Voltage Variation Analysis of Normally Closed-Loop Distribution Feeders Interconnected with Distributed Generation

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1. Introduction

The Kyoto Protocol went into effect on February 16, 2005. The need to reduce greenhouse gases has led to growing worldwide interest in renewable energy generation, especially wind power. Due to the desire for more renewable energy, many small power sources have been hooked up to distribution systems. The penetration of distributed generation (DG) is fast increasing in distribution networks throughout the world, especially in Europe. It is predicted that DG will account for more than 25% of new generation being installed by 2010. The major part of the increasing DGs should be covered by wind power. 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. Wind Force 12 points out that 12% of the world's electricity needs will be from wind power by 2020. As outlined in GWEC's Global Wind 2008 Report, global wind energy capacity could reach more than 1,000 GW by the end of 2020. Wind power could produce about 2,600 TWh of electricity per year, which is to supply 10-12% of global electricity demand by 2020. And, this would save as much as 1,500 million tons of CO_2 every year.
Distribution feeders have various arrangements, examples of which are radial, loop, mesh, and spot network (Chen et al., 2004), (Huang & Chen, 2002) and (Lakervi & Holmes, 1995). In Taiwan, most primary distribution feeders are in radial arrangement due to the simple construction and low installation cost involved for this arrangement. However, the reliability of radial distribution feeders is too low to meet the critical customers, such as hospitals, skyscrapers, and factories having sensitive loads. In order to solve this problem, the utility here set to upgrade the arrangements of primary distribution feeders supplying critical customers from radial into normally closed-loop arrangement. Fig. 1 shows the schematic diagram of a distribution feeder in a normally closed-loop arrangement. Two radial distribution feeders supplied by the same main transformer are connected to each other at their ends by a tie breaker and a tie line. The tie breaker is normally closed. In normal operating conditions, the main transformer supplies its loads via two paths. Hence, a normally closed-loop distribution feeder does have a higher reliability than a radial one.

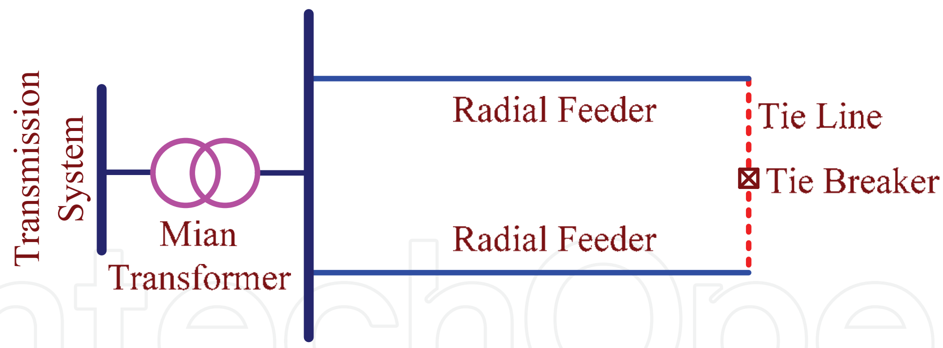

Fig. 1. Schematic diagram of a distribution feeder in a normally closed-loop arrangement

Furthermore, distribution generation has become a trend in Taiwan in recent years. More and more wind turbines, solar cells, small hydro generators, and biomass power plants are installed to generate green electric power and reduce greenhouse gas. In Taiwan, distribution generation sources (DGSs) are allowed to interconnect with the utility's distribution feeders so long as they obey the interconnection rules. When a DGS is interconnected with a normally closed-loop distribution feeder and starts generating electric power, the feeder voltages vary (Kojovic, 2002). Actually, the feeder voltages may vary largely. Once the feeder voltage deviates largely from the nominal voltage, this becomes harmful to the customers of the feeder. Hence, it is important for the utility's power engineers to understand the voltage variation of a normally closed-loop distribution feeder interconnected with DGSs. Hence, the impact of DG interconnection on the power system is a hot subject in recent years. In this chapter, the steady-state voltage variations of a normally closed-loop distribution feeder interconnected with a DGS are analyzed.

In this chapter, the voltage variation of a normally closed-loop distribution feeder interconnected with a distributed generation source is analyzed. First, the relevant background information of normally closed-loop distribution systems and DGS are introduced. Second, the interconnection rules for the steady-state voltage deviation caused by DG grid-connection in the US, Germany, and Denmark are introduced. Third, a model of a sample system involving a normally closed-loop distribution feeder and a DGS is constructed and the maximum allowable capacity of the DGS is evaluated. The relevant rules for DG interconnection in Taiwan are also introduced. Moreover, two formulas are presented, one for evaluating the voltage variation at the point of common coupling of a DGS connected to a distribution system, and another one for calculating the maximum allowable capacity of DGSs under a voltage variation limit. Forth, the definitions and purposes of each simulation scenario and sub-scenario are described. There are many factors affecting distribution feeder voltage variation. In this chapter, the major factors, such as interconnection location and the operating power factor of a DGS, plus the loading, power factor, and operating condition of a distribution feeder are taken into account. Finally, the steady-state voltage variation of a normally closed-loop distribution feeder interconnected with a DGS is analyzed. And, some valuable simulation results are summarized.

2. Interconnection rules for distributed generations

Table 1 outlines the requirements for the steady-state voltage deviation caused by DG grid-connection in the US, Germany, and Denmark. IEEE Std. 1547 states that the DR (distributed resource) unit shall parallel with the area electrical power system (Area EPS) without causing a voltage fluctuation at the point of common coupling (PCC) greater than ±5% of the prevailing voltage level of the Area EPS at the PCC, and meet the flicker requirements. The cumulative influence of the existing DR units parallel with the same Area EPS must be taken into account in the evaluated value of the voltage variation. The relevant codes of Germany and Denmark were established by considering single wind turbines and whole wind farms separately to bound the voltage variation at the PCC. Although the system characteristics, voltage levels and considerations are different from country to country, the requirements of maximum permissible steady-state voltage deviation caused by DG grid-connection are commonly bounded within 1 to 5% (IEEE 1547, 2003), (VDEW), (VDN, 2004), (Eltra: a, 2004) and (Eltra: b, 2004).

