A survey of power flow calculations considering distributed generation

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Abstract. With the construction of China’s smart grid and the gradual implementation of the power market, the traditional centralized power grid mode has been unable to meet the demand of electricity in today’s society. The introduction of distributed generation has become a new trend in the future development of power grids. Due to the introduction of distributed generation, many new node types will appear in the distribution network. It is often difficult to achieve the expected results when using traditional power flow algorithms when dealing with these nodes. Therefore, it is particularly important to study the power flow calculation of distribution networks with distributed generation. This paper discusses in detail the impact of distributed power sources on distribution networks and the current research status of distribution network power flow calculations with distributed generation.

1. Introduction

In recent years, with the increasing awareness of energy conservation, environmental protection and sustainable development, distributed power sources such as wind power generation, photovoltaic power generation, biomass power generation, and fuel cell power generation are increasingly being connected to the distribution network[1]. Distributed generation has attracted extensive attention for its advantages such as nearby absorption of power, reduction of transmission and transformation line investment, operation cost and transmission line loss, as well as assisting large power grids to improve peak and valley performance, to improve power supply reliability and to reduce environmental pollution.

Due to the access of these distributed power sources, the distribution network is transformed from a traditional passive network to an active network, which changes the tidal current flow, node voltage level, and network active loss in the distribution network, so the distribution network planning and transportation dimensions require higher requirements.

2. The Impact of Distributed Power on The Distribution Network

2.1. Impact on power flow calculation

The traditional distribution network is generally closed-loop design and open-loop operation. That is, the distribution network is a single-supply radiation type network under normal operation, and the tidal current direction is one-way. When the DG are connected to the distribution network, the topology of the network changes. A single-power radiating network becomes a multi-power network.
When the output of the DG is greater than the load value, the power flow is reversed. Therefore, the impact of DG access on power flow calculation during power distribution network reconstruction cannot be ignored. At present, in the reconstruction of distribution network, the processing of DG is divided into three cases[1].

1) The processing of DG is limited to the DG as a "negative" load, so that the processing does not reflect the operational advantages of DG;
2) Optimize the output of DG, but only to minimize the network loss in the distribution network reconstruction and not consider the power generation cost;
3) Considering the fluctuation characteristics of renewable energy such as wind power, establish a stochastic power flow model and establish a reconstruction model with the lowest expected value of network loss.

2.2. Impact on the reliability of distribution network systems
The normal operation of the distribution network will be affected by the distributed power supply, and the reliability of the system can be improved after the distributed power supply is connected. If a fault occurs somewhere in the system, the user who can distribute the distributed power supply is separated from the system by controlling the opening and closing state of the switch, and the distributed power supply can separately supply power to these users, thus forming an island operation state, avoiding Large-scale power outages and increased reliability of system power.

2.3. Impact on power quality
The access of DG to the distribution network will have a major impact on power quality, including harmonics, voltage quality, and frequency fluctuations. Since the output of DG such as wind power generation and photovoltaic power generation has the characteristics of intermittent, random and volatility, the input and exit operations will inevitably cause voltage fluctuations. Frequent start and stop of DG, randomness and volatility of output power, and uncoordinated cooperation with large power grids will cause frequency fluctuations, especially when DG are operated in island mode, if there are no energy storage components inside the island or Insufficient component capacity can easily cause frequency instability.

2.4. Impact on relay protection
Since the traditional distribution network is powered by a single power supply, there is no directional component in the relay protection. However, after the DG are connected, the distribution network becomes a multi-power network, and the current flow no longer simply flows from the substation bus to the load bus. When a transient fault occurs in the line, the DG may continue to deliver current to the short-circuit point for some reason, but not out of the fault line in time, thereby affecting the fault current flowing through the protection device, which makes it difficult to cooperate with the upper and lower stages of the line[2]. Due to the effect of infeed current of DG, a severe arc will occur at the fault point in severe cases, resulting in automatic reclosing failure.

3. Types of Distributed Generation and Their Power Flow Calculation Models

3.1. Type of distributed generation
At present, the types of distributed generation mainly include renewable energy power generation systems such as solar energy, wind power, biomass energy, etc. or new power generation technologies in the form of fuel cells and micro gas turbines [3-4].

1) Wind power generation
Wind energy refers to the energy generated by the movement of the air caused by solar radiation causing uneven heating of various parts of the earth, causing different temperature differences and pressures. Usually, it consists of one or more wind turbines that are electrically operated in parallel, mainly by rotating the fan blades to capture wind energy, and converting the wind energy into
mechanical energy, and then converting the mechanical energy into electrical energy by the generator. Finally, through the rectifier inverter circuit to achieve grid-connected operation. Wind turbines are generally divided into doubly-fed asynchronous generators and low-speed synchronous generators, which can be directly connected to the grid or connected to the grid by means of inverters.

Wind turbine power refers to the output power of a wind turbine, which can be calculated by:

\[ P_e = C_p C_0 \frac{\rho v^3 A}{204} \]  

(1)

In the formula, \( P_e \) is the wind turbine output power; \( \rho \) is the density of the air; \( A \) is the swept area of the wind turbine; \( v \) is the wind speed; \( C_0 \) is the efficiency coefficient of the transmission and the generator; \( C_p \) is the wind energy utilization efficiency. Ideal wind power generation. The maximum value of the machine is 0.593, and the \( C_p \) of the grid type wind turbine is generally above 0.4.

