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Impact of Distributed Generation Capacity on the Voltage of Distribution System

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Abstract. Large-scale grid-connected distributed generation (DG) will cause out-of-limit of voltage deviation. The model of voltage drop caused by loads and voltage rise caused by distributed generators are established under different loads or DG distribution modes along the line, and the maximum allowable capacity of power injected into the grid without causing over-voltage is calculated, assuming the bus voltage deviation reaching the upper limit. The maximum DG penetration level of typical distribution lines is derived under the condition that generators is of the same distribution mode with loads, and the voltage margin at the head end of the line without causing over-voltage is proposed. The results show that over-headlines can carry much more DG power than cables, and over-voltage will be avoided by controlling the DG capacity according to the connected bus voltage, and suitably lowering the bus voltage will allow much more DG to connect into the grid.

1 Introduction

In the aspects of sustainable development in energy area, improving the power distribution grid reliability level and solving power supply problem in distant districts, distributed generation such as Photovoltaic, wind and biomass power generation is widely getting more attention. DG connected into the grid can change the power flow distribution, and this trend affects the steady-state voltage distribution of the network[1-2]. On the one hand, the rational allocation of DG has a supporting role in voltage distribution[3], on the other hand, unconstrained DG connected to grid may cause over-voltage phenomenon[4]. Therefore, research about maximum allowable DG capacity is necessary, since it can be used to guide and regulate the rational use of the new power source.

In this paper, the method of calculating the maximum capacity DG power injected into the feeder without causing over-voltages is proposed assuming the bus voltage deviation reaching the upper limit, based on voltage deviation model in different loads or DG distribution modes along the line, such as concentrating in the end, increasing, decreasing or uniform distribution modes. The impact of reactive power losses of distribution transformers to feeder voltage is also considered. The results show that, according to feeder parameters, distribution of the load and DG, and load capacity , the maximum allowable capacity as the peak capacity of DG can be estimated by the method proposed in this paper. The paper concludes with a general adaptability, especially for a preliminary assessment of grid-connected DG capacity.

2 Voltage Deviation Model

2.1 Establishment of the Model

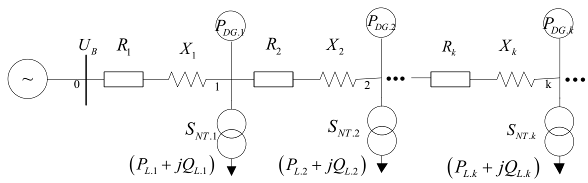

Figure 1. Circuit model of radial feeder with distributed loads and distributed generators

The city distribution network can be modeled as a single radiate grid in one normal operating state[5]. Since the capacity of entire power system is much greater than the total capacity of the loads linked with a distribution bus, therefore, the system above the distribution bus may be equivalent to a voltage source. Under the control of regulating devices, though bus voltage changes, it meets the requirements of the grid voltage deviation. Several loads and distributed generators are distributed in different position of feeders. Node load is illustrated by a constant power static model and also assumed as linear symmetrical. The DG power is characterized as pure

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active power source which does not participate in the voltage regulation of the distribution network, due to the balance of reactive power locally[6]. Under equivalent conditions above, circuit model of radial feeder with distributed loads and distributed generators is shown in Fig.1.1.

Assuming there are N nodes on a feeder, and each node is connected with the loads and distributed generators. If any node is not connected with the distributed generators or loads, the power of the node is set to zero. In Figure 1, No.0 node represents the distribution bus. (R_k,X_k)is the equivalent impedance of the k-th feeder. ($P_{L.k}$+$jQ_{L.k}$) is the the load power of the k-th node. $P_{DG\cdot k}$ is the generators power of the k-th node. It is emphasized that, the direction of active power flow of DG is contrary to the power flow of load.

2.2 Analysis of the Model

In Figure 1, voltage deviation between node *k* and the distribution bus can be calculated in the distribution network as Eq.1.

$$\Delta U_k(\%) = \frac{\sum_{j=1}^{k}\left[R_j \cdot \sum_{i=j}^{n} P_{L.i} + X_j \cdot \sum_{i=j}^{n} Q_{L.i}\right]}{U_N^2} \times 100 - \frac{\sum_{j=1}^{k}\left[R_j \cdot \sum_{i=j}^{n} P_{DG.i}\right]}{U_N^2} \times 100 \qquad (1)$$

Eq.1 shows that, distributed generators connected with any point in the distribution network will help to reduce the voltage loss on the line, which have a supporting role in the voltage on the feeder. The more it approaches the end of the feeder, the stronger the voltage supporting role is.