	Area, Regulation and Scope		Voltage Deviation
US	IEEE Std. 1547		± 5 %
Germany	VDEW	Medium voltage network	< 2 %
	VDN	Individual generating unit (wind turbine)	≤ 0.5 %
	VDN	Entire plant (wind farm)	≤ 2 %
	VDN	System faults	≤ 5 %
Denmark	DEFU	10 ~ 20kV grid	≤ 1 %
	Eltra Transmission grid	General constraint (wind farm)	< 3 %
		Until a freaquency of 10 per hour (wind farm)	< 2.5 %
		Until a freauency of 100 per hour (wind farm)	< 1.5 %
	Eltra Distribution grid	10 ~ 20kV grid (wind turbine)	≤ 4 %
		50 ~ 60kV grid (wind turbine)	≤ 3 %

Table 1. Overview of common requirements for voltage deviation

3. Description of the sample system

3.1 Structure of the sample system

Fig. 2 shows the one-line diagram of the sample system constructed by the present work. The sample feeder is in a normally closed-loop arrangement. It consists of two radial feeders, A and B. The radial feeders A and B have lengths of 10 and 6 km, respectively, and the tie line is 1 km. Hence, the sample feeder has a length of 17 km in total. The impedance of the sample feeder is 0.0901+j 0.1325 Ω. Buses are set on the sample feeder at intervals of 1 km, and a lumped load is connected to each bus. Every bus has the same loading. Moreover, the rating of the main transformer is 60 MVA. The nominal voltages on the primary and secondary sides are 161 kV and 22.8 kV, respectively. Short-circuit capacity on the primary side is 7500 MVA.

There is a DGS interconnected with the sample feeder. The interconnection location and operating power factor of the sample DGS are changed according to the needs of the current study. The maximum allowable capacities of the sample DGS under different operating conditions are calculated and presented in Section 4.

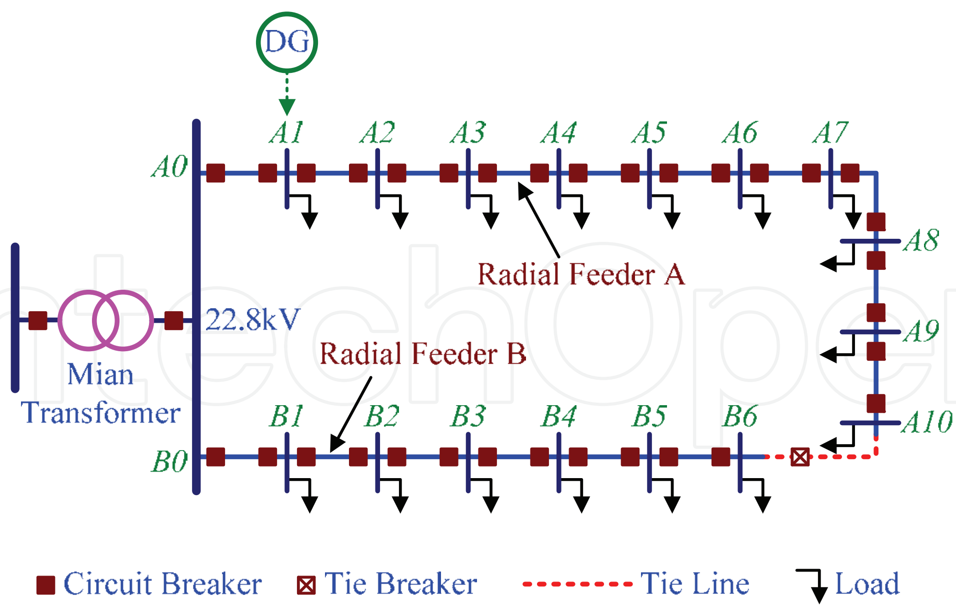

Fig. 2. One-line diagram of the sample system

3.2 Operating conditions of the sample feeder

A normally closed-loop distribution feeder can be operated under two conditions to supply its customers. The two conditions are normal and abnormal operating conditions. The normal condition is that when no fault occurred on the sample feeder. Hence, the sample feeder is operated normally and is kept in closed-loop arrangement. An abnormal condition occurs when a fault occurred on the sample feeder. Under this condition, the sample feeder cannot be kept in a closed-loop arrangement. It might become one or two radial feeders after the fault is cleared by the circuit breakers neighbouring it. In this chapter, the fault is assumed to have occurred on the segment of the sample feeder between buses A0 and A1. Under this condition, the sample feeder became a long radial feeder with the length of 16 km.

4. Calculation of the maximum allowable capacity of the sample DGS

4.1 Rules for DG interconnection

The interconnection of DGSs can surely affect the operation of a distribution system (Persaud et al., 2000), (Yang & Chen, 2005) and (Lopes, 2002). Hence, the maximum allowable capacity of a DGS should be limited in order to assure that the distribution system interconnected by it is safe. In Taiwan, the rules for DG interconnection in distribution systems have been made. Some of the rules related to this work are outlined in the following:

1. The voltage at the point of common coupling (PCC) of a DGS should not deviate more than ±2.5% while the DGS interconnects to the PCC.
2. The voltage profile along a distribution feeder should be kept within ±5% of the nominal voltage.
3. The maximum current generated by a DGS that flows into a distribution feeder should not exceed 300A.

4. The operating power factor of a DGS should be kept within 0.85 lagging and 0.95 leading.

4.2 Maximum allowable capacity of the sample DGS

Equation (1) is the formula for evaluating the voltage variation at the PCC of a DGS interconnected with a power system (Papathanassiou & Hatziargyriou, 2002). Rearranging this formula can obtain the formula for calculating the rated apparent power of a DGS under a voltage variation limit as shown in (2).

$$VR\% = \frac{S_G}{S_S} cos(\varphi_S + \varphi_G) \times 100 \tag{1}$$

where
VR is the voltage variation at PCC.
S_G is the apparent power of a DGS.
S_S is the short-circuit capacity at the PCC.
φ_S is the phase angle of the system impedance at PCC.
φ_G is the phase angle of the DGS's output power.

$$S_G = \frac{VR \times S_S}{cos(\varphi_S + \varphi_G)} \tag{2}$$

Based on (2) and the rules for DG interconnection as described above, the maximum allowable capacities of the sample DGS while the sample feeder operated under normal and abnormal operation conditions are calculated and are shown in Tables 2 and 3, respectively. These two tables represent that the maximum allowable capacity of a DGS will change with its interconnection location and operating power factor. Additionally, the maximum allowable capacity of a DGS under normal operating conditions is larger than the one under abnormal operating condition.

Interconnection Location	Operating Power Factor		
	0.85 lagging	1.0	0.95 leading
A1	11.91	12.00	12.00
A5	8.20	12.00	12.00
A10	7.60	12.00	12.00

Table 2. Maximum allowable capacities of the sample DGS under normal operating conditions of the sample feeder.

Interconnection Location	Operating Power Factor		
	0.85 lagging	1.0	0.95 leading
A1	3.23	5.13	10.00
A5	4.00	6.68	12.00
A10	4.55	7.85	12.00

Table 3. Maximum allowable capacities of the sample DGS under abnormal operating conditions of the sample feeder.

