ARTICLE IN PRESS

Electrical Power and Energy Systems xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

An improved CPF for static stability analysis of distribution systems with high DG penetration

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ARTICLE INFO

Article history:
Received 22 June 2016
Received in revised form 9 September 2016
Accepted 26 October 2016
Available online xxxx

Keywords:
Static stability
Continuation power flow (CPF)
Distributed generation (DG)
Distribution systems

ABSTRACT

This paper proposes an improved continuation power flow (CPF) method for the modelling and stability analysis of distribution systems with a high penetration of distributed generation (DG). This method aims at solving the flaws of conventional CPF in the description of DGs, the allocation of unbalanced power and the consideration of renewables. To indicate the power variations of DGs with respect to terminal voltage and system frequency precisely, the comprehensive static characteristics bus models are introduced into the calculation of the equilibrium point. Then, in the case of multiple generations, the distributed slack bus model based on incremental loss factors (ILFs) is used to allocate unbalanced power, making the results of CPF independent of slack bus selection. In addition, the load growth pattern involving the output characteristics of renewables is reinterpreted as the net load growth pattern to reflect the intermittency and fluctuation of renewables on the static stability of distribution systems. A detailed solution process of improved CPF is then elaborated. Case studies are presented on the IEEE 33-bus distribution system to illustrate the validity of the improved CPF method, and more simulations on the PG&E 69-bus distribution system are performed to assess the effect of DGs on the static stability of distribution systems.

1. Introduction

Power distribution systems containing a high penetration of distributed generation (DG) have become the desirable and sustainable implementations of new and renewable energy sources [1]. However, due to the unprecedented increase in energy demand, distribution systems have been driven to operate near their limits [2], losing static stability with unacceptable deviations of voltage and frequency [3,4], especially under islanded modes without main grid support [5].

In static stability analysis, continuation power flow (CPF) [6] has been widely adopted to calculate the distance between the current equilibrium point and critical operation point that corresponds to the maximum loading point (MLP) [7]. When the system reaches its MLP, the Jacobian matrix becomes singular, and consequently, the power flow method will face convergence problems [8]. The CPF method can trace voltages, namely PV curves, by repeatedly computing the equilibrium point using a predictor-corrector scheme [9] after introducing a continuation parameter even when the system Jacobian is ill conditioned.

In [10,11], CPF has been applied to stability analysis of distribution systems. However, since the implementation of high penetration of DGs in distribution systems, conventional CPF needs to be revisited due to: (1) the complexity of utility interfaces of DG in obtaining accurate representations of components in distribution systems, (2) the condition of multiple generations leading to alterations in the scale and direction of power flow, especially when the R/X ratio is high, and (3) the influence of the intermittency and fluctuation of renewables on the results of CPF by changing the power growth pattern.

During the calculation of the equilibrium point in CPF, considering the power electronic interfaces and control strategies of DGs, some researchers have used additional bus models such as the PI and PQV bus [11,12], which are based on three traditional types of buses: PV, PQ, and slack bus. However, these models cannot cover all components and lack universality, especially when DGs switch among different control strategies. All of the above bus models neglect system frequency, which is generally regarded as a fixed value in power flow based analysis. Although this treatment may be suitable for transmission systems, distribution systems

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http://dx.doi.org/10.1016/j.ijepes.2016.10.012
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with DGs would suffer from the fluctuation of system frequency due to the smaller system capacity and inertia [13], especially in islanded mode with droop control strategy [5]. Compared with a conventional distribution system, the islanded distribution is more likely to have a disturbance because of the randomness and uncertainty of renewables [14]. The power flow analysis of islanded microgrids is an active topic [15–17], but those proposed methods do not apply to CPF perfectly.

Conventional continuation distribution power flow assumes one single slack bus to act as the voltage reference bus and takes all the unbalanced power. In fact, a slack bus does not exist in real systems, and multiple sources can respond to unbalanced power in distribution systems integrating DGs. Moreover, because of high R/X ratios, the grid loss allocation should not be neglected. To remedy the flaw of one single slack bus, some improvements have been adopted. In [18], dynamic power flow is utilized, but without elaboration of allocation proportion. In [19], distributed slack bus based participation factors are calculated using generator domains, which require too high calculation cost to be used in CPF. Reference [20] introduced the concept of incremental loss factors (ILFs), which can be used to distinguish the loss contribution by each generation. ILFs based participating factors are straightforward, reasonable and easy to calculate [21].

