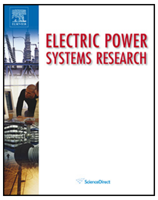
Electric Power Systems Research 161 (2018) 152–166

Contents lists available at ScienceDirect

Electric Power Systems Research

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



A detailed network model for distribution systems with high penetration of renewable generation sources

P.M. De Oliveira-De Jesus [a,*], C. Henggeler Antunes [b]

[a] Electric and Electronic Engineering Department, School of Engineering, Los Andes University, Bogotá, Colombia
[b] Department of Electrical and Computers Engineering, Polo II, University of Coimbra, Portugal

ARTICLE INFO

Article history:
Received 28 October 2017
Received in revised form 20 March 2018
Accepted 4 April 2018

Keywords:
Power distribution
Renewable generation
Smart grid
Power flow
State estimation
Optimization
Locational marginal pricing

ABSTRACT

One of the most important aspects that characterizes smart grids is the widespread integration of loads and renewable-based generators connected to the distribution network. In general, sequence or phase based network models have included the effect of ground return on equivalent phase and neutral impedances using the Kron's reduction and Carson equations. Under unbalanced grid operation, these traditional models can produce inexact results being inadequate for advanced grid analysis and optimization. This paper presents a detailed and compact formulation for the analysis of multi-grounded distribution systems. The key contribution of the paper is to introduce a detailed representation of the ground loops in the distribution system model suitable to be applied under different analysis methods as power flow, optimal power flow, state estimation and network pricing in an integrated manner. This contribution is meaningful since it allows to analyze future electrical systems with severe unbalanced operation due to high penetration of single-phase renewable and load sources. The ground parameters can be adjusted in the context of a state estimator that integrates ground voltages and currents. The proposed model is tested using illustrative and real-world large-scale test cases. Results reveal significant differences when compared with system analyses using standard three phase network model approach.

© 2018 Elsevier B.V. All rights reserved.

1. Introduction

Smart grids have brought renewed interest in the optimization of electrical power systems, in particular at distribution level. Traditionally, control of power flows and voltages in distribution systems is not complicated and the circuit operation and protection is also straightforward [1]. In general, a balanced operation is assumed and basic concerns of engineers are voltage drop control and power losses reduction. However, the smart grid paradigm entails new challenges [2]:

1. The distribution system must accommodate large amounts of intermittent distributed power injections, mainly from renewable resources and storage devices as electric vehicles. As a result, system optimization is required to achieve efficiency. Thousands of power electronics devices will be capable to generate, demand or store energy. Then, network operation under an alternating current scheme will be inherently unbalanced.
2. Load and generation models are not static. Energy producers and consumers connected to the distribution network will interact with global energy markets. As a result, energy agents should be exposed to economical signals as the price of energy and the costs of network losses and congested infrastructure.
3. Environmental and energy regulation policies as well as market forces will require overall power system optimization in order to reduce CO_2 emissions, congestion and power losses.

1.1. Literature review

To cope with the above-mentioned challenges, enhanced network models are needed. We can identify three types of network models. First, the traditional *3-phase/positive sequence models* used in most commercial packages. These models are based upon primitive impedance matrices where the effect of ground loops is embedded in the formulation through the well-known Carson equations [3] and neutrals are explicitly represented. The 3-phase and positive sequence matrices are derived from these primitive matrices using the Kron's reduction and symmetrical components transformation [4]. The second type is based on the direct use of

---

* Corresponding author.
E-mail address: pm.deoliveiradejes@uniandes.edu.co (P.M. De Oliveira-De Jesus).
URL: https://academia.uniandes.edu.co/AcademyCv/pm.deoliveiradejes (P.M. De Oliveira-De Jesus).

https://doi.org/10.1016/j.epsr.2018.04.005
0378-7796/© 2018 Elsevier B.V. All rights reserved.

Table 1
Review of network models applied on distribution system analysis.

Study type	Pos.Seq./3-Ph	Primitive matrix	Explicit ground loop
Power flow	[6–8]	[9–13]	[14]
Optimal power flow	[15–21]	[22,23]	–
State estimation	[24–29]	[30–33]	–
Locational marginal pricing	[34–37]	[38]	–

primitive matrix models. In this case, phases and neutrals are explicitly represented and no Kron's reductions are necessary. In the third type, phases, neutrals and ground loops are explicitly represented in the network model [5].

Table 1 summarizes a number of contributions where four standard procedures for power system analysis (power flow, optimal power flow, state estimation and network pricing analysis) were applied using any of the three types of network models previously defined.

The use of *3-phase/positive sequence models* is widespread. Regarding to *primitive matrix models*, the OpenDSS platform is able to perform power flow studies using a Newton-based solver [13]. Recently, procedures as optimal power flow [22,23], state estimation [31–33] and network pricing [38] have been presented using the OpenDSS engine and network models based on primitive matrices [30]. Regarding the application of the third type of network models, [14] proposed a power flow method where the ground loop was integrated in the backward–forward algorithm. In this important contribution, the load flow solution expressly includes all currents flowing though grounding paths. However, as seen in the third column of Table 1, a lack of contributions is observed with respect to standard procedures as optimal power flow, system state estimation and network pricing models where the ground loop is explicitly considered.