5. Definitions of the simulation scenarios

There are many factors affecting the voltages of a distribution feeder. The interconnection location and operating power factor of a DGS, and the loading and operating condition of a distribution feeder are the major factors. They are all taken into account in this chapter. In order to present the voltage variation of a normally closed-loop distribution feeder interconnected with a DGS completely, five simulation scenarios, in which each simulation scenario included four sub-scenarios, are selected and simulated. The definitions and purposes of each scenario and sub-scenario are described in the following.

5.1 The Simulation scenarios

The first scenario is used as a basic scenario. In this scenario, the sample feeder is operated with a normal load, and the loads along the sample feeder are uniformly distributed. The second scenario is used to present the effect of loading change on feeder voltage variation. In this scenario, the sample feeder is operated with a heavy load. The third scenario is used to present the effect of load power factor change on feeder voltage variation. In this scenario, the average load power factor of the sample feeder is changed to 0.8 lagging. The fourth and fifth scenarios are used to present the voltage variation of a normally closed-loop distribution feeder operated under abnormal conditions and with normal and heavy loadings, respectively.

Table 4 shows the operating conditions and load parameters of the sample feeder defined in each scenario. Observing this table in detail, the differences among the six scenarios can be easily determined.

Simulation Scenario Number	Parameters of the Sample Feeder		
	Total Load	Load Power Factor	Operating Condition
1	8MVA	0.95lagging	normal
2	12MVA	0.95lagging	normal
3	8MVA	0.80lagging	normal
4	8MVA	0.95lagging	abnormal
5	12MVA	0.95lagging	abnormal

Table 4. Simulation scenarios selected by this chapter

5.2 The Sub-scenarios

The four sub-scenarios are used to present the effect of the change in interconnection location and maximum allowable capacity of a DGS on distribution feeder voltages. In this chapter, the first sub-scenario is used to present the voltage variations along the sample feeder without DGS. Meanwhile, the second to fourth sub-scenarios are used to present the voltage variations along the sample feeder while the sample DGS was interconnected to the front, middle, and end, that is, bus A1, A5, and A10, of the sample feeder, respectively. For convenience, the four sub-scenarios are named "w/o DG", "A1," "A5," and "A10," respectively.

6. Analysis of feeder voltage variation

In this chapter, the power system simulation software CYME is used to simulate the sample system operated under various operating conditions as defined in the simulation scenarios. The simulation results are presented and discussed in the following.

6.1 Effect of the interconnection of a DGS

Figs. 3 to 5 show the voltage profiles along the sample feeder in scenario 1 while the sample DGS is operated with 1.0, 0.85 lagging, and 0.95 leading power factor, respectively. The three figures pointed out three phenomena. They are stated as follows:

1. The interconnection of the sample DGS made the voltages along the sample feeder go up. The maximum voltage variation appeared at the PCC of the sample DGS.
2. The voltage variation at PCC will become larger, while the electrical distance between the PCC of the sample DGS and the main transformer is becomes farther.
3. The voltage variations along the sample feeder are all within the limits of ±2.5% wherever the sample DGS is interconnected to.

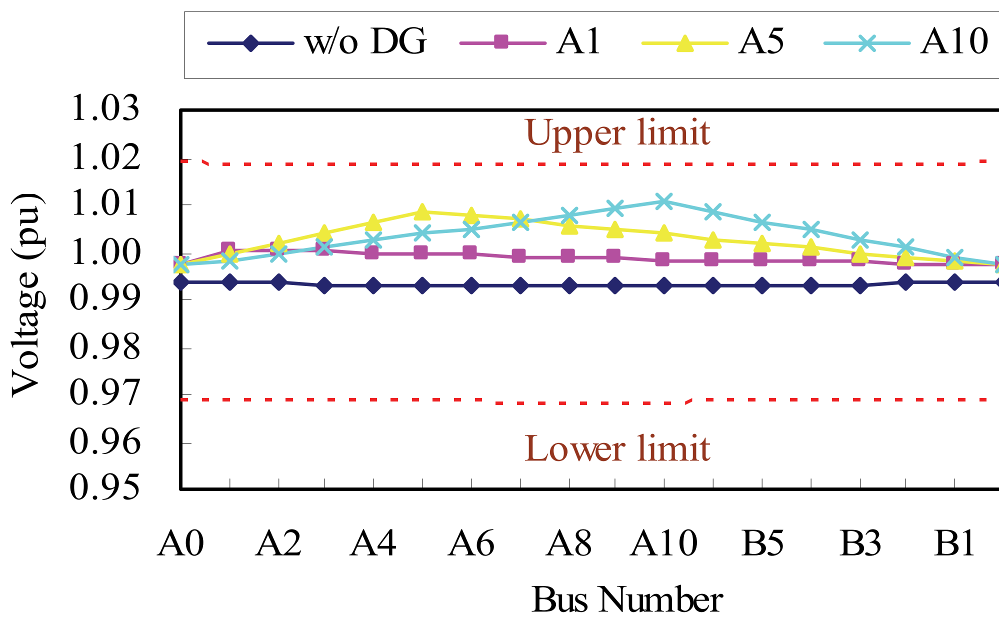

Fig. 3. Voltage profiles along the sample feeder in scenario 1 while the sample DGS is operated with 1.0 power factor

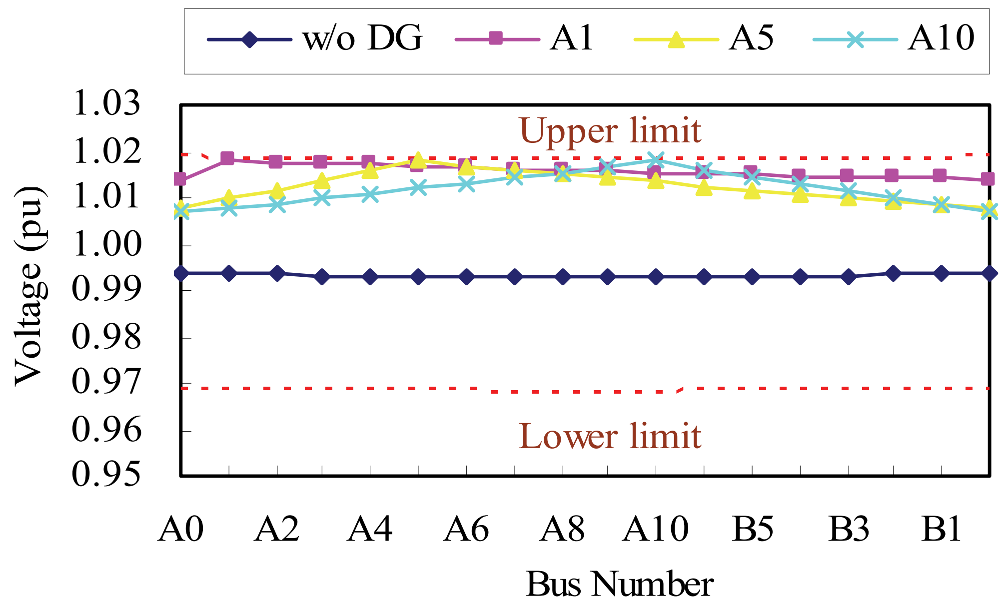

Fig. 4. Voltage profiles along the sample feeder in scenario 1 while the sample DGS is operated with 0.85 lagging power factor