Extended to the general case, p_l(x), q_l(x),and p_{DG}(x) is respectively considered as the distribution function of active loads , reactive loads, and distributed generators along the feeder, and L is the total length of feeder. The voltage deviation of distance l between the bus and any point of the feeder can be calculated as fllow Eq.2.

$$\Delta U_{(l)}(\%) = \frac{\int_0^l \left(\int_y^L p_L(x)dx\right) r_0 dy + \int_0^l \left(\int_y^L q_L(x)dx\right) x_0 dy}{U_N^2} \times 100 - \frac{\int_0^l \left(\int_y^L p_{DG}(x)dx\right) r_0 dy}{U_N^2} \times 100 \qquad (2)$$

Assuming $S_{NT.i}$ is the rated capacity of a distribution transformer connected with the i-th node, and α is active load ratio of the transformer. No-load reactive power loss rate of transformer is considered as the average 2.5%, and load power factor of urban 10kV distribution network is considered as 0.95. The active and reactive power of the node can be indicated as Eq.3.

$$P_{L.i} = \alpha S_{NT.i} \qquad (3)$$

$$\begin{aligned} Q_{L.i} &= 0.025 S_{NT.i} + \tan\left[\cos^{-1}(0.95)\right] \cdot P_{L.i} \\ &= (0.025/\alpha_i + 0.32) P_{L.i} = 0.37 P_{L.i} \end{aligned} \qquad (4)$$

Combining Eq.3 and Eq.4, the relationship between the reactive and active power on the feeder can be obtained as Eq. 5.

$$q(x) = 0.37 p(x) \qquad (5)$$

Eq.5 substituted into Eq.2, the voltage deviation between the bus and any point of the feeder can be calculated as fallow Eq.6.

$$\Delta U_{(l)}(\%) = \frac{(r_0 + 0.37 x_0)\int_0^l \left(\int_y^L p_L(x)dx\right) dy}{U_N^2} \times 100 - \frac{r_0 \cdot \int_0^l \left(\int_y^L p_{DG}(x)dx\right) dy}{U_N^2} \times 100 \qquad (6)$$

Eq.6 shows that due to the voltage drop caused by loads alone, over-voltage do not appear on the feeder. However, owing to the voltage rise caused by generators, over-voltage may appear in the middle of the feeder.

3 Peak Capacity of DG

3.1 Calculation Method of Voltage Deviation and Peak Capacity

In order to get a general adaptive conclusion about the voltage deviation and peak capacity, the following research is focused on different loads or DG distribution modes along the line, such as concentrating in the end, increasing, decreasing or uniform distribution.

Power distribution function *p(x)* can be obtained as Eq.7 to Eq.10, for different typical distribution mode. Assuming *L* is the total length of the feeder, and *P* is the total active power, and *x* is the position of a point on the feeder, δ *(L-x)*is the delta function.

1. concentrating in the end mode:

$$p(x) = P \cdot \delta(L - x) \qquad (7)$$

2. increasing distribution mode:

$$p(x) = 2P \cdot x / L^2 \qquad (8)$$

3. decreasing distribution mode:

$$p(x) = P / L \qquad (9)$$

4. uniform distribution mode:

$$p(x) = 2P \cdot (L - x) / L^2 \qquad (10)$$

Table 1. Voltage deviation in different load and Power distribution modes

Modes	Voltage drop $\Delta U_{L(l)}(\%)$	Voltage rise $\Delta U_{DG(l)}(\%)$
Concentrating in the end	$\frac{P_L(r_0+0.37x_0)}{U_N^2}l\times100$	$\frac{P_{DG}r_0}{U_N^2}l\times100$
Increasing distribution	$\frac{P_L(r_0+0.37x_0)}{U_N^2}\left(1-\frac{l^2}{3L^2}\right)\times100$	$\frac{P_{DG}r_0}{U_N^2}\left(1-\frac{l^2}{3L^2}\right)l\times100$
Decreasing distribution	$\frac{P_L(r_0+0.37x_0)}{U_N^2}\left(1-\frac{l}{2L}\right)l\times100$	$\frac{P_{DG}r_0}{U_N^2}\left(1-\frac{l}{2L}\right)l\times100$
Uniform distribution	$\frac{P_L(r_0+0.37x_0)}{U_N^2}\left(1-\frac{l}{L}+\frac{l^2}{3L^2}\right)l\times100$	$\frac{P_{DG}r_0}{U_N^2}\left(1-\frac{l}{L}+\frac{l^2}{3L^2}\right)l\times100$

Combining Eq.6 and Eq.7 to Eq.10, voltage deviation is calculated in Table 1.$\Delta U_{L(l)}(\%)$ is the voltage drop of distance l between the bus and any point of the feeder caused by load in different distribution modes, and $\Delta U_{DG(l)}(\%)$ is the voltage rise of distance l caused by DG.

Assuming the voltage of the distribution bus is qualified and just reached the upper limit, requirement for no over-voltage on the feeder is proposed as Eq.11.

$$\Delta U_{(l)}(\%)=\Delta U_{L(l)}(\%)-\Delta U_{DG(l)}(\%)>0 \tag{11}$$

Peak capacity of DG in different load and power distribution modes along the line is calculated based on Eq. 11 and Table 1.The result is summarized in Table 2.In Table 2, P_0 is equal to $(1+0.37x_0/r_0)P_L$.