In addition, as a basic prerequisite of the CPF method, the load growth pattern has two ways to emulate the loading trend: (1) assumption of increasing load at all buses, a certain area or one specific bus, which is used to find the weak buses [11]; and (2) prediction of loads by forecasting models, which is closer to the actual operation of systems [22,23]. The MLP depends on how the load is increased [24]. In [22–24], only realistic load direction has been discussed. In conventional CPF, load growth and generation regulation correspond to different processing methods. Owing to the intermittency and fluctuation, some renewables, such as wind generation and photovoltaic generation, act like load with a predictable power trend. Thus, loads and renewable DGs can be treated as similar power injection models, referred to as net loads in this paper.

In this paper, an improved CPF considering static characteristics and multiple generations is proposed, based on which a new load growth pattern is presented. The main issues are as follows:

(1) Comprehensive static characteristics bus models, which are used to indicate the power variations of loads and DGs with respect to the terminal voltage and system frequency under different control strategies.
(2) ILFs based distributed slack bus model, which is proposed to allocate grid loss among all generations to avoid the error caused by a single slack bus in low voltage distribution systems.
(3) Definition of net loads, which is used to reinterpret the load growth pattern in CPF to take the intermittency and fluctuation of renewables into consideration.

In addition, more simulations are proposed to assess the influence of DG on the static stability of distribution systems. The rest of this paper is organized as follows: Section 2 describes the calculation of equilibrium points of distribution systems with DG. Section 3 presents a detailed solution process of the improved CPF. Section 4 discusses the results of several case studies. Section 5 concludes this work and remarks possible future research.

2. Calculation of the equilibrium point

This section will present a modified formulation of power flow of distribution systems with DG for calculating the equilibrium point at each continuation step in CPF. First, the bus models are augmented by the comprehensive static characteristics. Next, the ILFs based distributed slack bus model is proposed to allocate grid loss. Finally, a power flow reformulation of distribution systems is offered.

2.1. Comprehensive static characteristics bus models

To ensure the convergence performance, CPF is generally based on the Newton Raphson (NR) method. PQ and PV buses can be dealt with directly, whereas PI and PQV buses should be reconstructed as a PQ bus before each iteration according to calculated voltage. PI bus and PQV bus both have variable reactive power depending on terminal voltage. Hence, the universal formula involved in voltage static characteristic can be obtained like in [13,25]. In addition, unlike transmission systems, the frequency regulation of load and generation in distribution systems should not be neglected due to less inertia. Especially, a droop regulation will be adopted in islanded mode [26,27]. The frequency would influence the load and generation allocation. Thus, the frequency static characteristic should be also built into bus models.

The comprehensive static characteristics bus models can be universally expressed as:

$$PQ-like: \begin{cases} P = P(V,f) \\ Q = Q(V,f) \end{cases} \tag{1}$$

$$PV-like: \begin{cases} P = P(V,f) \\ V = V_0 \end{cases} \tag{2}$$

During the calculation of the equilibrium point, the static characteristic bus could be regarded as a PQ-like or PV-like bus with variable power within permissible voltage, frequency and power range. Considering the control strategies of DGs, once the calculated voltage, frequency or power exceeds its limits, the power should be fixed in the next iteration.

According to (1) and (2), bus models can be described in a uniform way even with switching operation among different control strategies. The treatment process of a comprehensive static bus model can be easily integrated into the continuation method, which will simplify the program implementation and improve efficiency. The comprehensive static characteristic bus models of some components adopted in this paper are described as follows.

2.1.1. Distributed generator

In general, a DG unit can be connected to a distribution system by one of three interfaces, including asynchronous generators, synchronous generators and electronic converters. The wind generation is usually interfaced with the network through an asynchronous generator, which can be described as static voltage characteristics model (SVCM) as follows [25]:

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

This SVCM could be regard as a PQ-like bus as discussed before. In [25], the authors also elaborate that the power flow model of synchronous generator with constant excitation voltage is similar to (3) with some degree. In addition, the wind generation with automatic load-frequency control could be considered as PQ-like bus with frequency support capability [13].

The gas power station is generally equipped with the split shaft or the single shaft gas turbine. The split shaft gas turbine is usually connected into network by synchronous generator with regulating excitation voltage. There are two different modes of controlling the excitation system, voltage control mode and power factor control mode, which are considered as conventional PV bus and PQ bus,