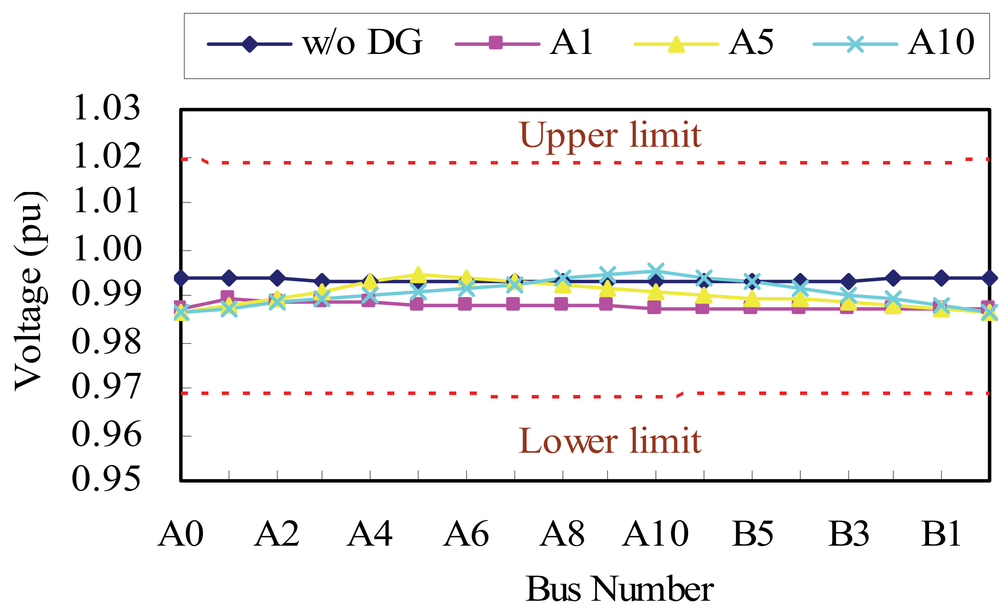

Fig. 5. Voltage profiles along the sample feeder in scenario 1 while the sample DGS is operated with 0.95 leading power factor

6.2 Effect of the change in feeder loading

Figs. 6 to 8 show the voltage profiles along the sample feeder in scenario 2, while the sample DGS is operated with 1.0, 0.85 lagging, and 0.95 leading power factor, respectively. The three figures pointed out two phenomena. They are stated as follows.

1. If the feeder loading is increased, the voltage variations along the sample feeder will be increased.

2. The voltage variation at PCC of the sample DGS will exceed the upper limit while the sample DGS is operated with 0.85 lagging power factor. The results demonstrate that the evaluation of the maximum allowable capacity of a DGS as described in Section 4 is not very precise because (2) does not involve the uncertainty of feeder loading.

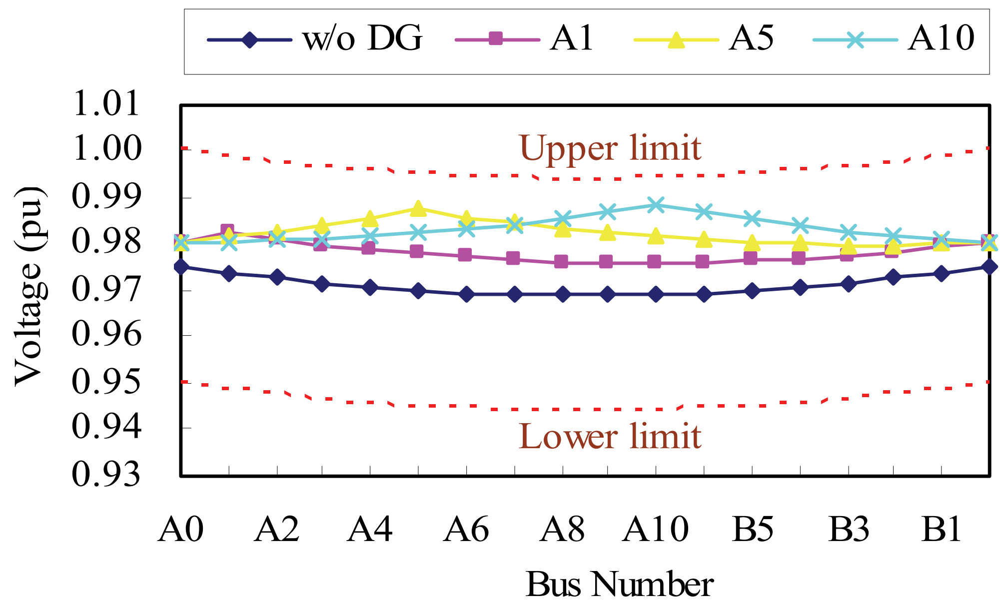

Fig. 6. Voltage profiles along the sample feeder in scenario 2 while the sample DGS is operated with 1.0 power factor

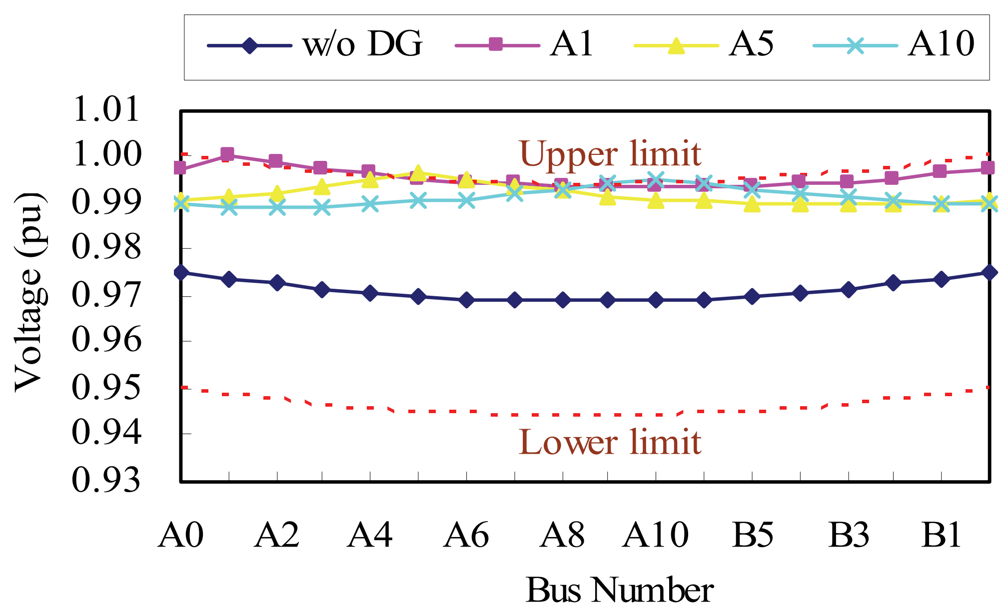

Fig. 7. Voltage profiles along the sample feeder in scenario 2 while the sample DGS is operated with 0.85 lagging power factor

