Analysis and Optimization of the Admission Capability of Distribution Network to Distributed Power Sources

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Abstract. This paper establishes a model for the ability of the distribution network to adopt distributed power sources, and proposes adoption constraints that consider the safe operation of the distribution network. The optimized assessment method of the ability of the distribution network to adopt distributed power sources proposed by analysis of simulation examples can help distribution network planners to ascertain the main limiting factors affecting the ability of the distribution network to adopt distributed power sources. According to the identified main limiting factors, distribution network planners can take appropriate measures to improve the ability of the distribution network to adopt distributed power sources.

1. Introduction
For the sake of the safe operation of the distribution network, it is essential to quantitatively estimate the ability of the distribution network to adopt distributed power sources. Due to the great uncertainty in the power generation of the distributed power sources based on renewable sources such as wind and light, how to consider the uncertainty of distributed power sources and loads when evaluating the ability of distribution networks to adopt distributed power sources has always been the focus of researchers.

2. Model of assessing the ability of adopting DG of distribution network considering DG and load uncertainty

![Figure 1. Radial distribution network.](attachment:image)

Cogitate the radial distribution network revealed in figure 1. According to the DisrFlow power flow equation [1], the following series of equations can be used to represent the branch active power, reactive power, and node voltage: \( \forall i \in N \),
\[ V_0 = V_{sub}(1 + tp \cdot a) \]  
\[ P_{i+1} = P_i - r_i(P_i^2 + Q_i^2)/V_i^2 - p_{i+1} \]  
\[ Q_{i+1} = Q_i - x_i(P_i^2 + Q_i^2)/V_i^2 - q_{i+1} \]  
\[ V_{i+1}^2 = V_i^2 - 2(r_iP_i + x_iQ_i) + (r_i^2 + x_i^2)(P_i^2 + Q_i^2)/V_i^2 \]  
\[ p_i = p_i^L - p_i^S \]  
\[ q_i = q_i^L - q_i^S - q_i^r \]

In the equation: \( p_i^L + jq_i^L \) represents the load level of node \( i \); \( p_i^S + jq_i^S \) represents the output power of the distributed power source of node \( i \); \( q_i^r \) represents the reactive power output by the static reactive compensator of node \( i \); \( r_i + jx_i \) represents the impedance of the line between node \( i \) and node \( i + 1 \).

Active management measures of the distribution network mainly comprise of coordinated voltage control, reactive power compensation, the control of power factors of distributed power source, the reduction of active power of distributed power source, and network reconstruction. These adjustment methods managed actively by the distribution network will affect the ability of absorbing distributed power by the distribution network. Therefore, when calculating the maximum capacity of distributed power sources that can be accessed in the distribution network, the above-mentioned active management methods need to be modelled and embedded in the established model of assessing the ability of the distribution network to adopt distributed power sources.

The reactive power adjustment equipment of the distribution network mainly includes shunt capacitor banks, static var compensators, etc. The selection of the static var compensators as the adjusting equipment for reactive power compensation in the research in this chapter is based on the following considerations:

1. The investment cost of static var compensation devices is usually higher than that of shunt capacitors. The cost of static var compensation devices has the potential to further decrease.

2. The high-permeability distributed power source brings a series of new problems to the power distribution system. Shunt capacitor banks can only compensate capacitive reactive power. Static var compensation devices can not only compensate capacitive reactive power [2], but also issue inductive reactive power to alleviate the problem of high voltages [3].

3. The static var compensation device operates faster than a shunt capacitor bank [4], and can act more quickly after an unexpected situation occurs to support the node voltage.

3. Constraints on safe operation of power distribution system

When assessing the maximum capacity of distributed power sources allowed in the distribution network, the following security operation constraints for the distribution system need to be considered:

1. Node voltage safety constraints

\[ V_{i,\text{min}} \leq V_i \leq V_{i,\text{max}}, \forall i \in N \]  

In the equation: \( V_{i,\text{max}} \) and \( V_{i,\text{min}} \) are the maximum and the minimum of the voltage amplitudes of node \( i \) specified by the safe operation of the power distribution system.

