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Short Communication

Convergence problem in forward/backward sweep power flow method caused by non-positive-sequence impedance of distributed generators and its solution ☆

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ABSTRACT

A variety of distributed generators (DGs) are integrated in distribution system which is usually operated under three-phase unbalanced conditions. The zero and negative sequence impedances of DGs may vary within a large range. In this paper, the convergence problem caused by the zero and negative sequence impedances of DGs in forward/backward sweep three-phase power flow is found through numerical experiments. The reason of this phenomenon is explained and an impedance compensation method is proposed to solve this problem.

1. Introduction

A considerable amount of research on power flow algorithms in distribution networks has been published. Most of these literatures focus on Newton's method and ladder technique [1–5]. Compared with Newton Raphson (NR) method, the ladder technique is more suitable for distribution power flow. Represented procedures include forward/backward sweep (FBS) with compensation [1] and Distflow [2]. The convergence of this power flow method deteriorates where the network becomes more meshed. Therefore, a loop-analysis-based power flow (LBPF) method is proposed for radial and weakly meshed distribution networks [3], which can be categorized into a revised FBS method and has strong ability to deal with meshed network. On the contrast, NR methods have good characteristics on meshed network, but may meet convergence issues caused by a mix of long and short branches [4]. Gomez Esposito et al. [4] proposed a revised iteration frame to improve NR method's convergence. Garcia et al. [5] developed a revised NR method for distribution network, whose power flow formulation is based on current injections mismatch equations. A combined method was presented in [6], in which NR is used to solve three-phase part and FBS is adopted for single-phase lateral branches.

As a popular method, FBS power flow algorithm has been widely used in some commercial software packages. Further study on FBS power flow method is still needed to improve its performance. In the past decades, various distributed generators were integrated in distribution network. And some technical challenges emerged in FBS power flow method. The zero and negative sequence impedances of DGs may vary within a large range, which may lead to convergence problem in FBS. This phenomenon is founded in the paper and an impedance compensation method is proposed to solve this problem.

2. Convergence characteristics for FBS

The loop-analysis-based power flow (LBPF) method [3] has strong ability to deal with meshed network, which is a revised version of FBS. LBPF is taken as example to explain the convergence characteristics of FBS. Theoretically, LBPF is a type of fixed-point iteration method for solving nonlinear equations. A detailed process of deriving the Jacobian matrix $\boldsymbol{J}_\Phi$ for LBPF is introduced in Appendix A. To guarantee the convergence of LBPF, the spectral radius of $\boldsymbol{J}_\Phi$ should satisfies:

$$\rho(\mathbf{J}_\Phi) < 1, \quad (1)$$

which is the sufficient condition for a contraction mapping [9].

Improper parameters of DGs may lead to un-satisfaction of this condition and lead to the divergence of three-phase power flow.

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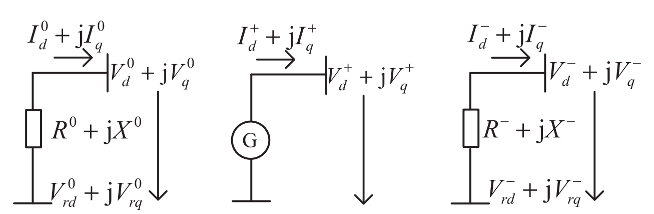
3. The convergence problem caused by distributed generators

Three-phase power-flow analysis models for certain types of DGs have been proposed in [6–8]. These models usually are formulated in sequence-component frame first for convenience, and then they are translated into phase-component frame model. In this section, a power electronic interface DG is taken as example, whose equivalent circuits are shown in Fig. 1 in sequence-component frame and models for other types of DGs have similar structure. $I_d^0 + jI_q^0$, $I_d^+ + jI_q^+$, $I_d^- + jI_q^-$ denote the zero-sequence, positive-sequence and negative-sequence injection currents from DGs to its host grid. $V_d^0 + jV_q^0$, $V_d^+ + jV_q^+$, $V_d^- + jV_q^-$ are respectively the zero-sequence component, positive-sequence component and negative-sequence component of the DG terminal voltages. $R^0 + jX^0$ and $R^- + jX^-$ are the equivalent zero-sequence and negative-sequence impedances. $V_{rd}^0 + jV_{rq}^0$, $V_{rd}^- + jV_{rq}^-$ are the zero-sequence component and negative-sequence component of converter output voltages.

For three-phase electronically-coupled DG, the zero-sequence component and negative-sequence component of its internal impedance may vary within a very large range such as [0.001j, 0.1j] p.u. [6]. These widely varied DG's impedances may lead to FBS power flow divergence. A two nodes system is used to demonstrate this phenomenon as shown in Fig. 2.