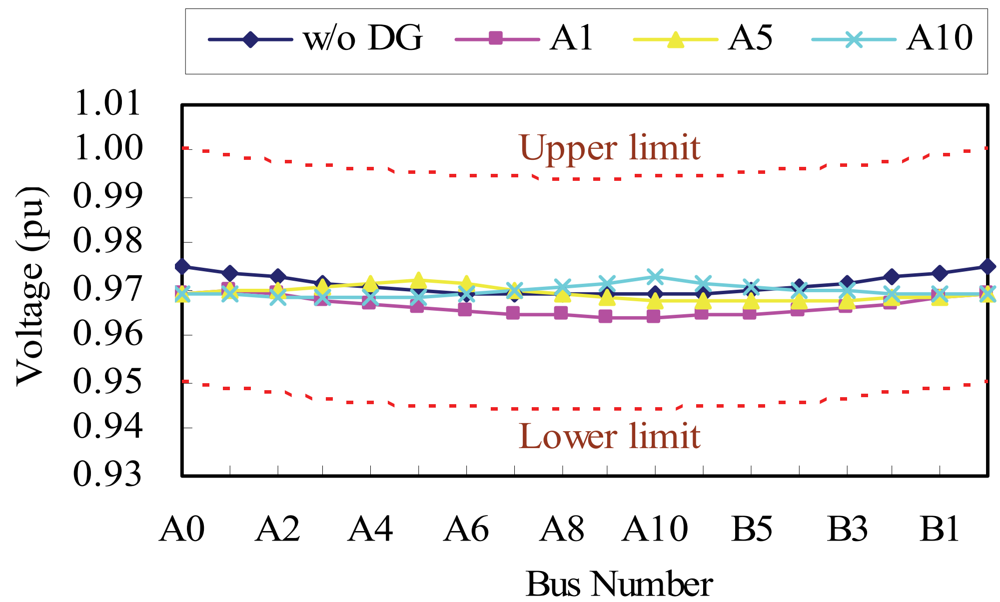

Fig. 8. Voltage profiles along the sample feeder in scenario 2 while the sample DGS is operated with 0.95 leading power factor

6.3 Effect of the change in load power factor

Figs. 9 to 11 show the voltage profiles along the sample feeder in scenario 3 while the sample DGS is operated with 1.0, 0.85 lagging, and 0.95 leading power factor, respectively. Comparing the three figures with Figures 3 to 5, we can find that the load power factor do not have much effect on the voltage variations along the sample feeder. This means that the voltage variation of a normally closed-loop distribution feeder does not exceed the voltage variation limits so long as the load power factors of feeder are kept in reasonable values.

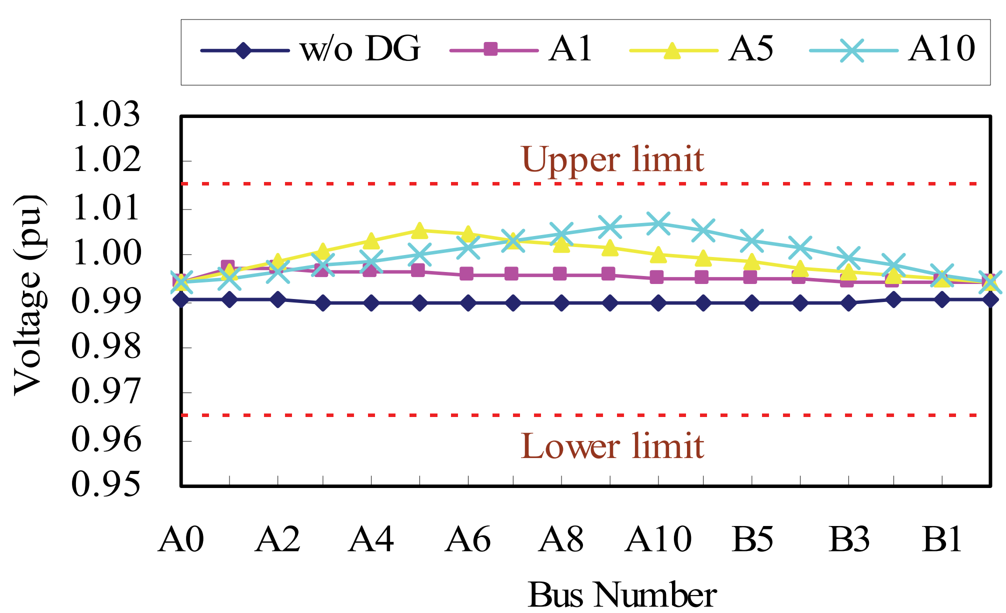

Fig. 9. Voltage profiles along the sample feeder in scenario 3 while the sample DGS is operated with 1.0 power factor

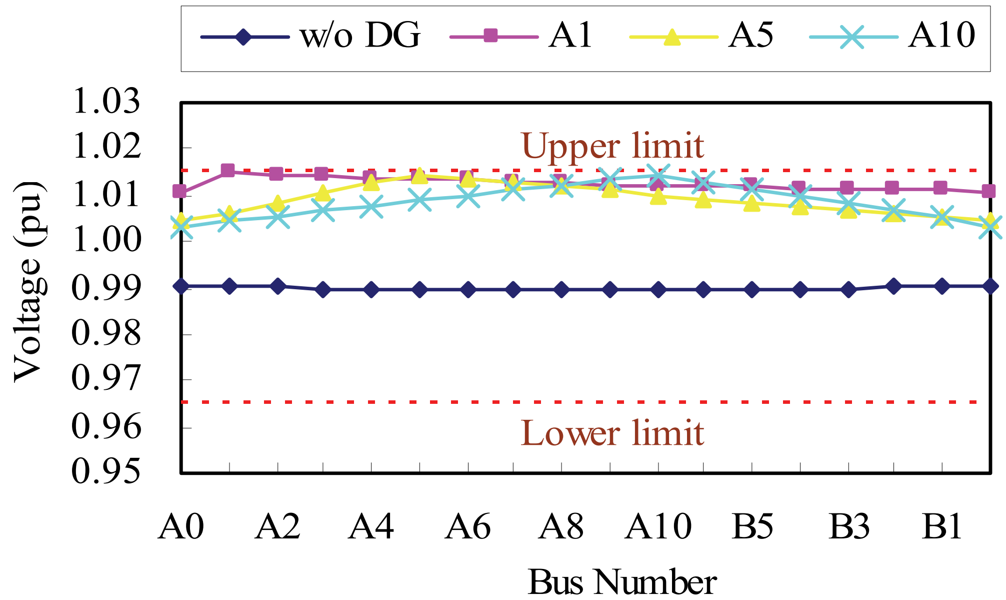

Fig. 10. Voltage profiles along the sample feeder in scenario 3 while the sample DGS is operated with 0.85 lagging power factor