Table 2. Peak capacity of DG in different load and generators distribution modes

Modes	Load concent-rating	Load increasi-ng	Load unifor-m	Load decreas-ing
DG concentrating in the end	$P_{DG}< P_0$	$P_{DG}< 2/3P_0$	$P_{DG}< 1/2P_0$	$P_{DG}< 1/3P_0$
DG increasing distribution	$P_{DG}< P_0$	$P_{DG}< P_0$	$P_{DG}< 3/4P_0$	$P_{DG}< 1/2P_0$
DG uniform distribution	$P_{DG}< P_0$	$P_{DG}< P_0$	$P_{DG}< P_0$	$P_{DG}< 2/3P_0$
DG decreasing distribution	$P_{DG}< P_0$	$P_{DG}< P_0$	$P_{DG}< P_0$	$P_{DG}< P_0$

As can be seen from Table 2, if the load distribution mode is the same as DG's, as long as the capacity of DG power is less than P_0 value, the over-voltage on the feeder does not occur. If the load distribution and DG distribution is not the same, the maximum allowable capacity as the peak capacity is much smaller than above.

3.2 DG penetration level

Table 3 shows the maximum DG penetration level β (P_{DG}/P_L)of different feeders under the voltage constraints when the load distribution is the same as DG's.

Table 3. Maximum DG penetration level in same distribution mode of load and DG along the line

Feeder types		r_0/ (Ω /km)	x_0/ (Ω /km)	β / (P_{DG} /P_L)
Overhead lines	LGJ-70	0.414	0.38	1.34
	LGJ-150	0.197	0.36	1.68
	LGJ-240	0.121	0.34	2.05
Cables	YJV-70	0.267	0.101	1.14
	YJV-150	0.124	0.093	1.28
	YJV-240	0.076	0.087	1.43

Concerned overvoltage issue, data in Table 3 shows that:

1. In terms of the same type of line, the larger conductor cross-section, the higher the maximum DG penetration level.
2. Under the same conductor cross-section, the overhead lines can carry a higher DG penetration level compared with cables.
3. In the actual system, load and DG power is random. If DG power still meets the requirements of the Table 1 and Table 3 in the condition that P_L is considered as the minimum load power, and DG power as its rated, overvoltage will not appear on the feeder.

3.3 Overvoltage Solutions

If the DG power and load power can't meet the requirements above, necessary measures should be taken to resolve over-voltage problem.

3.3.1 Restricting the DG power capacity

Distributed generators should have the ability of adjust their power or quiting running according to bus voltage. Once the bus voltage is higher than the permissible limit, the control system of generators is capable to adjust it.

3.3.2 Regulating bus voltage and reserving margin

If distributed generators do not have the ability of adjust the power, regulating bus voltage measures such as adjusting transformer taps need to be taken, to make sure that there is a certain margin between the bus voltage and the voltage limit.

The maximum voltage rise $U_{DG.\max}(\%)$ caused by generators, and the short-circuit capacity S_{PI} at the end of feeders can be respectively calculated as Eq.12 and Eq.13.

$$\Delta U_{DG.\max}(\%)=\frac{P_{DG}r_0L}{U_N^2}\times100 \tag{12}$$

$$S_{PI}=\frac{U_N^2}{L\sqrt{r_0^2+x_0^2}}=\frac{U_N^2}{r_0L\sqrt{1+x_0^2/r_0^2}} \tag{13}$$

According to *Q/GDW480-2010 The Technical Requirements of Distributed Power Connected to the Grid*, the ratio of short-circuit current of the grid connected point and rating current of distributed power is not less than 10. Integrating Eq.12 and Eq.13, the maximum voltage rise under the voltage constraints can be obtained as Eq.14.

$$\Delta U_{DG.\max}(\%) \le \frac{1}{\sqrt{1+x_0^2/r_0^2}} \times 10 \qquad (14)$$

If the actual reserved voltage deviation of the bus is greater than the maximum voltage rise $\Delta U_{DG.\max}(\%)$ calculated above, over-voltage does not appear on the feeder. With LGJ-240 overhead lines as an example, since its x_0/r_0 is about 3, the maximum voltage rise or bus voltage regulator margin is 3.16%.

4 Conclusions

Equations should be centred and should be numbered with the number on the right-hand side.

It is necessary to restrict the capacity of distributed generators connected into the grid because of over-voltage problems it caused on the feeder.

1. The peak capacity of DG can be estimated by the method proposed in this paper, according to feeder parameters, distribution mode of the load and distributed generators, and load capacity.
2. In the actual system, load and DG power is random. If the DG power and load power can't meet the requirements, it is necessary to restrict the capacity of DG, and regulate bus voltage or reserve voltage margin. The method of calculating voltage margin at the head end of feeder is also provided.

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