2) Photovoltaic power generation

The main form of solar power generation is photovoltaic power generation. The photovoltaic power generation system is mainly composed of three parts: solar panels, controllers and inverters. Usually, according to the photovoltaic effect of the semiconductor interface, the solar energy can be directly converted into electricity by using solar cells. It has many advantages such as no fuel consumption, flexible scale, no pollution, and simple maintenance. The distributed grid-connected photovoltaic system is shown in Fig 1.

\[ T(v) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} \beta^{-\beta-1} \left( 1 - \frac{E}{E_{\text{max}}} \right)^{\beta-1} \]  

(2)

Where, \( \alpha \) and \( \beta \) are the shape parameters of the Beta function; \( E \) and \( E_{\text{max}} \) represent the actual light intensity and the maximum values of actual light intensity over time.

Photovoltaic generators are usually connected to the system via an inverter, so the power flow calculation can be regarded as a PI type node.

3) Micro gas turbine

The micro gas turbine is a small gas turbine fueled by natural gas, gasoline, diesel, etc, which has the characteristics of small volume, light weight, high efficiency, low pollution, and simple operation and maintenance. The working principle is as follows: the high-pressure air from the centrifugal compressor is preheated by the turbine exhaust in the regenerator, and then mixed into the combustion chamber to mix with the fuel, and the high-temperature gas is sent to the centripetal turbine to directly drive the high-speed generator to generate electricity. The generator first emits high-frequency alternating current, which is then converted into high-voltage direct current, and then converted into alternating current for the user to use. Its grid connection schematic is shown in Fig 2.
The active power of its output is calculated as follows:

\[ P_e = \eta \times \left[ \frac{1 - N}{2} + 1.3 \left( W_f - 0.23 \right) \right] \tag{3} \]

Where, \( \eta \) is the power factor; \( N \) is the speed; \( W_f \) is the flow.

4) The fuel cell

A fuel cell is an electrochemical device that converts chemical energy into direct current electrical energy under isothermal conditions, consisting of an anode, a cathode, and a solid or liquid electrolyte between the two electrodes. When the fuel cell is in operation, hydrogen in the fuel (oil, natural gas, etc.) is chemically reacted with oxygen in the air by means of the electrolyte to generate electricity while generating water. Since it is required to continuously supply fuel and oxidant thereto during operation, it is called a fuel cell.

As a new type of electrochemical device, fuel cell energy conversion method is: chemical energy (fuel) - electrical energy, which is significantly different from traditional thermal power generation energy conversion method: chemical energy - thermal energy - mechanical energy - electrical energy mode, which can be regarded as a new technology that promotes the transformation of energy forms. The fuel cell output voltage is calculated as follows:

\[ U_{\text{cell}} = N \times \left[ K_0 + \frac{RT}{2} \ln \frac{x_{H_2} x_{O_2}}{x_{H_2O}} \right] - E_{\text{losses}} \tag{4} \]

Where, \( N \) is the number of series connection of the battery; \( K_0 \) the performance index; \( T \) is the temperature; \( x_{H_2}, x_{O_2}, x_{H_2O} \) is respectively the molar concentration of hydrogen, oxygen and fuel, \( E_{\text{losses}} \) is the pressure drop.

After grid connection, active power and reactive power are:

\[ P = \frac{m U_{\text{cell}} V}{X} \sin \phi \]
\[ Q = \frac{m U_{\text{cell}} V}{X} \cos \phi - \frac{V_f^2}{X} \tag{5} \]

In the formula, \( m \) is the converter parameter; \( X \) represents the reactance; \( V_f \) is the voltage measured by the distribution network, \( \phi \) is the phase angle.

3.2. Processing method and model of distributed generation in power flow calculation

In traditional power grid power flow calculation, there are generally only two types of nodes: PQ nodes and balanced nodes. However, with the access of distributed power, this classification method is no longer applicable, so it is necessary to establish a new node type classification method.

Generally, in the power flow calculation, the control strategy of the converter needs to be combined to divide the DG type. There are three main ways of DG grid connection: asynchronous generator, synchronous generator, DC/AC or AC/DC power electronic converter. Therefore, we can classify distributed power sources into the following categories:

1) PQ nodes with constant P and Q;
2) PV nodes with constant P and constant U;
3) PI node with constant P and constant I;
4) PQ (V) node with constant P, and Q related voltage.
In the distribution network, the load node and the intermediate node can be regarded as PQ nodes. After the distributed power is added to the network, the power distribution system generates new node types different from the traditional node types, and these node types cannot be directly embedded in the traditional power flow calculation, it is necessary to establish their own mathematical models of power flow calculation and their processing methods.