As shown in Fig. 2, a DG connects to a slack bus via a branch whose impedances are $\dot{Z}_{\text{line}}^0 = 0.3 + 0.3\text{j}$ p.u., $\dot{Z}_{\text{line}}^+ = 0.1 + 0.1\text{j}$ p.u. and $\dot{Z}_{\text{line}}^- = 0.1 + 0.1\text{j}$ p.u. respectively. The converter output voltage $V_{rd}^0 + jV_{rq}^0$, $V_{rd}^- + jV_{rq}^-$ are controlled to zero. The power generation of DG is $1 + 1\text{j}$ p.u.. And the voltage of the slack bus is set as $[1 \quad 0.98\angle-120 \quad 0.97\angle 120]^T$ p.u.. To analyze the convergence performance of the FBS under various DG's impedance, the zero-sequence impedance and negative-sequence impedance of DG are both set as $(1 + 1\text{j}) * \lambda$ p.u.. Here, λ is a multiplier. As λ decreases from 1 to 0.1, the performance of FBS is listed in Table 1. From Table 1, we can see that the spectral radius of $\boldsymbol{J}_\Phi$ increase, and FBS power flow diverges when the DG's impedances decrease to 0.1–0.3. This is because the internal zero-sequence impedance of DG is smaller than the branch's zero-sequence impedance and the sufficient condition for a contraction mapping in this fixed-point iteration is no longer satisfied.



(a) Zero equivalent model (b) Positive equivalent model (c) Negtive equivalent model

Fig. 1. Sequence-component frame model of power electronic interface DG.

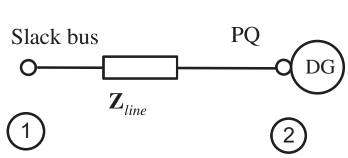


Fig. 2. Two nodes system.

4. Solution

According to the observation in previous section, if we can decrease the spectral radius of $\boldsymbol{J}_\Phi$ smaller than 1, then the convergence problem can be solved. As shown in Fig. 3, a compensation impedance $\dot{Z}$ is inserted into the DG and a branch with $-\dot{Z}$ is added in serial to keep the character of the whole circuit unchanged. For the compensation impedance $\dot{Z}$, its positive-sequence component $\dot{Z}^+ = 0$, negative-sequence component $\dot{Z}^- = \dot{Z}_{\text{line}}^- = 0.1 + 0.1\text{j}$ p.u. and zero-sequence component $\dot{Z}^0 = \dot{Z}_{\text{line}}^0 = 0.3 + 0.3\text{j}$ p.u.

After compensation, the voltages of node 2′ and 2″ are to be solved instead of the voltage on node 2, i.e. the compensation impedance $\dot{Z}$ is treated as part of DGs' internal impedance.

The zero-sequence power injection $\dot{S}_{\text{DG}}^0$ and negative-sequence power injection $\dot{S}_{\text{DG}}^-$ on node 2 can be formulated as the functions of the voltage of node 2″:

$$-\left[(\dot{V}_2'')^{(0)} + \frac{-(\dot{V}_2'')^{(0)}}{\dot{Z}^0 + \dot{Z}_{\text{DG}}^0}\dot{Z}^0\right]\left[\frac{(\dot{V}_2'')^{(0)}}{\dot{Z}^0 + \dot{Z}_{\text{DG}}^0}\right]^* = \dot{S}_{\text{DG}}^0, \quad (2)$$

$$-\left[(\dot{V}_2'')^{(-)} + \frac{-(\dot{V}_2'')^{(-)}}{\dot{Z}^- + \dot{Z}_{\text{DG}}^-}\dot{Z}^-\right]\left[\frac{(\dot{V}_2'')^{(-)}}{\dot{Z}^- + \dot{Z}_{\text{DG}}^-}\right]^* = \dot{S}_{\text{DG}}^-, \quad (3)$$

where $\left(\dot{V}_2''\right)^{(0)}$, $(\dot{V}_2'')^{(-)}$ is the zero-sequence component and negative-sequence component of node 2″ voltage; $\dot{Z}_{\text{DG}}^0$, $\dot{Z}_{\text{DG}}^-$ is the zero-sequence component and negative-sequence component of DGs' internal impedance, "*" denotes conjugate of complex value.

Accordingly, the zero-sequence power injection $(\dot{S}_2'')^{(0)}$, positive-sequence power injection $(\dot{S}_2'')^{(+)}$ and negative-sequence power injection $(\dot{S}_2'')^{(-)}$ on node 2″ can be calculated as:

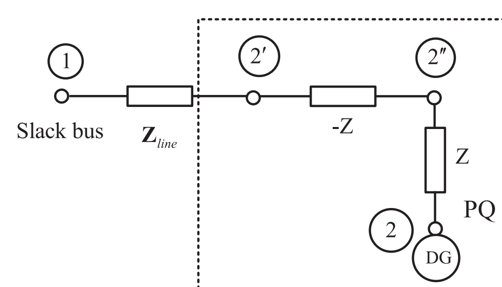


Fig. 3. Two nodes system after compensation.

Table 1
Convergence of two nodes system power flow with different impedances of DG.

Multipler of impedence (λ)	Total iter. number	Positive/zero/negative sequence voltage at node 2 (p.u.)	Spectral radius of J_Φ
1	8	1.0470–0.0000j/0.0064 + 0.0022j/0.0076–0.0026j	0.3
0.8	10	1.0470–0.0000j/0.0061 + 0.0021j/0.0074–0.0026j	0.375
0.4	32	1.0470–0.0000j/0.0048 + 0.0016j/0.0067–0.0023j	0.75
0.3	Not converge	–	1
0.2	Not converge	–	1.5
0.1	Not converge	–	3

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