Impact of Distributed Generation on Voltage Profile and Losses of Distribution Systems

JIANG Fengli, ZHANG Zhixia, CAO Tong, HU Bo, PIAO Zailin*

Department of Information and Electrical Engineering, Shenyang Agricultural University, Shenyang 110866, P.R.China
E-mail: fengli0308@163.com

Abstract: A new backward/forward algorithm is presented based on constant power load model for the analysis of radial distribution systems. In the proposed method, active and reactive power is used as flow variables. The mathematical model of different types of distributed generation (DG) is modeled as PQ, PV and PQ(V) nodes in the power flow program. The voltage profile and active power losses prior and after introducing DG to radial distribution systems are calculated corresponding to DG units in different modes. IEEE 33-bus test system is used to obtain the results. The results of simulation indicate that the adopted models, different location and capacity of DG can significantly affect the system voltages and losses.

Key Words: Distributed generation, voltage profile, active power losses, distribution systems

1 Introduction

Distributed generation (DG) is related with the use of small generating units installed in strategic points of the electric power system close to load centers. DG technologies include small gas turbines, micro-turbines, fuel cells, wind and solar energy, etc. In distribution systems, DG can provide benefits for the consumers as well as for the utilities, especially in sites where the central generation is impracticable or where there are deficiencies in the transmission system[1,2] . However, the introduction of DG can change the structure distribution systems and have a significant impact on the power flow, voltage profile, and stability [3, 4].The extent of the impacts is related to the types, locations and capacity of DG. A "voltage rate index" is presented in [5] and [6] to analyze the voltage profiles prior and after introducing DG. Reference [6] studies the influence of the change of locations and capacity of DG on the voltage profile and power losses of distribution systems. However, both of them modeled DG as PQ type nodes. In [7], analytical approaches for optimal placement of DG with unity power factor in power systems are proposed.

This paper divides different distributed generations into three types: PQ type，PV type，PQ(V)type, respectively. Moreover, it proposes a power flow solution based on backward/forward sweep technique. The proposed methods are tested by simulations on an IEEE 33-bus test system to obtain the impact on voltage and active power losses with different location and output of different DGs.

2 DG modeling for power flow calculation

2.1 Node types of DG

In general, there are only slack node and PQ nodes in traditional distribution systems. But due to the difference of DG's operation mode and the type of its connection to the grid, different mathematical models will be used for DG according to the specific algorithm. Common DG types and its corresponding node type are shown in table 1.

2.2 DG modeled as PQ node

The DG units, which are modeled as PQ nodes can be treated as negative PQ loads in power flow calculation.

The following equation describes it:

$$\begin{cases} P = -P_S \\ Q = -Q_s \end{cases} \tag{1}$$

where P and Q are produced by active and reactive power of DG, respectively.

Table 1: Node types of DG for power flow calculation

DG types	Node type
(a)The DG is connected to the grid via synchronous generator with excitation control mode for power factor control. (b)Photovoltaic systems, fuel cells, micro-turbines, and part of wind turbines are connected to the grid via power electronic interface devices.(the control circuit of the inverter is designed to control P and Q, respectively)	PQ
(a)The DG is connected to the grid via synchronous generator with excitation control mode for voltage control. (b) Photovoltaic systems, fuel cells, etc, via an inverter with voltage control mode. (c)Photovoltaic systems ， fuel cells, micro-turbines, and part of wind turbines are connected to the grid via power electronic interface devices. (the control circuit of the inverter is designed to control P and V, respectively)	PV
(a)Wind turbines via asynchronous motor interface. (b)The DG via synchronous generator without excitation devices.	PQ(V)

2.3 DG modeled as PV node

For PV node, the output of active power and voltage of generator are specified. The model is described as follows:

$$\begin{cases} P = -P_S \\ U = U_s \end{cases} \tag{2}$$

2.4 DG modeled as PQ (V) node

For PQ (V) node, assuming P is a constant，the output of reactive power is related to bus voltage of the generator. The model is described as follows:

$$\begin{cases} P = -P_S \\ Q = -f(V) \end{cases} \tag{3}$$

3　Power flow solution

3.1 Backward/forward sweep power flow algorithm

A radial distribution system is shown in Fig. 1. For any branch $l(i,j)$, assuming DG whose output power is $P_j^I + jQ_j^I$ is introduced at node j , and then DG is equivalent to the load with power $-(P_j^I + jQ_j^I)$.
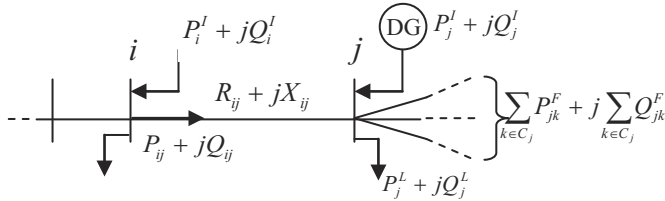

Fig.1: A radial distribution networks

The main contents of iterative algorithm solving the radial system are as follows:

(1) Set the voltage magnitude of all nodes as $U^{(0)}$.

