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Analysis on Voltage Profile of Distribution Network with Distributed Generation

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Abstract. Penetration of distributed generation has some impacts on a distribution network in load flow, voltage profile, reliability, power loss and so on. After the impacts and the typical structures of the grid-connected distributed generation are analyzed, the back/forward sweep method of the load flow calculation of the distribution network is modelled including distributed generation. The voltage profiles of the distribution network affected by the installation location and the capacity of distributed generation are thoroughly investigated and simulated. The impacts on the voltage profiles are summarized and some suggestions to the installation location and the capacity of distributed generation are given correspondingly.

1. Introduction

Conventional power systems are facing some problems of poor energy efficiency, the gradual depletion of fossil fuel resources, and environmental pollution, which have led to a new trend of generating power near residential consumers. This type of power generation is termed as distributed generation (DG). In the late 1990s, the major issues related to DG were extensively investigated by the working groups of CIGRE and CIRED in their review reports [1]. DG refers to the unit which directly generates the power in a small scale, outputs electricity, heat and cold for specific users independently. And DG can also be connected to one distribution network.

In a conventional distribution network, electric power is supplied to the customers from substations. Therefore, the normal direction of power flow is from a substation towards the consumers. A small number of DG units scattered over a large distribution area may not impact the network severely, as the generation from DG units may not exceed feeder load. With an increasing level of DG penetration, however, when numerous DG units are connected to the same distribution feeder in a small area, it is a possibility that the total power generated from DG units may exceed the total load demand. This could lead that the power would flow to the head terminal of the network, i.e. reverse power flow, and bus voltage would rise in the feeders of the distribution network as discussed in [2, 3]. If DG is allowed to inject reactive power into the distribution network, some situations may arise depending on the control strategies, such as voltage control, maximum reactive power control, and power factor control. The impacts on the feeder in terms of voltage profiles, feeder load and power losses are also different for each of the control strategies [4]. In reference [5], an assessment is provided on voltage profiles in residential neighbourhoods in the presence of photovoltaic units. A simultaneous network reconfiguration is presented with DG sizing and tap changer adjustment to minimize power loss and maintain voltage within allowable limit in a distribution system [6]. However, the impact analysis on
the voltage profiles of the distribution network is not done in depth by considering DG installation location and capacity.

Based on the existing research, the impacts of DG on the voltage profiles of the distribution network are summarized and analyzed in the paper. The back/forward sweep method is applied to calculate the load flow of the distribution network with distributed generation. The impact of the voltage profiles is discussed for DG installation location and capacity. Some suggestions to the impact are given.

2. Impact of DG on Distribution Network
Now the integration of DG units directly into the distribution network becomes a common practice. The penetration of DG is higher and higher in the distribution network. There are two basic types of DG units, direct current (DC) and alternating current (AC) voltage producing sources. Some grid-interfacing inverters should be used. These inverters produce three-phase or single-phase AC grid voltage (50 or 60 Hz). Some kinds of DG units are shown in Table 1.

| DG Unit                        | Grid-connected mode | Energy type          | Capacity range |
|-------------------------------|---------------------|----------------------|----------------|
| Mini-hydroelectric generator  | Direct connection   | Renewable energy     | W-kW           |
| Photovoltaic unit             | DC/AC Inverter      | Renewable energy     | W-MW           |
| Wind turbine generator        | AC/AC Inverter      | Renewable energy     | W-MW           |
| Fuel cell                     | DC/AC Inverter      | Renewable energy, Fossil energy | W-kW |
| Micro gas turbine generator   | AC/AC Inverter      | Fossil energy        | kW-MW          |
| Diesel generator              | Direct connection   | Fossil energy        | kW-MW          |
| Combined heat and power (CHP) | Direct connection   | Fossil energy        | kW-MW          |
| Biogas generator              | Direct connection   | Renewable energy     | kW-MW          |
| Geothermal generator          | Direct connection   | Renewable energy     | kW-MW          |

When a large number of DG units are connected to the distribution network, some significant impacts are presented on network reliability, power quality, energy loss, power flow, voltage profile, and so on.