2. Ampacity constraints (power flowing through a transformer or a line is limited by its maximum apparent power):

\[ p_{\text{sub}}^2 + q_{\text{sub}}^2 \leq S_{\text{sub}}^2 \]
In the equation: $p_{sub}$ and $q_{sub}$ are the active and reactive power flowing through the transformer respectively.

From observation, it can be seen that the feasible region represented by the equations (8) and (9) is the interior of a circle, so the circle can be linearized with the regular polygon [5] ampacity constraint, and its expression is:

$$\alpha_c p_{sub} + \beta_c q_{sub} + \delta_c S_{sub,max} \leq 0, \forall c \in \{1,2,\ldots,12\}$$

$$\alpha_i p_i + \beta_i q_i + \delta_i S_{i,max} \leq 0, \forall c \in \{1,2,\ldots,12\}, \forall i \in N$$

In the equation: $c, c$ and $c$ are the coefficients of this series of linearization constraints. The following uses equation (8) as an example to further explain how to linearize this quadratic constraint.

(3) Constraints of exchange power between the distribution network and the superior grid

$$p_{sub,min} \leq p_{sub} \leq p_{sub,max}$$

$$q_{sub,min} \leq q_{sub} \leq q_{sub,max}$$

In the equation: $p_{sub,max}$ and $p_{sub,min}$ are the maximum and the minimum of the active power allowed to be exchanged by the superior grid; $q_{sub,max}$ and $q_{sub,min}$ are the maximum and the minimum of the reactive power allowed to be exchanged by the superior grid.

(4) Gear constraints of on-load transformer taps

$$t_{p,min} \leq t_p \leq t_{p,max}, t_p \in \text{int.}$$

In the equation: $t_{p,max}$ and $t_{p,min}$ are the maximum and the minimum of the adjustable range of the on-load transformer tap.

(5) Reactive power constraints output by static var compensator

$$q_{j,min}^s \leq q_j^s \leq q_{j,max}^s, \forall j \in S.$$  

In the equation: $q_{j,max}^s$ and $q_{j,min}^s$ are the maximum and the minimum of the reactive power that can be output by the static var compensator connected to node $j$; $S$ is the set of all nodes installed with static var compensator.

4. Example analysis

Through the improved IEEE 33 node example system, detailed numerical analysis and simulation tests are performed by the assessment method of the ability of the distribution network to adopt distributed power sources which proposed in this chapter.

Figure 2. Improved IEEE 33 node distribution network.
The example system used in the section is an improvement based on the IEEE 33 node example [6]. As revealed in figure 2, because the gear position of the on-load transformer tap and the reactive power output by the static var compensator will affect the maximum capacity of the distributed power allowed in distribution network, an on-load tap changer (OLTC) and two static var compensators (S1 and S2) are installed in the IEEE 33 node example above. In this simulation analysis in this section, the on-load transformer and the static reactive power compensator are linked to the distribution network in three phases. It is assumed that the distribution network is three-phase balanced, and that all the loads and the power factor of the distributed power source are all constant. Photovoltaics is selected as the distributed power. According to the IEEE 1547 standard, the example system in this section assumes that all photovoltaic power generation units work in unit power factor mode. In the example system revealed in figure 2, the rated power of the on-load transformer is 6MVA, the taps of the on-load transformer have 17 gears, and the voltage amplitude adjustment range of the secondary side is ± 10%. The single-phase reactive power adjustment range of each static var compensator is [-100kVar, 300kVar]. The safety range of the voltage amplitudes of the nodes in this example system is [0.95p.u., 1.05p.u.] and the maximum ampacity of each line is 6.6MVA. The allowable range of exchangeable active power between this distribution network and the superior grid is [-6MW, 6MW] and that of exchangeable reactive power is [-3MVar, 3MVar].