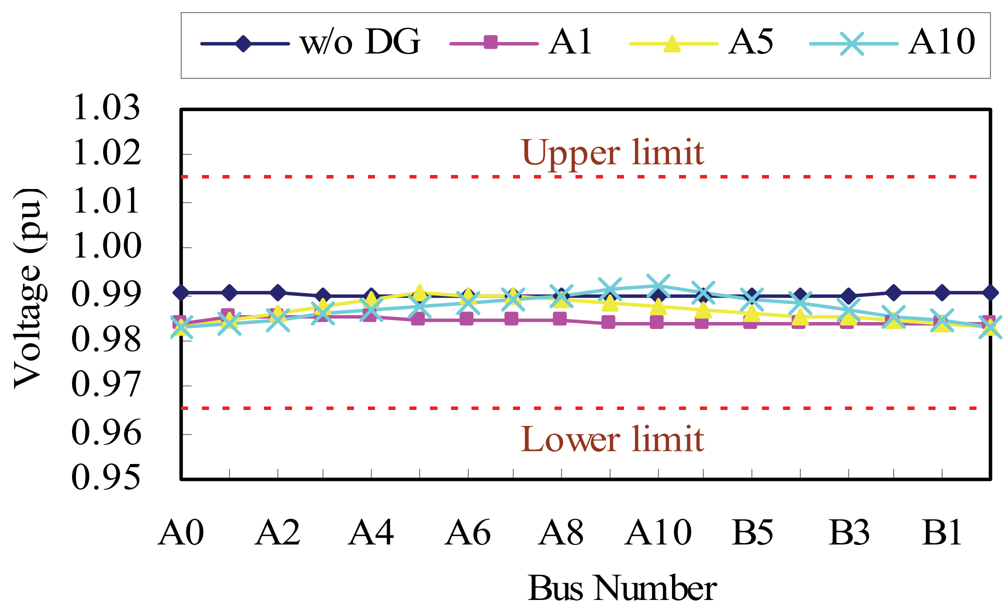

Fig. 11. Voltage profiles along the sample feeder in scenario 3 while the sample DGS is operated with 0.95 leading power factor

6.4 Effect of the change in feeder operating condition

Figs. 12 to 14 show the voltage profiles along the sample feeder in scenario 4 while the sample DGS is operated with 1.0, 0.85 lagging, and 0.95 leading power factor, respectively. In this scenario, the sample feeder is under abnormal operating conditions and becomes a long radial feeder. Under this circumstance, its voltage profiles may change largely. Fig. 13 shows that the voltages along the sample feeder have exceeded the voltage tolerance limits of ±5% while the sample DGS is interconnected to bus A1 and operated with 0.85 lagging power factor. The reason is that the sample DGS is interconnected to the end of the sample feeder and produced a lot of reactive power into the sample feeder.

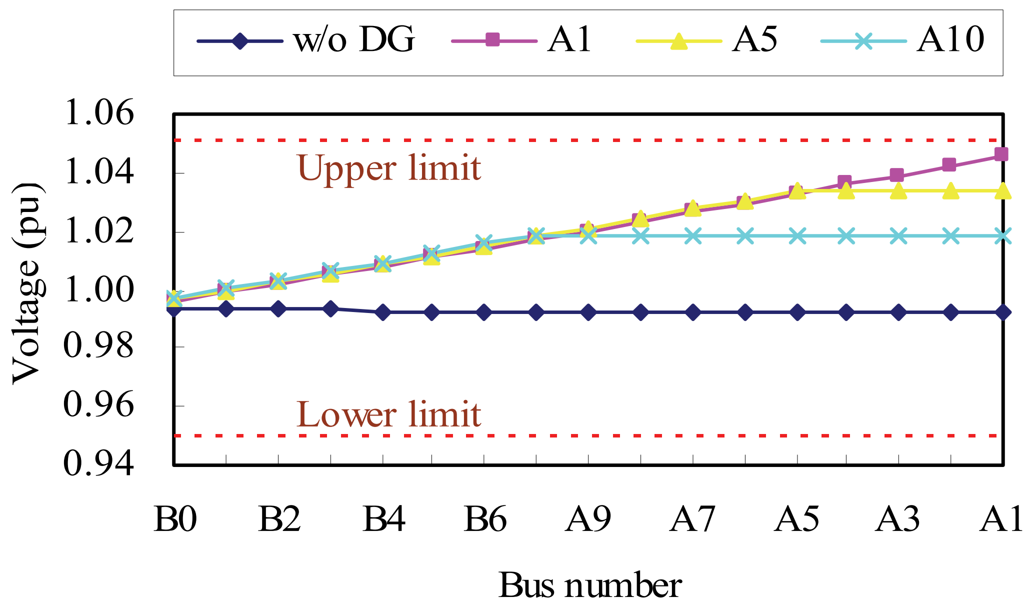

Fig. 12. Voltage profiles along the sample feeder in scenario 4 while the sample DGS is operated with 1.0 power factor

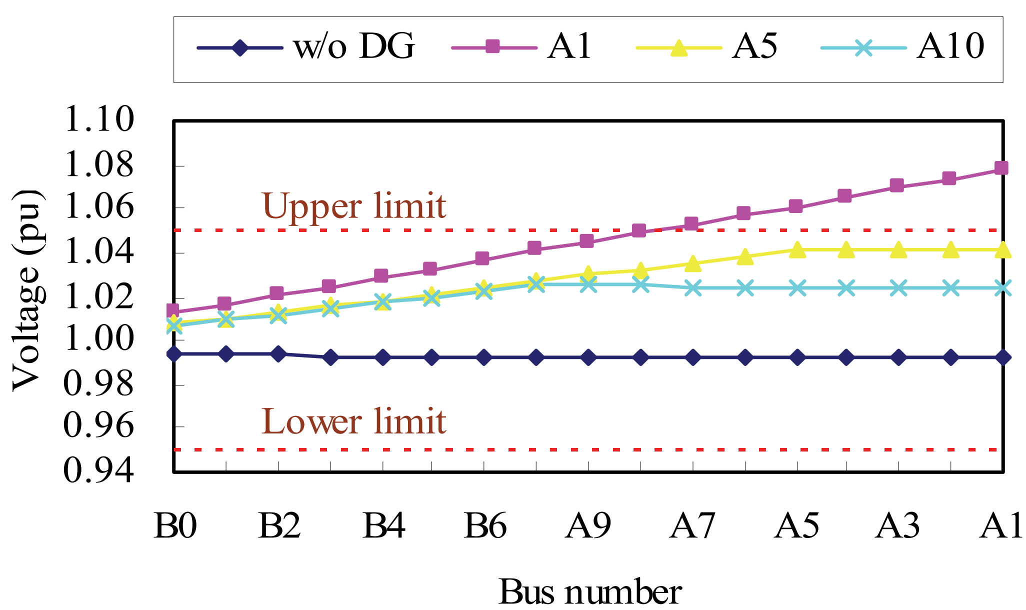

Fig. 13. Voltage profiles along the sample feeder in scenario 4 while the sample DGS is operated with 0.85 lagging power factor