1) Reliability. As a standby power supply, DG can be used to eliminate the overload and congestion of the distribution network. However, DG inappropriate installation location, capacity and connection mode can reduce the security and reliability of the distribution network with the power regulation and balancing issues resulted from the randomness and the intermittency of renewable energy sources, such as wind energy and solar energy.

2) Power quality. In the traditional distribution network, the changes of active power and reactive load cause voltage fluctuation. After DG is connected to the distribution network, the voltage fluctuation may increase because of the uncoordinated operation of DG and local load. In addition, the grid-interfacing inverters produce harmonic components which are injected into the distribution network.

3) Energy loss. The power distribution and the loss of the distribution network will change after DGs are connected near the consumers [7]. For example, if the load power at all load buses is greater than the output of DG, the loss of the distribution network will be reduced. If the load power at least one load bus is less than the output of DG, and the total load power of the distribution network is more than the output of all DG, the loss of some lines rises, but the overall line loss of the distribution network may decrease.
4) Protection. The installation of DG units in the distribution network increases the complexity of selective protection coordination, which results in the conflicts in the normal operation of the existing network. DG influences significantly the lightning performance of the distribution lines resulting in a higher lightning failure rate [8].

5) Power flow and voltage profile. The integration of DG into the distribution network can result in the power flow change from unidirectional to bi-directional in a radial structure. Therefore, both magnitude and direction of power will be changed, and the steady-state voltage of the distribution network will be fluctuated. This is the study focus in the paper.

3. Load Flow Calculation of Distribution Network with DG

Voltages at various buses and power injection into the network are mainly interested in load flow analysis. The general structure or topology of the distribution network is radial, as shown in Figure 1. The loop structure is also used in the distribution network, which is normally radial in operation with some switchers being off. Therefore, the back/forward sweep method of load flow calculation can be used in the distribution network [9].

The equivalent circuit of the network in Figure 1 is shown in Figure 2. The back/forward sweep method of load flow calculation includes the forward derivation equations of the branch power, as displayed in equation (1), and backward substitution equations of bus voltages, as displayed in equation (2).

\[
\begin{align*}
\tilde{S}_i^{(k)} &= \tilde{S}_i + (U_i^{(k)})^2 y_{ii0} - \tilde{S}_G_i \\
\tilde{S}_i^{(k)} &= \tilde{S}_i + (U_i^{(k)})^2 y_{ii0} - P_{Gi} - j Q_{Gi} \\
\tilde{S}_j^{(k+1)} &= S_j^{(k)} + \sum_{k \in j} \tilde{S}_j^{(k+1)} \\
\tilde{S}_j^{(k+1)} &= S_j^{(k+1)} + (P_j^{(k+1)})^2 + (Q_j^{(k+1)})^2 z_{ij}
\end{align*}
\]

**Figure 1.** A radial distribution network

**Figure 2.** The equivalent circuit of the network
\[
\begin{align*}
U_j^{(k+1)} &= \sqrt{\left(U_i^{(k+1)} - \Delta U_i^{(k+1)}\right)^2 + \left(\delta U_i^{(k+1)}\right)^2} \\
\Delta U_i^{(k+1)} &= \frac{P_{ij}^{(k+1)} r_{ij} + Q_{ij}^{(k+1)} x_{ij}}{U_i^{(k+1)}} \\
\delta U_j^{(k+1)} &= \frac{P_{ij}^{(k+1)} x_{ij} + Q_{ij}^{(k+1)} r_{ij}}{U_j^{(k+1)}} \\
\delta_j^{(k+1)} &= \delta_j^{(k+1)} - \arctan \frac{\Delta U_j^{(k+1)}}{U_j^{(k+1)} - \Delta U_i^{(k+1)}} \tag{2}
\end{align*}
\]

