

## Impact of Distributed Generation on Voltage Profile in Radial Feeder

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### Abstract

The use of distributed generation (DG) within distribution systems has increased for the last two decades due to worldwide increase in demand for electricity and governmental policy change from “conventional” energy to “green” energy. High levels of penetration of DG have many significant benefits but also come with many drawbacks such as voltage drop and power losses. This study presents the impact of DG at different locations in a distribution feeder in terms of the feeder voltage profile. A radial distribution system is simulated using PSCAD/EMTDC simulation software while changing the size and location of DG in the system. The obtained results are used for better understanding on the impact of DG on voltage profile in radial distribution feeder.

**Keywords:** voltage profile, radial distribution network, distributed generation, distribution systems

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### 1. Introduction

Electrical power generation, transmission and distribution sectors are the three different categories of electrical power systems where each category are owned and operated by a separate company. For profitable operation, these electrical companies often maximize their profits and minimize their operating costs. This is done by way of reducing spending on the maintenance, which leads to a lot of technical problems in the electrical network [1].

The most expensive technical problems usually happen in the distribution system. Voltage regulation is one of the main problems in radial distribution network [2]. The most common devices and techniques used for maintaining the voltage levels are transformer equipped by load tap changer (LTC), supplementary line regulators installed on distributed feeders, shunt capacitor switched on distribution feeders [3] and shifting transformers towards the load center [4]. A substation's LTC transformer equipped with a Line Drop Compensator (LDC) operation increases its output voltage to readjust the voltage level and to compensate the expected increase of the feeder's voltage drop [5]. Feeder's voltage regulator regulates the voltage at the utilization point between  $\pm 10\%$  of the base voltage. Shunt capacitor is used to regulate the voltage and the reactive power flow at the point of connection with the distribution feeder with the aim of improving the voltage profile at the far-end feeder point. Switch shunt capacitor are usually placed in distribution feeder together with voltage regulators in the same distribution network to maintain adequate voltage profile especially for long feeders [6].

Implementing DG as a source of active power in the distribution system is considered a new effective approach to solve the voltage regulation problem [7]. DG includes conventional and renewable technologies such as photovoltaic, wind turbines and hydro, storage energy devices, batteries and flywheel, fuel cells [8, 9], combined heat and power modules (CHP) and microturbines. In the past, DGs were available in small size and designed to serve a single end-user's site but nowadays it is considered as large co-generation providing up to hundreds of MWatts to customers or back to grid. Characteristics of distributed sources are different. While synchronous generators can produce real power and produce and consume reactive power, induction generators used for wind applications can only produce active power and they need reactive power [10]. Photovoltaics and fuel cells are DC sources and require power electronics interface to connect to an AC system [10].

Based on IEEE Standard 1547, all types of distributed sources should not actively regulate distribution system voltages [11]. Therefore, constant power factor control mode of

operation is preferred although synchronous generators are capable of controlling voltage at the point of connection point of DG. The selection of DG size and location is important since otherwise, adverse effects, such as voltage rise, mis-operation of protection relays may occur [12]. The purpose of this paper is to examine the change in feeder voltage profile depending on the size and location of DG in the system.

## 2. Research Method

Most developing countries have experienced progressing demand on their power system network [13]. Therefore DGs are employed to cater for these demands. The most common type of voltage control method is by using on-load tap changer transformer [5]. For operating the tap changer of a power transformer, the automatic voltage control (AVC) relay initiates a signal to bring the controlled voltage back within the specified limits. When automatic load-tap-changing transformers operating in parallel are located remotely from each other, interconnecting control wires are impractical and a modification of the line-drop compensator setting is necessary to obtain satisfactory operation. This type of control is sometimes referred to as the "reduced" or "reversed" reactance method. This method serves to distinguish between circulating current and load current and does this by virtue of a difference in power factor between these currents. A compensator which employs normal resistance and reverse reactance results in a characteristic such that high power-factor currents cause the transformer to increase the voltage and low power-factor currents cause it to decrease. Thus, it is possible to set compensators so that load currents will cause a boosting operation and circulating currents will cause a slight bucking operation of transformers with no intervening impedance. These are the two methods from which we can control the AVC relay namely the negative reactance compounding (NRC) and LDC. The negative reactance compounding (NRC) method helps to maintain similar tap positions for paralleled transformers by changing the polarity of reactance of LDC setting –  $X_{LDC}$ .