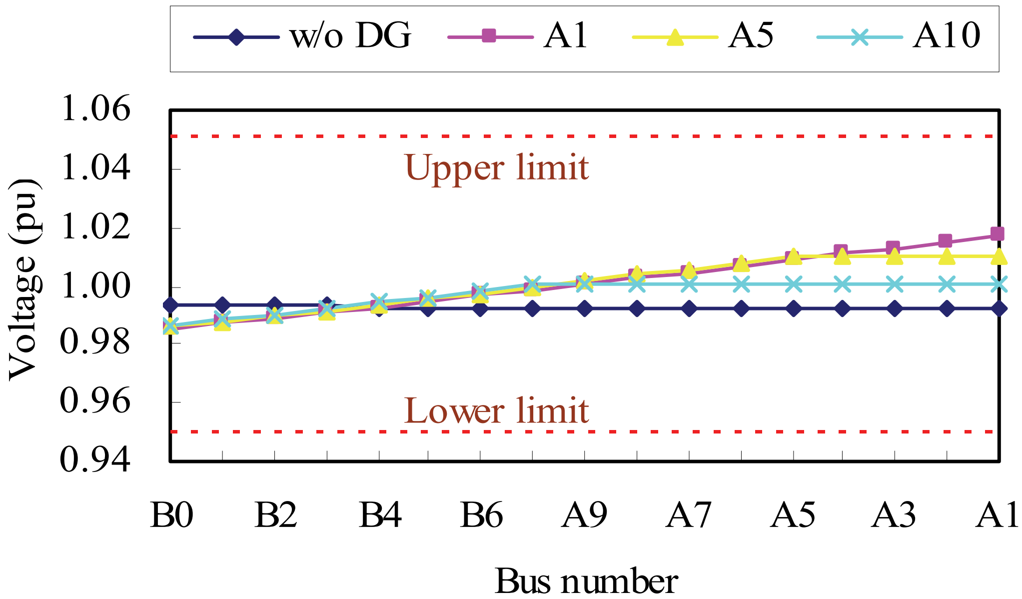

Fig. 14. Voltage profiles along the sample feeder in scenario 4 while the sample DGS is operated with 0.95 leading power factor

Figs. 15 to 17 show the voltage profiles along the sample feeder in scenario 5 while the sample DGS is operated with 1.0, 0.85 lagging, and 0.95 leading power factor, respectively. In this scenario, the sample feeder is still operated under abnormal conditions. However, the voltages along the sample feeder do not exceed the voltage tolerance limits of ±5%. The reason is that the sample feeder is operated with heavy loading. The reactive power produced by the sample DGS is all absorbed by the sample feeder loads.

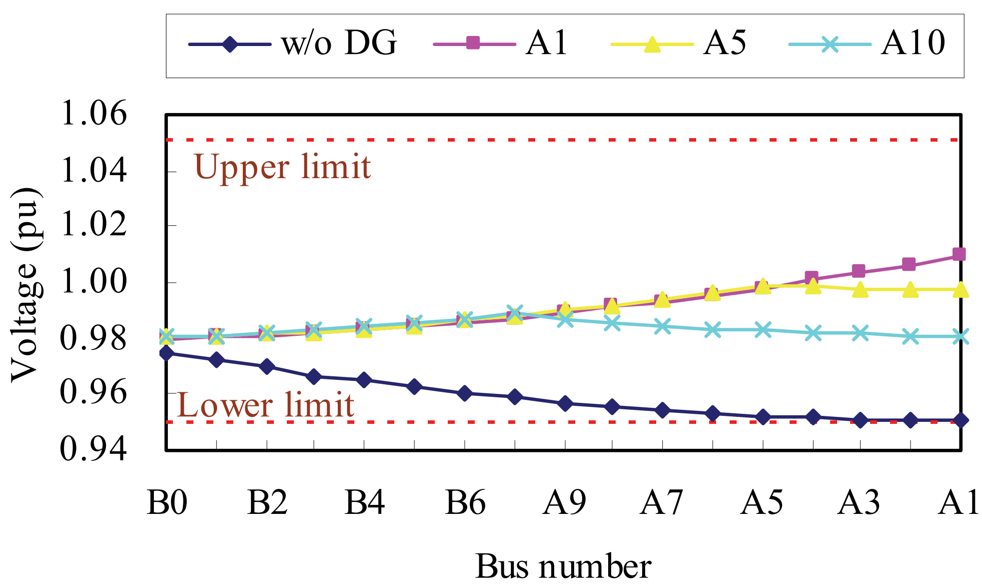

Fig. 15. Voltage profiles along the sample feeder in scenario 5 while the sample DGS is operated with 1.0 power factor

