Electrical Power and Energy Systems 100 (2018) 193–200

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Two-tier static equivalent method of active distribution networks considering sensitivity, power loss and static load characteristics

Wei Dai[a], Juan Yu[a,*], Xuan Liu[b], Wenyuan Li[a]

[a] State Key Laboratory of Power Transmission Equipment & System Security and New Technology, College of Electrical Engineering, Chongqing University, Chongqing 400030, China

[b] Robert Gavin Electric Innovation Center, Illinois Institute of Technology, Chicago IL 60616, USA

ARTICLE INFO

Keywords:
Active distribution networks
Static equivalent method
Sensitivity
Power loss
Static load characteristics

ABSTRACT

This paper presents a two-tier static equivalent method that can accurately simplify active distribution networks. This method proposes a new physical equivalent network composed of equivalent generator, branch and load. Based on the physical equivalent network, the two-tier static equivalent model is further constructed. In the upper tier equivalent model, the consistency of sensitivity and power loss are considered. In the lower tier equivalent model, static load characteristics are retained to further enhance the accuracy of the equivalent model. The test systems, containing both transmission and active distribution networks, are used to demonstrate the effectiveness of the proposed two-tier static equivalent method.

1. Introduction

Normally, a transmission network connects with a great number of distribution networks. Furthermore, the dimension of distribution networks is large due to large number of sections, branches, load points and distributed generations (DGs) [1–4]. Thus, the analysis of the transmission network with detailed distribution networks becomes difficult and inefficient. Moreover, it may have a convergence issue due to the large-scale information exchange and calculation complexity. Therefore, it is significant to develop equivalent models that can simplify the complex distribution networks and capture their important behaviors.

Equivalent models for simplifying distribution networks can be categorized into dynamic equivalent model and static equivalent model in terms of different purposes. The dynamic equivalent model [5–10], which has similar dynamic characteristics with distribution networks, can be used for dynamic power system analysis (e.g., transient stability, frequency stability, and short-term voltage stability analysis). The static equivalent model [11–15], which retains the major static characteristics of distribution networks, can be used for steady-state analysis (e.g., static security, reactive power optimization, and optimal power flow analysis). This paper focuses on the latter.

For static equivalent model, distribution networks are commonly represented by the constant power load model (PQ model) or a combination of constant impedance, current and power load models (ZIP model) [11–14] in real-world power systems. PQ model [11] is the simplest and the most widely used equivalent model, in which the distribution networks are replaced with their equivalent power injections/extractions. ZIP model [12–14] further considers static load characteristics, i.e. the nonlinear characteristics of loads with respect to voltage changes. In order to achieve power system sustainability, a massive number of DGs are integrated into distribution networks. In general, the DGs can be categorized into DG_{SPQ} (the voltage and reactive power cannot be regulated) and DG_{SPV} (the voltage and reactive power can be regulated) in terms of control modes. However, the PQ and ZIP models ignore the equivalence of DGs and thus cannot retain the voltage and reactive power support characteristics of DG_{SPV}. Most of the utilities and system operators represent DGs as negative loads [4,10]. In [15], the DGs in active distribution networks are represented as an equivalent generator. The equivalent generator can retain the reactive power support characteristics of DGs with some control modes. However, all of these models concentrate on retaining the characteristics of loads. The characteristics of DGs and lines in active distribution networks are not fully considered. Moreover, these models can only ensure the consistency of power flow states before and after equivalence, the consistency of sensitivity and power loss are ignored.

Sensitivity is important in power system analysis because it describes how the output of the system varies when one variable (generator voltage or load power) changes. It is shown in [16] that the sensitivity equivalent method considering the consistency of sensitivity before and after equivalence is much more accurate than Thevenin equivalence [17], REI equivalence [18] and Ward equivalence [19] for

* Corresponding author.
E-mail address: 148454745@qq.com (J. Yu).

https://doi.org/10.1016/j.ijepes.2018.02.032
Received 10 September 2017; Received in revised form 18 December 2017; Accepted 18 February 2018
0142-0615/

large-scale interconnected transmission systems. However, the sensitivity equivalent method ignores both static load characteristics and power loss. In fact, power loss is considerable in distribution networks. In electric power generation and distribution systems, about 10% of the produced electric power is lost in distribution networks [20]. Therefore, in order to ensure the accuracy of the equivalent model, it is necessary to incorporate sensitivity, power loss and static load characteristics in the equivalence of active distribution networks.