In NRC operation, transformer  $T_1$  has much higher tap position compared to transformer  $T_2$ . Due to the difference in tap position, a circulating current will flow between transformer  $T_1$  and transformer  $T_2$ . The circulating current causes current  $I_{T1}$  to be shifted in clockwise direction and current  $I_{T2}$  in anti-clockwise direction. Both current  $I_{T1}$  and  $I_{T2}$  which passes through the  $Z_{NRC}$  setting create a voltage drop  $I_T \cdot Z_{NRC}$ . The AVC relay uses this voltage drop to determine the proper tap position. Since the voltage at transformer  $T_1$  is higher than the target voltage therefore the AVC relay initiates a tap down operation. Similarly the AVC relay of transformer  $T_2$  initiates a tap up operation. The action stops with a similar tap position of both the parallel transformers when the circulating current is eliminated and target voltage is achieved. The advantage of NRC scheme is that it can operate with transformers at different positions in the networks and it does not need to be identical anymore due to the independent action of each transformer. However, the NRC fails to operate satisfactorily when the power factor changes from a set point. Integration of irregular DG into the network effects the NRC operation. Apart from that, negative value of  $X_{LDC}$  setting could cause poor performance of LDC. An increased value of  $R_{LDC}$  is needed in order to maintain the performance of LDC.

The aim of line-drop compensation is to keep the voltage constant, not at the local bus bar on the transformer secondary, but at some remote load center. Normal practice is to sense the load current (local to the transformer) and from this to simulate the voltage drop in the line to the remote load center. Modern voltage-control relays include line-drop compensation as standard. OLTC consist of two fixed windings and a third tap winding (regulation winding) connected in series with either winding 1 or winding 2. A  $+30^\circ$  or  $-30^\circ$  phase shift is introduced when winding 1 or winding 2 are connected in delta. In automatic mode voltage regulator on and the signal applied at the  $V_m$  inputs is monitored and the voltage regulator asked for tap change. The three-phase two-winding transformer or autotransformer uses an on-load tap changer (OLTC) for regulating voltage on a transmission or distribution system. Controlling voltage on a transmission system will affect primarily flow of reactive power, which, in turn, will affect the power transfer limits. Although the regulating transformer does not provide as much flexibility and speed as power-electronics based FACTS, it can be considered as a basic power flow controller.

To overcome frequent tap operation due to DG interconnection, several artificial intelligence methods are introduced for AVC relay operation. Fuzzy logic systems are much

preferred compared to other artificial intelligent systems because the control rules can be implemented using simple "IF-THEN" relations [5].

#### 1) Fuzzy Membership Function

- a. Secondary voltage of the OLTC transformer: very high (VH), high (H), normal (N), low (L), very low (LV)
- b. Phase angle of current through the OLTC transformer: high (H), normal (N), low (L)
- c. Change of current: negative (N), zero (Z), positive (P)
- d. Tap position: low (L), normal (N), high (H)
- e. AVC relay voltage: high (H), normal (N), low (L)

#### 2) Fuzzy Control Rules

- a. If voltage is very low, then AVC relay voltage is low.
- b. If voltage is low, tap position is normal and power angle is normal, then AVC relay voltage is normal.
- c. If voltage is low, tap position is low and power angle is normal, then AVC relay voltage is low.
- d. If voltage is normal and power angle is low, then AVC relay voltage is low.
- e. If voltage is normal and power angle is normal, then AVC relay voltage is normal.
- f. If voltage is normal and power angle is high, then AVC relay voltage is low.
- g. If voltage is high, tap position is normal and power angle is normal, then AVC relay voltage is normal.
- h. If voltage is high, tap position is high, then AVC relay voltage is high.
- i. If voltage is very high, then AVC relay voltage is high.
- j. If voltage is normal and power angle is low, then AVC relay voltage is normal.
- k. If voltage is normal and power angle is normal, then AVC relay voltage is normal.
- l. If voltage is normal and power angle is high, then AVC relay voltage is high.