(2) Backward sweep to sum up branch power: Starting from the branches connected to the end buses and moving toward the root node, the output power in branch l is

$$P_{ij} = P_j^L + \sum_{k \in C_j} P_{jk}^F - P_j^I + \Delta P_{ij} \tag{4}$$

$$Q_{ij} = Q_j^L + \sum_{k \in C_j} Q_{jk}^F - Q_j^I + \Delta Q_{ij} \tag{5}$$

where P_{ij} , Q_{ij} are sending power of branch l ; i , j represents the sending node and the receiving node of branch l ; P_j^L , Q_j^L are the load active and reactive power at node j , respectively; P_j^I , Q_j^I are injected power of DG; C_j is the set of branches which are connected to the ending node of branch l ; P_{jk}^F , Q_{jk}^F are the power of branch k ; ΔP_{ij} , ΔQ_{ij} are power losses of branch l .

(3) Forward sweep to update nodal voltages: Starting from the first branch, which is connected to the slack node, and moving toward the ending branches:

$$U_j = \sqrt{(U_i - \frac{P_{ij}R_{ij} + Q_{ij}X_{ij}}{U_i})^2 + (\frac{P_{ij}X_{ij} - Q_{ij}R_{ij}}{U_i})^2} \tag{6}$$

where R_{ij}, X_{ij} are resistance and reactance of branch l , respectively.

The solution for distribution load flow can be obtained by equation (4)-(6). It is stressed that the most important

part of the method is to get the injected power (P^I, Q^I) of DGs.

3.2 Incorporating DG units in power flow solution

The DG units, the main idea of this paper is to regard them as negative loads. Equations (1) and (2) can be used to get the P^I, Q^I （which are mentioned in 2.1） when the DGs are modeled as PQ nodes or PQ(V) nodes in power flow solution. For the DG, which are represented by PV node, reactive power is needed to maintain the specified voltage value. The paper adopts the method of literature [7], the equation is as follows:

$$X\Delta Q = \Delta U \tag{7}$$

Therefore,

$$\Delta Q = X^{-1}\Delta U \tag{8}$$

where X is the $n \times n$ positive sequence sensitivity reactance matrix corresponding to PV nodes and n is the number of them. The solution of the diagonal element x_{ii} and the off-diagonal elements x_{ij} is introduced in literature [8]. ΔQ is the $n \times 1$ reactive power injections vector corresponding to PV nodes. ΔU is the $n \times 1$ vector of the positive sequence voltage mismatches corresponding to PV nodes.

After each iteration, the injected reactive power at PV nodes is updated as follows:

$$Q^{k+1} = Q^k + \Delta Q^k \tag{9}$$

where k is the iteration count.

4 Numerical results

A 33 bus radial distribution test system was chosen to analyze the impact of DG on voltage profile and losses of distribution systems. The topological structure and system parameter of the 33 bus network are obtained from [9]. The specified power is set as 10MW, voltage is 10.5 kV, and convergence is $\varepsilon < 10^{-4}$.

In order to ensure the entire network is strictly absorption type, it is assumed that the load is always greater than DG capacity. The power flow calculation results of node voltages for 0-17 nodes in the main feeder are shown in figure 2-7.

4.1 Impact of different location of DG on voltage profile and losses

In order to analyze the impact of different location of DG on voltage profile and losses, three different types of DGs were introduced at different nodes with constant capacity.

4.1.1 Impact on voltage profile

(1) Voltage profile of nodes when DG as PQ node
A DG as PQ node was introduced at node 3,8,10,12,14,16, respectively. Its apparent power was $S = 500 + j500 kVA$. The results are shown in Fig. 2.

Fig.2 shows the comparison of voltage profile without and with DG as PQ node introduced at different nodes.
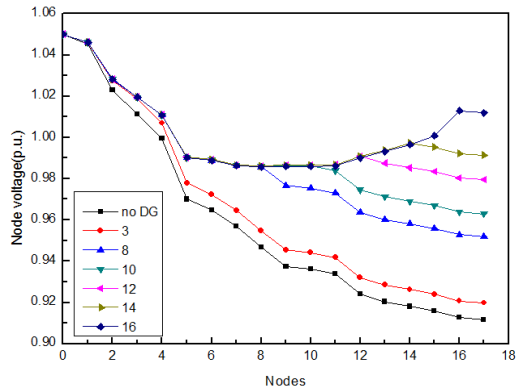
Fig. 2: DG as PQ node

The following conclusions can be drawn:

(a) The voltages of all nodes have improved after DG is introduced.