where \( y_{i0} \) is all admittance in parallel at bus \( i \), \( z_{ij} \) is the branch impedance between bus \( i \) and bus \( j \), \( k \) is iteration number, \( \tilde{S}_j^{(k)} \) is calculation power in the \( k \)th iteration at bus \( i \), \( \tilde{S}_{li} \) is load power at bus \( i \), \( U_i^{(k)} \) is the voltage magnitude in the \( k \)th iteration at bus \( i \), \( \tilde{S}_{Gi} \) is apparent injection power of DG at bus \( i \), \( P_{Gi} \) is active injection power of DG at bus \( i \), \( O_{Gi}^{(k)} \) is reactive injection power of DG in the \( k \)th iteration at bus \( i \), \( \tilde{S}_j^{(k+1)} \) is branch power in the \((k+1)\)th iteration between bus \( i \) (the start bus of a branch) and bus \( j \) (the end bus of the branch), \( \delta_j^{(k+1)} \) and \( \delta_j^{(k+1)} \) are voltage phase angle in the \((k+1)\)th iteration at bus \( i \) (the start bus of the branch) and bus \( j \) (the end bus of the branch), respectively.

Once obtaining the active and reactive injection power at the AC bus connected with DG, e.g., photovoltaic unit, the AC bus can be regarded as PQ bus in the load flow calculation. The bus voltage magnitude and phase angle are updated for all PQ buses in once iteration. In addition, the bus voltage phase angle and reactive injection power of DG should be updated after once iteration according to equation (3) and (4), respectively.

\[
\hat{U}_i^{(k+1)} = U_i < \delta_i^{(k+1)} \tag{3}
\]

\[
Q_{Gi}^{(k+1)} = U_i^{(k+1)} \sum_{j \in i} U_j^{(k+1)} (b_j \cos \delta_{ij} - g_j \sin \delta_{ij}) - (U_i^{(k+1)})^2 \left( \sum_{j \in i} b_{ij} + b_{i0} \right) + Q_{Li} \tag{4}
\]

where \( \delta_{ij} = \delta_i - \delta_j \), \( g_{ij} \) and \( b_{ij} \) are the branch conductance and susceptance between bus \( i \) and bus \( j \), \( Q_{Li} \) is load power at bus \( i \), \( j \in i \) means all the buses that are directly connected to bus \( i \), i.e., PV bus.

All voltages are obtained until the load flow calculation converges. If \( \max \left| \hat{U}_i^{(k+1)} - \hat{U}_i^{(k)} \right| < \varepsilon \) is satisfied, the sequential iteration stops.

### 4. Simulation and Analysis of Test Network with DG

The load flow calculation and the voltage profile are done in IEEE 33-bus distribution network, as shown in Figure 3. The voltage at bus 0 is set to 1.05 p.u.
4.1. Different DG capacity at same location

When DG is connected to bus 8, i.e. the middle bus of the trunk line, the bus voltage variation is shown as Table 2 with different capacity or injection power. It is obvious that when the DG capacity increases, the bus voltages of the distribution network will rise. And increasing voltage amplitudes of the load side buses are greater.

When DG is connected to bus 17, i.e. the end bus of the trunk line, the bus voltage variation is shown as Table 3 with different capacity. It is obvious that when the DG injection power increases, increasing bus voltage amplitude is greater. And when DG is connected to the line end, it easily causes the bus voltage over-limit near the line end.

| DG injection power /MW | Voltage at bus 2 /p.u. | Voltage at bus 8 /p.u. | Voltage at bus 17 /p.u. | Voltage at bus 24 /p.u. | Voltage at bus 32 /p.u. |
|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| 0                      | 1.03                   | 0.99                   | 0.97                   | 1.02                   | 0.97                   |
| 0.5                    | 1.04                   | 1                      | 0.98                   | 1.02                   | 0.98                   |
| 1                      | 1.04                   | 1.02                   | 1                      | 1.03                   | 0.99                   |
| 1.5                    | 1.04                   | 1.03                   | 1.01                   | 1.03                   | 1                      |
| 2                      | 1.04                   | 1.05                   | 1.03                   | 1.03                   | 1                      |
| 2.5                    | 1.04                   | 1.06                   | 1.04                   | 1.03                   | 1.01                   |