The other advantages of these systems are that they are simpler and able to simplify design complexity and lessen the hardware cost. Fuzzy logic systems are beneficial because they allow the usage of fuzzy rules which are more expressive than crisp values [14]. The fuzzy logic systems also requires less computation time.

### 2.1. Case Study

Small scale DG of less than 10MW is normally connected directly to the utility system at the sub transmission and distribution level [15]. In this study, a radial distribution test system operating at nominal voltage level of 11kV is modelled using PSCAD/EMTDC software for simulation purpose. The radial test system used in the simulation is shown in Figure 1. Different operating scenarios of DG connections were considered as follows:

- a. Case 1, a DG unit consisting of a 4.0 MW, 5.5 MW, 6.5 MW and 7.0 MW synchronous generators each is connected at bus 4.
- b. Case 2, a DG unit consisting of a 4.0 MW, 5.5 MW, 6.5 MW and 7.0 MW synchronous generators each is connected at bus 3.
- c. Case 3, a DG unit consisting of a 4.0 MW, 5.5 MW, 6.5 MW and 7.0 MW synchronous generators each is connected at bus 2.
- d. Case 4, a DG unit consisting of a 4.0 MW, 5.5 MW, 6.5 MW and 7.0 MW synchronous generators each is connected at bus 1.

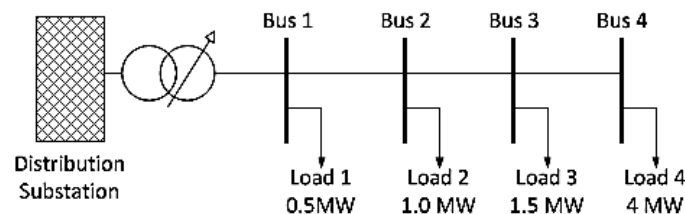


Figure 1. 11 kV radial type test system

## 2.2. The Simulation Process

First, the simulation is carried out without inserting the DG into the network. The voltage at each bus and the active and reactive power feed by the distribution substation are measured. Second, the simulation is run with implementing the DG into the network (at bus 4). Again, the voltage at each bus and the active and reactive power feed by the distribution substation and the installed DG are measured. Third, repeat the second step two times and at each time vary the location and size of DG at several buses (bus 3, bus 2 and bus 1). The output power of the DG is kept constant at all cases. The summary of the simulated cases are shown in Table 1. No tap operation is initiated to study the effect of DG on the feeder voltage profile.

Table 1. The comparison between each case

Test Case	Description
	No DG connection
1 (a)	The distribution system operates with 4.0 MW DG connected at bus 4.
(b)	The distribution system operates with 5.5 MW DG connected at bus 4.
(c)	The distribution system operates with 6.5 MW DG connected at bus 4.
(d)	The distribution system operates with 7.0 MW DG connected at bus 4.
2 (a)	The distribution system operates with 4.0 MW DG connected at bus 3.
(b)	The distribution system operates with 5.5 MW DG connected at bus 3.
(c)	The distribution system operates with 6.5 MW DG connected at bus 3.
(d)	The distribution system operates with 7.0 MW DG connected at bus 3.
3 (a)	The distribution system operates with 4.0 MW DG connected at bus 2.
(b)	The distribution system operates with 5.5 MW DG connected at bus 2.
(c)	The distribution system operates with 6.5 MW DG connected at bus 2.
(d)	The distribution system operates with 7.0 MW DG connected at bus 2.
4 (a)	The distribution system operates with 4.0 MW DG connected at bus 1.
(b)	The distribution system operates with 5.5 MW DG connected at bus 1.
(c)	The distribution system operates with 6.5 MW DG connected at bus 1.
(d)	The distribution system operates with 7.0 MW DG connected at bus 1.