(b) Through the comparison, it is found that the closer the DG is from feeder terminal, the better the improvement of the voltage is.

(c) The voltage of terminal node is not the lowest with the presence of DG. In addition, the node voltages are improved obviously behind the introduced node and remain the same before the node.

(2) Voltage profile of nodes when DG as PV node

A DG as PV node was introduced at node 8, 10, 12, 14, 16, respectively. Its active power was $P = 500kW$ and the voltage was $V_s = 10kV$.
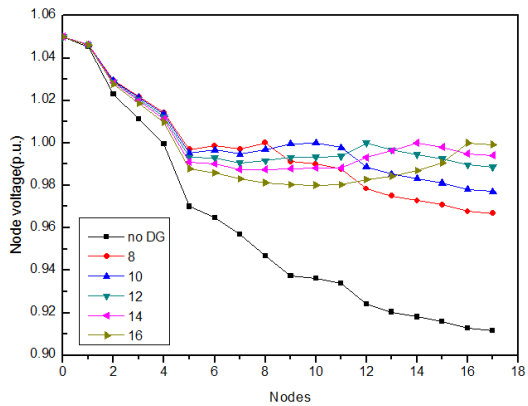

Fig. 3: DG as PV node

Fig. 3 shows the comparison of voltage profile without and with DG as PV node introduced at different nodes.

The following conclusions can be drawn:

(a) Compared to PQ node, PV node has more apparent improvement on voltage profile due to the impact of the injected reactive power.

(b) The voltage of the node where introduced DG was maintained a specific value and the voltage of other nodes reduced slightly (almost flat along the feeder).

(c) The voltage improvement of PV node is different from PQ node; the best location is not at the terminal of the feeder line but at the middle location.

(3)Voltage profile of nodes when DG as PQ(V) node

A DG as PQ(V) node was introduced at node 3,8,10,12,14,16, respectively. It is connected to the grid via asynchronous generator interface. Its active power was $P = 500kW$ and the relationship of reactive power and voltage was described as:

$Q = -\dfrac{U^2}{x_m} + \dfrac{-U^2 + \sqrt{U^4 - 4P^2 x^2}}{2x}$. Its parameters are $x_m = 3.8$, $x = 0.195$.

Fig. 4 shows the comparison of voltage profile without and with DG as PQ (V) node introduced at different nodes.
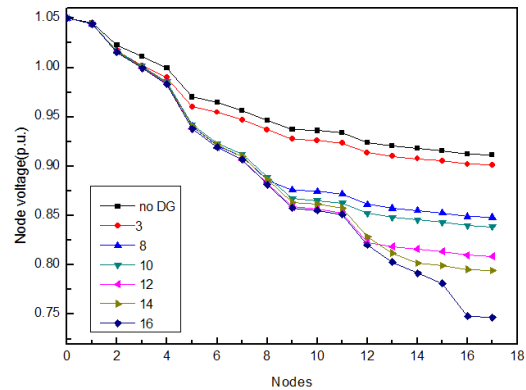

Fig. 4: DG as PQ (V) node

The voltages of all nodes reduced after introducing DG as PQ (V) node. The reason maybe the DG unit absorbed the reactive power from the distribution systems. For the location, when the introduced node moves to the terminal node, the voltages reduced gradually. However, the reduction is not obvious.

4.1.2 Impact on active power losses

Table 2: losses at different location

DG type	Active power losses at different locations (kW)					
	No DG	Introduced node				
		8	10	12	14	16
PQ	318.03	207.11	200.83	196.70	197.19	203.03
PV	318.03	191.40	191.22	192.92	196.23	206.93
PQ(V)	318.03	756.35	789.42	935.39	968.37	1049.4

Table 2 shows a comparison of losses prior and after three kinds of DG installation. It can be observed that the losses are related with the type of DGs closely. For DG as PQ node, when the introduced node of DG was from substation to loads, the losses reduced first, and then improved along the feeder. It is noted that the minimum loss is at the node which is located relatively medial, posterior of the feeder (such as node 12 in the table 2). For the PV type DG, the losses will reduce if the location is reasonable. The minimum loss is at the node which is located in the medial of the feeder (such as node 10 in the table 2). Due to absorbing reactive power from distribution systems, the PQ (V) type DG makes the losses increased significantly. Moreover, the losses increase when the introduced node is along the feeder.