The following is the processing method for each DG type in power flow calculation.

a. PQ node
   The calculation process of such load nodes is the simplest and can be regarded as a negative load node, so the traditional power flow calculation method can be directly used. In practice, the most common method for calculating the power flow of a grid-connected wind turbine using an asynchronous motor as a PQ node is:

\[
P_i = -P_s, \\
Q_i = -Q_s.
\]  
(6)

Where, \(P_i\) and \(Q_i\) respectively are the active power and reactive power of the distributed power supply.

b. PI node
   Photovoltaic generators usually belong to this type of distributed power supply, and their reactive power is as follows:

\[
Q^{t+1} = - \sqrt{P^2 - (E^t)^2 - (F^t)^2}.
\]  
(7)

In the formula, \(Q^{t+1}\) is the reactive power of iteration \(t+1\) times; \(E^t\) is the voltage active component of iteration \(t\) times; \(F^t\) is the voltage reactive component of iteration \(t\) times; \(I\) is the current amplitude; \(P\) is the active power.

When calculating the power flow, the initial voltage of the PI type load node generally takes the reference voltage \(U_a\). The initial value of reactive power \(Q_0\) is calculated as \(Q_0 = -\sqrt{P^2 - (U_a)^2}\).

c. PV node
   For \(P, V\) constant distributed power supplies, \(P\) and \(V\) are constant values, and their power flow calculation model:

\[
P = -P_s, \\
U = U_s.
\]  
(8)

In the formula, \(P_s\) and \(U_s\) are the active and voltage of DG of \(P\) and \(V\) constant type. If the power flow calculation adopts the forward-backward sweep method, which is inconsistent with the condition that the forward-backward sweep method requires the load to be of the PQ type, it is necessary to correct \(Q\) according to equation (9):

\[
Q^{t+1} = \begin{cases} 
- Q_{\text{max}}, & Q' + \Delta Q \leq - Q_{\text{max}} \\
Q' + \Delta Q, & - Q_{\text{max}} \leq Q' \leq - Q_{\text{min}} \\
- Q_{\text{min}}, & Q' + \Delta Q \geq Q_{\text{min}}
\end{cases}
\]  
(9)

Where, \(Q_{\text{max}}\) and \(Q_{\text{min}}\) are the maximum and minimum values of reactive power respectively.

In the calculation, the initial value \(Q_0\) of the reactive power of the PV type load node is generally considered to be 0 or \(- (Q_{\text{max}} + Q_{\text{min}})/2\), which is a commonly used simplified calculation method, which makes the calculation process more convenient, but with the actual reactive power initial. There is still some error compared to the value.

d. PQ(V) node
   For this type of DG, the power flow calculation model is shown in equation (10). The regulation of reactive power during the iteration is calculated from the voltage amplitude of the last iteration.
\[
\begin{align*}
P &= -P_i \\
Q^{t+1} &= -f(U^t)
\end{align*}
\] (10)

Where, \( Q^{t+1} \) is the reactive power of iteration \( t+1 \) times; \( U^t \) is the voltage of iteration \( t \) times.

Some of the papers establish models corresponding to different types of distributed power, so that distributed power can be added to the power flow calculation of the distribution network in a universal form. In paper [5], the power flow calculation is carried out on the distribution network with distributed power supply using the improved forward-forward method. The solar energy and fuel cells are regarded as the PV node model, and the wind farm is regarded as the PQ(V) node model. In paper [6], combined with the operation mode and control characteristics of the distributed power supply, the corresponding mathematical models are established in the power flow calculation, and the reactive power compensation amount of the PV nodes is calculated by establishing the sensitivity compensation matrix.

4. Conclusion
This paper summarizes the development status of new energy sources, and focuses on several common distributed power sources of solar power generation, wind power generation, fuel cells and micro gas turbines, and analyzes their power generation principles and processes as well as mathematical models. At the same time, for the case that the distributed power supply grid connection will cause the traditional power flow calculation method to be no longer applicable, the four power flow calculation models of PQ type, PI type, PV type and PQ=f(v) type are summarized to meet power flow calculation for the distribution network with distributed power supply.

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References
[1] Shen Xin, Cao Min. Study on the Influence of Distributed Power Grid Connection on Distribution Network [J].Transactions of China Electrotechnical Society,2015,30(S1):346-351 (in Chinese).
[2] Zhang Nankai. The Influence of Distributed Power Access on Distribution Network[J].Value Engineering,2018,37(36):223-224 (in Chinese).
[3] LüXueqin, Wu Chenning. Research on Improvement Method of Power Flow Calculation for Distribution Network with Distributed Power Supply[J].Power System Protection and Control,2012,40(21):48-51 (in Chinese).
[4] A distribution network expansion planning model considering distributed generation options and tech-o-economical issues[J]. Alireza Soroudi, Mehdi Ehsan. Energy.2010 (8).
[5] Chen Hai-zhen,Chen Jin-fu,DUAN Xian-zhong. The Power Flow Calculation of Distribution Network with Distributed Power Supply[J]. Automation of Electric Power Systems,2006(01):35-40 (in Chinese).
[6] Zhang Limei,Tang Wei. Preliminary calculation of power flow in front of power distribution network with distributed power supply[J]. Transactions of China Electrotechnical Society,2010,25(08):123-130(in Chinese).