## 3. Results and Analysis

Figure 2 shows the voltage profile through the whole system's buses under study without DG connection. It is observed that the voltage drops linearly starting from the distribution substation to the far-end load in the distribution network under study.

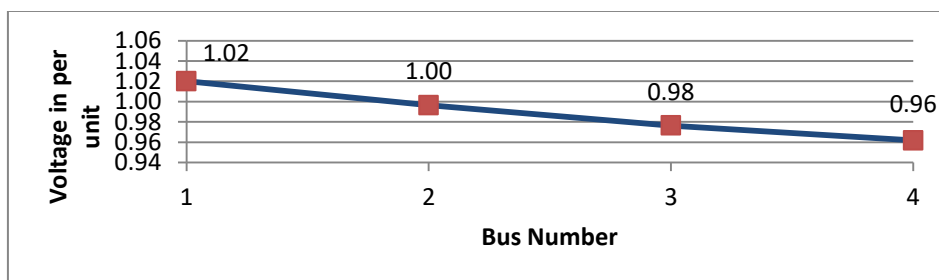


Figure 2. The distribution's network voltage profile without DG

From Figure 4 it is obvious that the voltage level at bus 4 increases when DG is connected (at bus 4). DG's function of providing part of the required demand in the distribution network improves the voltage at the point of DG connection.

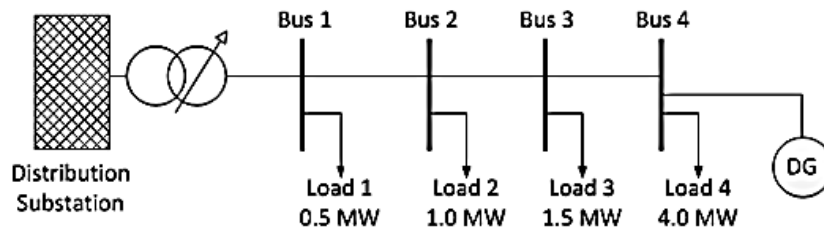


Figure 3. 11 kV radial type test system for case 1

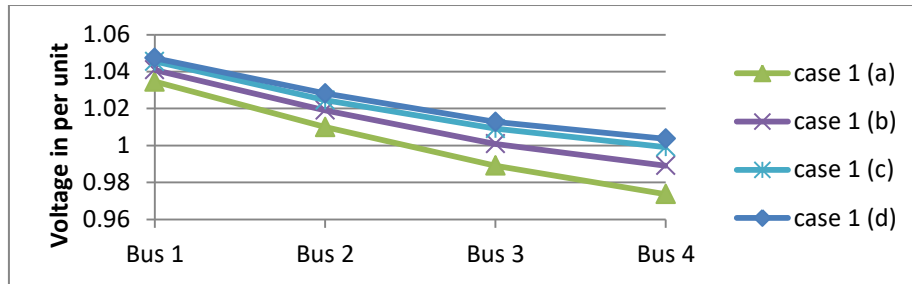


Figure 4. The distribution's network voltage profile for case 1

Figure 4 shows that the DG is able to further improve the voltage profile along the feeder when its capability is increased. Larger DG size contributes to increased source of active power which improves the voltage profile throughout the distribution network. It is observed that a more uniform voltage profile along the distribution feeder is achievable if the DG is supplying a large percentage of the required demand. However, generation exceeding the feeder load could cause DG saturation to occur. DG saturation refers to the point at which large DGs are installed such that it becomes technically infeasible to operate on a single distribution feeder.

