeders' short-circuit currents when a three-phase short-circuit fault occurred along the sample feeders in order and the sample DG source connected with the end of the sample feeder FD_3

5.4 System Losses

Fig.29 and 30 show the active and reactive power losses of the sample system, respectively, when the connecting location of the sample DG source changed. The four cases performed by this paper are described as follows:

Case 1: The sample DG source was not connected with the sample system.

Case 2: The sample DG source was connected to the middle of sample feeder FD_1, as shown in Fig. 31.

Case 3: The sample DG source was connected to the end of sample feeder FD_2, as shown in Fig. 32.

Case 4: The sample DG source was connected to the front of sample feeder FD_3, as shown in Fig. 33.

The generation capacity and power factor of the sample DG source were 6 MVA and 1.0, respectively. The simulation results indicate that the sample system losses changed when the connecting location of the sample DG source changed. The increment or decrement of system power losses largely affects the utility's benefit. Hence, finding the optimal location for DG source interconnection to reduce system losses is very important for power engineers.

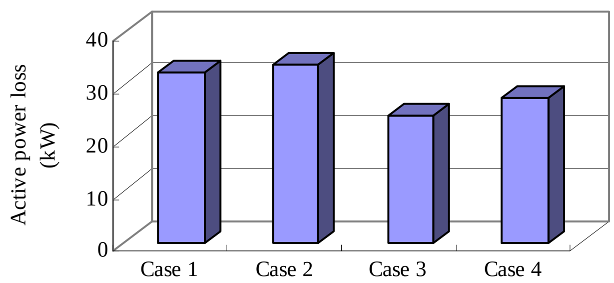

Fig.29 Active power losses of the sample system when the connecting location of sample DG source changed

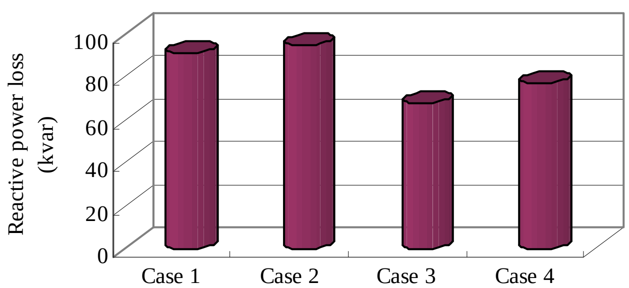

Fig.29 Active power losses of the sample system when the connecting location of sample DG source changed

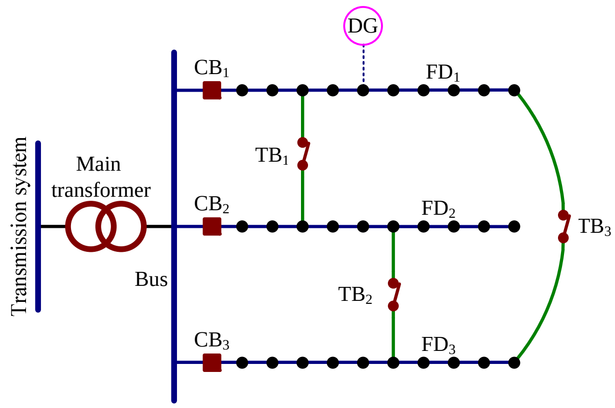

Fig.31 The sample system with the sample DG source connected to the middle of the sample feeder FD_1

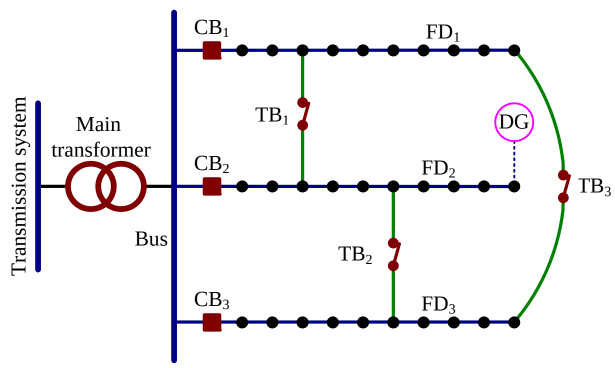

Fig.32 The sample system with the sample DG source connected to the end of the sample feeder FD_2

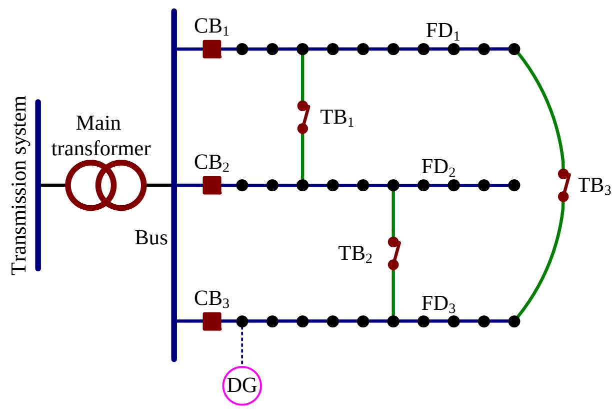

Fig.33 The sample system with the sample DG source connected to the front of the sample feeder FD_3

6 Conclusion

This paper has successfully developed the constant power model of a DG source and constructed the network model of a meshed distribution system in Matlab/Simulink. The effects of DG sources on the feeder voltages, feeder currents, short-circuit currents, and system losses of meshed distribution systems were also evaluated and presented in this paper.

The results of this study indicate that the power factor of DG sources is an important factor affecting distribution feeder voltage variation. The power factor is lower than 1.0, the distribution feeder voltages vary the more largely In addition, DG sources may make the distribution feeder voltages exceed the voltage limits more if the system's configuration is not of the meshed type. This work also indicated that DG sources may make the feeder currents and short-circuit currents exceed the related limits if their generation capacities are too large, and may increase system losses if their connecting location is not suitable.

Distribution systems with meshed configurations are popular with critical customers. These types of systems are more reliable and robust than others. However, DG sources can also affect their operation, supply capability, and power quality. Hence, utilities that intend to operate medium-voltage meshed distribution systems should take heed of the interconnection problems and adopt measures to assure the security of their distribution systems.

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