An accurate active distribution network equivalent model is significant for effective steady-state analysis [21,22]. These drawbacks mentioned above may deteriorate the accuracy of the equivalent model and thus lead to large errors in power system analysis. In order to avoid these drawbacks, a new two-tier static equivalent method considering the sensitivity, power loss and static load characteristics is proposed to replace active distribution networks. The main advantages of this paper are threefold:

(1) A new physical equivalent network composed of equivalent generator, branch and load is used to simplify an active distribution network and capture the characteristics of DGs, lines and loads in the active distribution network.
(2) The proposed upper tier equivalent model can retain the consistency of sensitivity and power loss before and after equivalence based on the proposed physical equivalent network. By doing so, the accuracy of the equivalent model can be improved.
(3) The proposed lower tier equivalent model, building the least square model of the border power measurement equations with ZIP coefficients based on the upper tier equivalent parameters, can further retain static load characteristics. Thus, the accuracy of the equivalent model is further enhanced.

The rest of the paper is organized as follows. The physical equivalent network of the active distribution network is built in Section 2. The upper tier equivalent model considering sensitivity and power loss is presented in Section 3. The lower tier equivalent model considering static load characteristics is established in Section 4. Case studies are shown in Section 5, followed by the conclusions in Section 6.

2. Physical equivalent network of active distribution network

In this section, a new physical equivalent network is constructed to simplify an active distribution network and capture the characteristics of DGs, lines and loads in the active distribution network.

The original transmission network connected with an active distribution network before equivalence is shown in Fig. 1(a). The simplified active distribution networks, as shown in Fig. 1(b) and (c), are used for the upper and lower tier equivalent models, respectively. The physical equivalent network in Fig. 1(c) is the final network to replace the active distribution network.

For the upper tier equivalent network in Fig. 1(b), the original active distribution network is simplified by the border node *B*, equivalent load node *Leq*, equivalent generator node *Geq*, and three following types of equivalent components:

(1) Equivalent generator: S_{Geq}, I_{Geq} and V_{Geq} are power, current and voltage of the equivalent generator at node *Geq*, respectively, representing the equivalence of the DG_{SPV} in the active distribution network.
(2) Equivalent branch: Z_{eq1} and Z_{eq2} are impedances of the equivalent branches between *B* and *Leq*, and between *Leq* and *Geq*, respectively, representing the equivalence of the lines in the active distribution network.
(3) Equivalent load: S_{Leq}, I_{Leq} and V_{Leq} are power, current and voltage of the equivalent load at node *Leq*, respectively, representing the equivalence of the loads and the DG_{SPQ} in the active distribution network.

V_B is the voltage of border node *B*. S_B and I_B are the injected power and current from transmission network to the active distribution network at *B*, respectively. Compared with the upper tier equivalent network in Fig. 1(b), the equivalent load of the lower tier equivalent network in Fig. 1(c) is further represented by the constant impedance (Z), constant current (I) and constant power (P).

Although the physical equivalent network is constructed, the equivalent parameters of the physical equivalent network are not obtained. Only the physical equivalent network with the accurate equivalent parameters can retain the important behaviors of the active distribution network. Based on the physical equivalent network, the upper tier equivalent model considering sensitivity and power loss and the lower tier equivalent model considering static load characteristics are proposed. These two models are used to obtain equivalent parameters in the following sections.

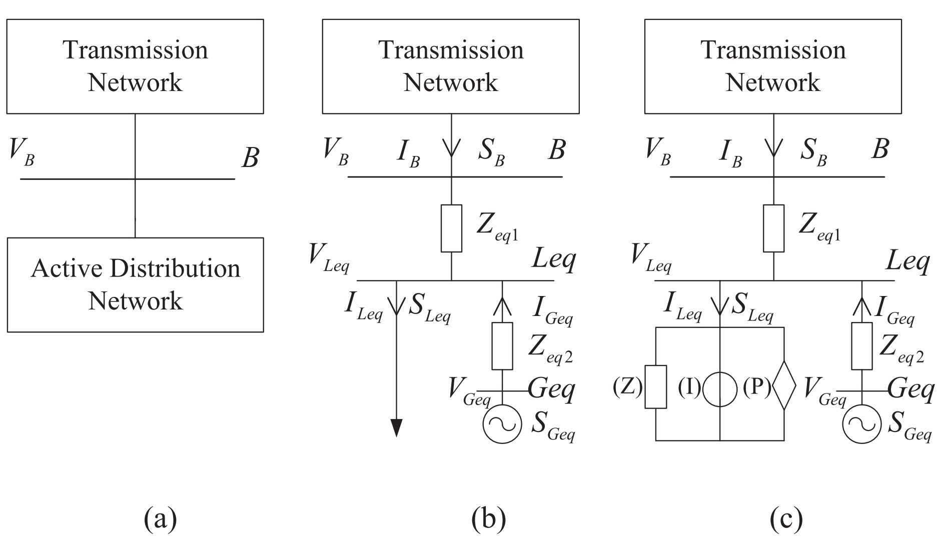

Fig. 1. Active distribution network before and after equivalence. (a) Original transmission and active distribution networks before equivalence. (b) Physical equivalent network for the upper tier equivalence. (c) Physical equivalent network for the lower tier equivalence.