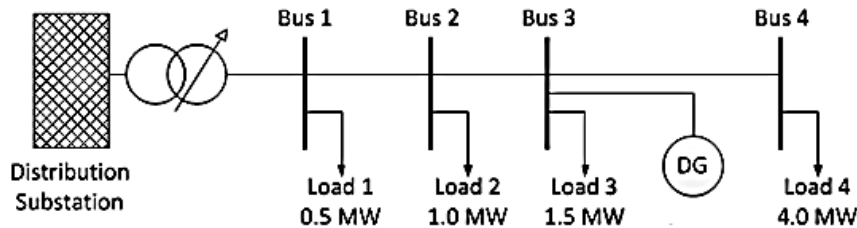


Figure 5. 11 kV radial type test system for case 2

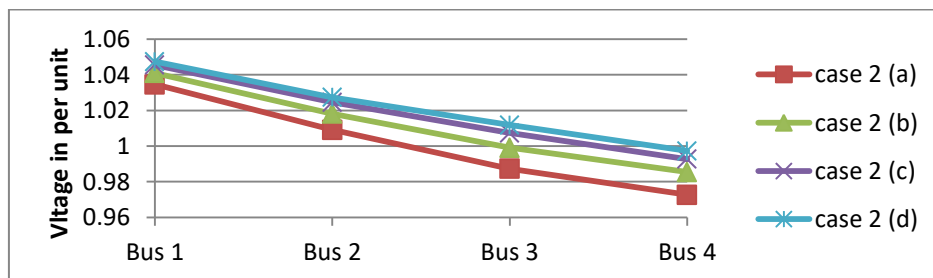


Figure 6. The distribution's network voltage profile for case 2

Figure 6 shows that the voltage level at bus 3 increases when DG is connected (at bus 3). Based on simulation results, it is also observed that DG connection at bus 3 reduces the distribution substation required capabilities all over the distribution network. The results shows that a more improved voltage profile along the feeder is achievable if the DG is capable of providing a larger percentage of the required demand in the distribution network.

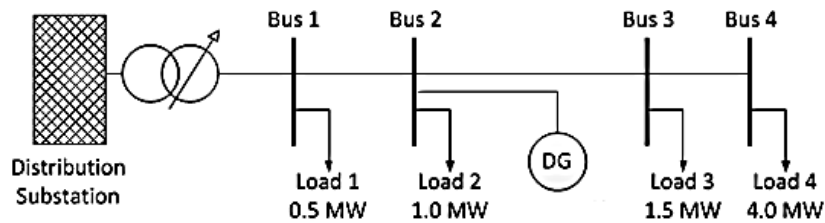


Figure 7. 11 kV radial type test system for case 3

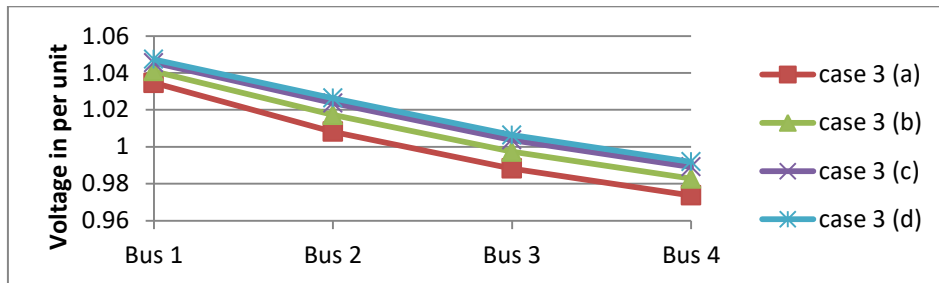


Figure 8. The distribution's network voltage profile for case 3

Figure 8 proves that DG output power supplying for a larger part of required demand is able to improve the overall voltage profile along the distribution feeder. It is observed that higher voltage level of the far-end load side of the distribution network is achievable when the DG capability is increased.