4.2 Impacts of different capacity of DG on voltage profile and losses

4.2.1 Impact on voltage profile

In this section, through altering active and reactive power of DG at node 16, the impact on voltage of capacity is analyzed. In the calculation, the power output of DGs modeled as PQ node and PQ (V) node increase from 300 + j150kVA, and increase with 100 + j50kVA once. The

active power output of PV type DG is the same as the other two types DG, and assuming reactive initial output is zero, the voltage is 10kV. In table 3, the outputs are given in six cases for each type DG.

Table 3: Power output of DGs in six cases

Case	Active power (kW)	Reactive power(kvar)
Case 1	300	150
Case 2	400	200
Case 3	500	250
Case 4	600	300
Case 5	700	350
Case 6	800	400

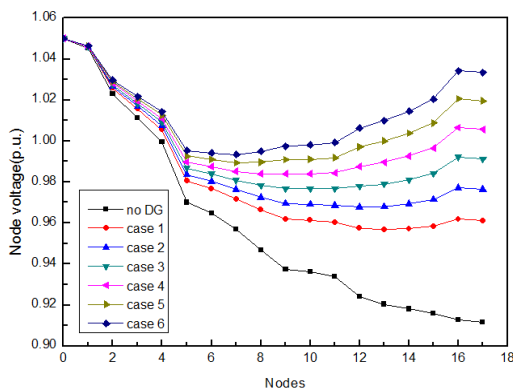(1)Voltage profile of nodes when DG as PQ node

Fig. 5: DG as PQ node

Fig.5 shows the comparison of voltage profile without and with DG of different capacity.

It can be seen that when the capacity of DG increase, the voltages of all nodes improve.

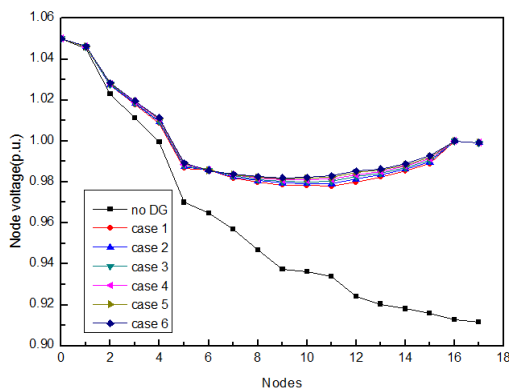(2) Voltage profile of nodes when DG as PV node

Fig. 6: DG as PV node

Fig. 6 shows the voltage curve and the results are almost the same at the six cases with DG. This is because the PV type DG requires that its node voltage remains the same specified value, and the voltage has nothing to do with capacity. It is noted that the output and losses of DG power may change correspondingly.

(3)Voltage profile of nodes when DG as PQ(V) node

In Fig. 7, similar with the PQ type DG, node voltage increase with the increase of power output of DG, but the voltage was improved unobviously.
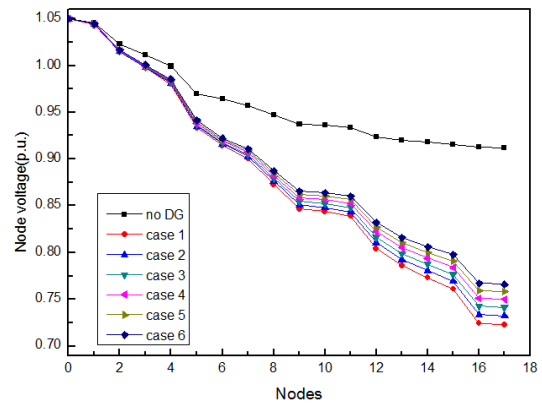

Fig. 7: DG as PQ (V) node

4.2.2 Impact on active power losses

Table 4: losses of different capacity

Case	Active power losses (kW)		
	PQ	PV	PQ(V)
No DG	318.03	318.03	318.03
Case 1	243.11	227.33	1082.8
Case 2	225.87	213.94	1078.9
Case 3	211.91	206.92	1078.9
Case 4	200.94	205.69	1082.8
Case 5	192.73	209.76	1090.2
Case 6	187.06	218.72	1100.9

From the table 4, it can be observed that the PV type DG is best for the loss reductions of the three types. With the increase of capacity of PQ type DG, the power losses reduce gradually. The change of power does not affect power loss significantly. For PV type DG, the power losses decreased first and then increased. And for PQ(V) type DG, the power losses increase greatly compared to no DG.

5 Conclusions

Because of the variety of DG, DG was divided into three types for power flow solution in this study. An algorithm to evaluate the impact on voltage profile and losses of different location and capacity of DG units of distribution systems was presented in this paper. Results of IEEE 33 bus system through altering location and capacity of three types DG verified the applicability of the proposed method. The results will be able to provide a reference for DG planning.

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