As revealed in figure 2, 7 candidate nodes (G1 to G7) in the distribution network may be installed with distributed power sources. There are loads at 32 nodes, so there are 39 power injection sources with uncertainty in total. This method is first used to evaluate the maximum capacity revealed in figure 2 in the most conservative case (Γ = 39). Table 1 shows the photovoltaic installed capacity configuration at 7 candidate nodes when Γ = 39. At this time, the total capacity of distributed power sources allowed in the distribution network is 6.508MW. Table 2 shows the on-load transformer tap gear and the robust solution of the reactive power output by the static var compensator in the most conservative case when the accessed distributed power capacity is maximum.

According to the robustness of the proposed robust optimization-based assessment method of the ability of the distribution network to adopt distributed power sources, the configuration is based on the installed photovoltaic capacity given in Table 1, even if the greatest threat to the security of the distribution system occurs, the power distribution system revealed in figure 2 can also operate safely. Generally speaking, the scenarios that pose the greatest threat to the power distribution system usually refer to "the smallest system load and the largest photovoltaic power generation" (named scenario A) and "the largest system load and the photovoltaic power generation is zero" (named scenario B).

Variable values obtained through robust optimization can insure that the power distribution system can preserve its own safe operation under the power output and load levels of distributed power sources with uncertainty. Figure 3 and Table 3 show the calculation results of the power flow for scenarios A and B.

**Table 1.** Photovoltaic installed capacity in the assessment results.

| G1 | G2 | G3 | G4 | G5 | G6 | G7 |
|----|----|----|----|----|----|----|
| 1.063 | 0 | 0 | 2.732 | 2.713 | 0 | 0 |

**Table 2.** OLTC gear and SVC reactive power in the optimization results.

| OLTC gear | SVC reactive power (kVar) |
|-----------|---------------------------|
| S1        | 521.5                     |
| S2        | 814                       |
Table 3. Exchange power between the distribution network and the superior grid.

| scenario | active power (MW) | reactive power (MVar) |
|----------|------------------|-----------------------|
| A        | -5.481           | -0.634                |
| B        | 3.864            | 1.068                 |

It can be found from figure 3 and Table 3 that only the voltage amplitudes of extremely few nodes (such as node 12) in scenario B violate the security constraints slightly. In order to explain the violation of the voltage constraints of extremely few nodes, a linear power flow calculation is performed again for scenarios A and B, and the resulting voltage amplitudes of each node are revealed in figure 4. It can be found from figure 4 that the voltage amplitudes of the nodes in scenarios A and B meet the safety constraints. It can be known from the above simulation calculation that the error of the voltage amplitude of each node is resulted in the difference between the two power flow calculation methods. The average relative error of the voltage amplitudes obtained by the accurate power flow calculation and linear power flow calculation is 0.24%.

![Figure 3. Results of accurate power flow calculations for node voltage levels in scenarios A and B.](image1)

![Figure 4. Results of linear power flow calculations for node voltage levels in scenarios A and B.](image2)
In addition, as revealed in figure 4, the voltage amplitudes of nodes 22 and 25 in scenario A are 1.05 p.u., and that of nodes 13 and 30 in scenario B are 0.95 p.u. Therefore, scenario A and scenario B are the worst cases. It can be known from the above simulation analysis that the maximum access capacity of distributed power source under the most conservative conditions given by the proposed assessment method based on robust optimization can ensure that the system maintains its own safe operation under severe situations.

5. Conclusion
Through the analysis of two simulation examples in this section, we can know that the robust optimization-based assessment method of the ability of the distribution network to adopt distributed power sources which proposed in this chapter can help distribution network planners to ascertain the main limiting factors affecting the ability of the distribution network to adopt distributed power sources. According to the identified main limiting factors, distribution network planners can take appropriate measures to improve the ability of the distribution network to adopt distributed power sources.

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