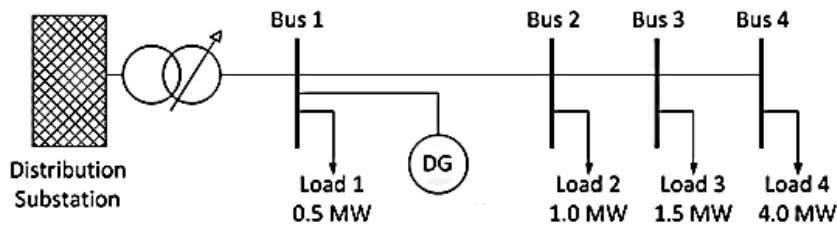


Figure 9. 11 kV radial type test system for case 4

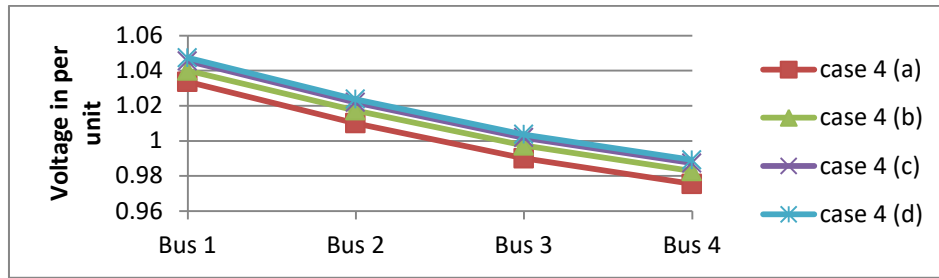


Figure 10. The distribution’s network voltage profile for case 4

Figure 10 shows that the voltage drops linearly starting from the substation to the far-end load in the distribution network when DG is connected at bus 1. However, the voltage level at all the buses is higher compared to without DG connection into the system. Simulation result proves that the connected DG shares the responsibility of supplying the required demand with the substation. It is observed that a larger capacity of DG contributes to a larger part of required demand therefore increasing the voltage level in each bus compared to the scenario without DG connection.

The summary of the simulation results are shown in Table 2.

Table 2. Simulation result for each case

Test Case	Voltage Level (in per unit value)			
	Bus 1	Bus 2	Bus 3	Bus 4
No DG	1.02	1.00	0.98	0.96
1 (a)	1.03	1.01	0.99	0.97
(b)	1.04	1.02	1.00	0.99
(c)	1.05	1.02	1.01	1.00
(d)	1.05	1.03	1.01	1.00
2 (a)	1.03	1.01	0.99	0.97
(b)	1.04	1.02	1.00	0.99
(c)	1.05	1.02	1.01	0.99
(d)	1.05	1.03	1.01	1.00
3 (a)	1.03	1.01	0.99	0.97
(b)	1.04	1.02	1.00	0.98
(c)	1.05	1.02	1.00	0.99
(d)	1.05	1.03	1.01	0.99
4 (a)	1.03	1.01	0.99	0.98
(b)	1.04	1.02	1.00	0.98
(c)	1.05	1.02	1.00	0.99
(d)	1.05	1.02	1.00	0.99

The siting of DGs at various locations shows positive impact on voltage profile. However there is a possibility of voltage rise if the DG penetration level is too high [16]. The rise in voltage could cause misoperation of protective devices and therefore adjustment or changes of protective devices are required. In order to accommodate more DGs, the voltage profile along the feeder should be kept within statutory limits (voltage between  $\pm 10\%$  of the base voltage) and there is a need to employ intelligent devices for this purpose. Development of smart grid allows for the use of intelligent devices and thus helps to keep the voltage level within statutory limits.

**4. Conclusion**

A number of cases are simulated while changing the size and location of DG in the system. The following conclusions can be drawn from this study.

- a. DG mainly provides part of the required demand in the distribution network.
- b. DG implementation as a source of active power has a great positive impact on improving the voltage profile through the entire distribution network.
- c. DG reduces the distribution substation required capacities all over the distribution system.

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