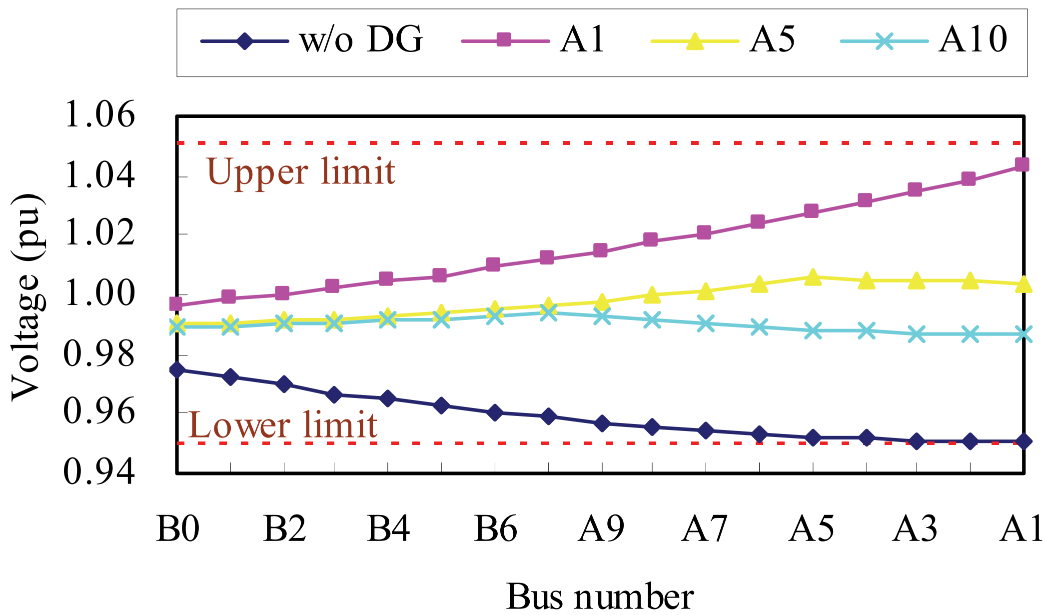

Fig. 16. Voltage profiles along the sample feeder in scenario 5 while the sample DGS is operated with 0.85 lagging power factor

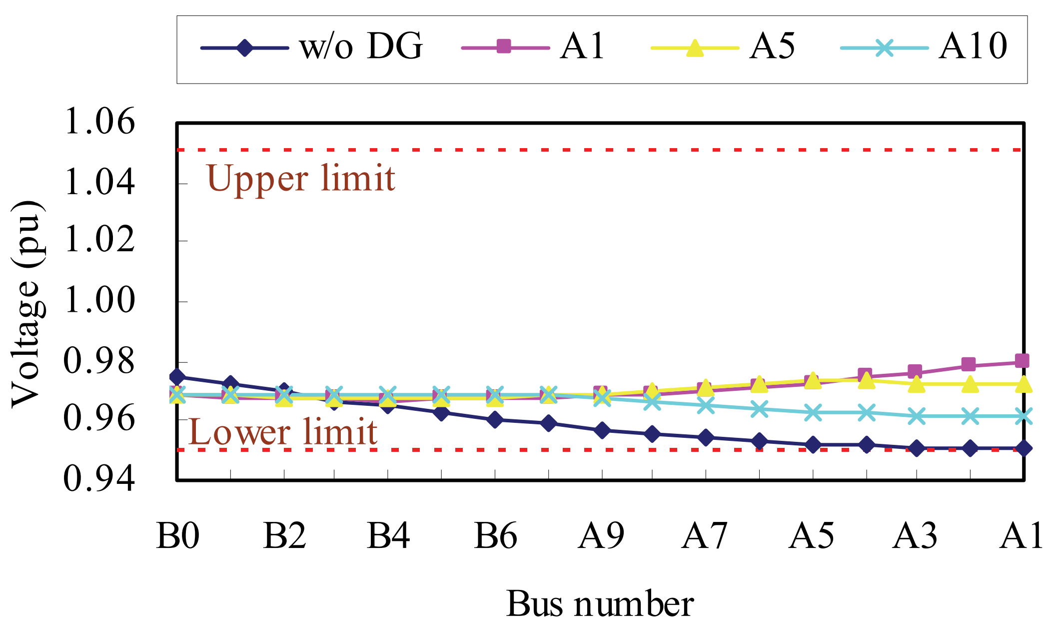

Fig. 17. Voltage profiles along the sample feeder in scenario 5 while the sample DGS is operated with 0.95 leading power factor

7. Conclusions

The steady-state voltage variation of a normally closed-loop distribution feeder interconnected with a DGS has been analyzed in this chapter. The simulation results of the sample system are also presented in this chapter. Some important results are summarized in the following:

1. The interconnection location of a DGS is an important factor affecting the voltage variation of a normally closed-loop distribution feeder. The voltage variation at the PCC increases with the electric distance of a DGS from the main transformer to the PCC.
2. When a DGS is operated with lagging power factor, reactive power is produced. A DGS with low lagging power factor can enlarge the voltage variation of the distribution feeder interconnected by it.
3. The loading of a normally closed-loop distribution feeder is an important factor affecting its voltage variation as well. When a normally closed-loop distribution feeder is operated with heavy loading, the voltage variation along the feeder may exceed voltage variation limits, especially when the DGS is operated with lagging power factor.
4. When a normally closed-loop distribution feeder is operated in a normal condition and the interconnection location of a DGS is nearer to the main transformer, the voltage variation along the feeder is smaller. In contrary, when a normally closed-loop distribution feeder is operated in an abnormal condition and the interconnection location of a DGS is nearer to the end of the feeder, the voltage variation along the feeder is larger.

Upgrading distribution feeders from radial into a normally closed-loop arrangement is an important measure to heighten power supply reliability. However, the interconnections of DGSs make the voltage variations of normally closed-loop distribution feeders to become complex. The results of this chapter are particularly useful to power engineers so they can have a better understanding of the effects of DGSs on the voltages of normally closed-loop distribution feeders and so that they can be helped also in operating their distribution systems safely.

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Distributed Generation
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In the recent years the electrical power utilities have undergone rapid restructuring process worldwide. Indeed, with deregulation, advancement in technologies and concern about the environmental impacts, competition is particularly fostered in the generation side, thus allowing increased interconnection of generating units to the utility networks. These generating sources are called distributed generators (DG) and defined as the plant which is directly connected to distribution network and is not centrally planned and dispatched. These are also called embedded or dispersed generation units. The rating of the DG systems can vary between few kW to as high as 100 MW. Various new types of distributed generator systems, such as microturbines and fuel cells in addition to the more traditional solar and wind power are creating significant new opportunities for the integration of diverse DG systems to the utility. Interconnection of these generators will offer a number of benefits such as improved reliability, power quality, efficiency, alleviation of system constraints along with the environmental benefits. Unlike centralized power plants, the DG units are directly connected to the distribution system; most often at the customer end. The existing distribution networks are designed and operated in radial configuration with unidirectional power flow from centralized generating station to customers. The increase in interconnection of DG to utility networks can lead to reverse power flow violating fundamental assumption in their design. This creates complexity in operation and control of existing distribution networks and offers many technical challenges for successful introduction of DG systems. Some of the technical issues are islanding of DG, voltage regulation, protection and stability of the network. Some of the solutions to these problems include designing standard interface control for individual DG systems by taking care of their diverse characteristics, finding new ways to/or install and control these DG systems and finding new design for distribution system. DG has much potential to improve distribution system performance. The use of DG strongly contributes to a clean, reliable and cost effective energy for future. This book deals with several aspects of the DG systems such as benefits, issues, technology interconnected operation, performance studies, planning and design. Several authors have contributed to this book aiming to benefit students, researchers, academics, policy makers and professionals. We are indebted to all the people who either directly or indirectly contributed towards the publication of this book.