| DG injection power /MW | Voltage at bus 2 /p.u. | Voltage at bus 8 /p.u. | Voltage at bus 17 /p.u. | Voltage at bus 24 /p.u. | Voltage at bus 32 /p.u. |
|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| 0                      | 1.03                   | 0.99                   | 0.97                   | 1.02                   | 0.97                   |
| 0.5                    | 1.04                   | 1                      | 0.98                   | 1.02                   | 0.98                   |
| 1                      | 1.04                   | 1.02                   | 1                      | 1.03                   | 0.99                   |
| 1.5                    | 1.04                   | 1.03                   | 1.05                   | 1.03                   | 0.99                   |
| 2                      | 1.04                   | 1.04                   | 1.12                   | 1.03                   | 1                      |
| 2.5                    | 1.04                   | 1.05                   | 1.15                   | 1.03                   | 1.01                   |

4.2. Same DG capacity at different location

When DG is connected to different buses with injection power of 1.5MW, the bus voltage variation is shown as Table 4. When DG is connected to start bus of a line, the influence effect of voltage profile
in the line is not obvious. When DG is connected to the central bus of the trunk line, the increasing
effect of the voltage profile is obvious. When DG is connected to the line end, the increasing effect of
the voltage profile is most significant, and it may not maintain the bus voltage within allowable limit
near the line end.

| No  | Voltage at bus 2 /p.u. | Voltage at bus 8 /p.u. | Voltage at bus 17 /p.u. | Voltage at bus 24 /p.u. | Voltage at bus 32 /p.u. |
|-----|-----------------------|------------------------|------------------------|------------------------|------------------------|
| 1   | 1.03                  | 0.99                   | 0.97                   | 1.02                   | 0.97                   |
| 8   | 1.04                  | 0.99                   | 0.97                   | 1.02                   | 0.97                   |
| 17  | 1.04                  | 1.03                   | 1.08                   | 1.03                   | 0.99                   |

4.3. **DG at different location and DG at one bus with same total capacity**

The voltage profiles of five operation cases are show in Figure 4.

1) **Case 1.** DG is connected to bus 1 with 1.5MW total injection power.
2) **Case 2.** DG is connected to bus 8 with 1.5MW total injection power.
3) **Case 3.** DG is connected to bus 17 with 1.5MW total injection power.
4) **Case 4.** There is no DG in the network.
5) **Case 5.** DG is connected to 4 buses with 1.5MW total injection power, i.e. 0.375MW at bus 4,
bus 9, bus 14 and bus 18, respectively.

It is obvious that the increasing effect of voltage profile in a line is quite small when the DG is
connected to the head terminal bus of the line, as shown in Figure 4. When the DG is connected to
the middle bus of the trunk line, the increasing effect of the voltage profile is obvious. When DG is
connected to the line end, the increasing effect of the voltage profile is most significant, and it can
easily cause the bus voltage over-limit near the line end. It is a better effect to the voltage profile that
DG units of small capacity are connected at different buses. In other words, compared with the
centralized connection, DG units should be dispersed to connect into the distribution network.

![Figure 4. One line diagram of IEEE 33-bus distribution network](image)

5. **Conclusion**

The voltage profile of the distribution network is analyzed for different DG installation location and
capacity. The back/forward sweep method is applied to the load flow calculation and the simulation of
the distribution network with distributed generation. The impact result caused by DG connection on
the voltage profile is obtained.
In fact, the voltage profile changes with arbitrary location of DG in the distribution network. But the voltage change is not obvious when DG is connected to the head terminal bus of the line. The increasing effect of the voltage profile is more obvious when DG is connected to the middle bus of the trunk line. When DG is connected to the line end, the increasing effect of the voltage profile is most significant, and it may not maintain the bus voltage within allowable limit near the line end. To ensure the voltages of all buses in the distribution network within allowable limit, DG units should be dispersed to connect into the distribution network.

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