The extreme unbalanced operation condition associated with the intermittent generation and loads connected to a single phase or two-phases can produce inexact results when the advanced simulation procedures listed in Table 1 are applied. The use of network model reductions and approximations must be avoided when analyzing a power system operated under highly unbalanced load/generation conditions, e.g. power unbalance produced by Plug-in Electric Vehicle (PEV) charging [39,40] or high penetration of renewable generation sources [6]. For this reason, the use of detailed network models in advanced simulation procedures is clearly justified. Nevertheless, we did not find in literature or commercial packages any procedure that use the explicit ground loop representation except the power flow presented in [14]. In this paper, a detailed network model for analysis of multigrounded distribution systems is presented. The key contribution of the paper is to introduce a detailed model of the ground loops in the distribution system model suitable to be applied in the context of different system assessment/optimization standard procedures as power flow, optimal power flow, state estimation and network pricing in an integrated manner. This contribution allows to analyze future electric systems with severe unbalanced operation due to high penetration of single-phase renewable and load sources. The conjunction of a detailed network model and an increased network observability will allow to estimate and adjust ground parameters according to the Carson equations enabling also some optimization tasks with a more realistic representation of the distribution network. Model extensions for different transformer groupings in multiphase weakly meshed systems with several neutrals and ground paths are also discussed.

Test-case results illustrate the application of the model considering a wide range of variability and unbalanced loading/generation conditions. In order to assess the accuracy and applicability of the proposal in the real world, test cases were run and results were compared with simulations performed using the standard three-phase network model approaches as well as other multiphase models as the OpenDSS platform.

This paper is organized as follows. Section 2 discusses the proposed model. Sections 3–6 are devoted to present specific formulations of power flow, optimal power flow, state estimation and network pricing. Case studies are analyzed in Section 7. Conclusions are drawn in Section 8. Nomenclature is provided in Appendix A.

2. Distribution system model

This section presents the proposed distribution system model. All variables declared in the formulation are expressed in per unit. In the following, overlined entries are complex numbers and bold entries are vectors or matrices. Matrices and vectors with complex numbers are overlined and bold. Widehat entries refer to complex numbers in primitive matrices.

Given a single distribution feeder with m nodes and a root node 0, the relationship between nodal voltages and currents can be established by Eq. (1):

$$\mathbf{x} = \mathbf{x}_0 + \mathbf{TRX} \cdot \mathbf{i} \tag{1}$$

The entry $\mathbf{x}$ is defined as the *state of the system vector* with $10\,m\times 1$ dimension comprising three phases, neutral and ground voltages across m nodes of the distribution feeder. This state of the system vector is expressed in rectangular form as $\mathbf{x}=[\mathbf{x}_r, \mathbf{x}_i]^T$ with $x_{rqj} \in \mathbf{x}_r$ and $x_{iqj} \in \mathbf{x}_i$ where $x_{rqj} = \Re e\{\overline{x}_{qj}\ \}$ and $x_{iqj} = Im\{\overline{x}_{qj}\}$. In the following, r and i subindexes refer to real and imaginary parts of a complex number, subindex q refers to a given phase, neutral or ground, $q = a, b, c, n, g$ and subindex j refers to the receiving node of $k-j$ line section. Then, the detailed structure of $\mathbf{x}$ is given by

$\mathbf{x}=[\mathbf{x}_r, \mathbf{x}_i]^T = [x_{ra1}\ x_{rb1}\ x_{rc1}\ x_{rn1}\ x_{rg1}\ \ldots\ x_{rqj}\ \ldots x_{ram}\ x_{rbm}\ x_{rcm}\ x_{rnm}\ x_{rgm}, x_{ia1}\ x_{ib1}\ x_{ic1}\ x_{in1}\ x_{ig1}\ \ldots\ x_{iqj}\ \ldots\ x_{iam}\ x_{ibm}\ x_{icm}\ x_{inm}\ x_{igm}]^T$

The entry $\mathbf{x}_0$ is a $10\,m\times 1$ elements vector with three phases, neutral and ground voltages at root node 0 (distribution substation). This root node 0 vector is expressed in rectangular form as $\mathbf{x}_0=[\mathbf{x}_{r0}, \mathbf{x}_{i0}]^T$ with $x_{rq0} \in \mathbf{x}_{r0}$ and $x_{iq0} \in \mathbf{x}_{i0}$ where $x_{rq0} = \Re e\{\overline{x}_{q0}\ \}$ and $x_{iq0} = Im\{\overline{x}_{q0}\}$. Then, the detailed structure of $\mathbf{x}_0$ is given by

$\mathbf{x}_0=[\mathbf{x}_{r0}, \mathbf{x}_{i0}]^T = [x_{ra0}\ x_{rb0}\ x_{rc0}\ x_{rn0}\ x_{rg0}\ \ldots\ x_{rq0}\ \ldots x_{ra0}\ x_{rb0}\ x_{rc0}\ x_{rn0}\ x_{rg0}, x_{ia0}\ x_{ib0}\ x_{ic0}\ x_{in0}\ x_{ig0}\ \ldots\ x_{iq0}\ \ldots\ x_{ia0}\ x_{ib0}\ x_{ic0}\ x_{in0}\ x_{ig0}]^T$

To obtain a 10-dimensional vector $\mathbf{x}_0$ at root node, it is necessary to repeat $m/2$ times each voltage value x_{rq0} and x_{rq0} for $q = \mathrm{a}, b, c, n, g$.

Nodal currents $\mathbf{i}$ are structured as a real $10\,m\times 1$ dimension vector with three phases and unbalanced currents expressed as: $\mathbf{i}=[\mathbf{i}_r, \mathbf{i}_i]^T$ with $i_{rqj} \in \mathbf{i}_r$ and $i_{iqj} \in \mathbf{i}_i$ where $i_{rqj} = \Re e\{\overline{i}_{qj}\ \}$ and $i_{iqj} = Im\{\overline{i}_{qj}\}$. Then, the detailed structure of $\mathbf{i}$ is given by

$\mathbf{i}=[\mathbf{i}_r,\ \ \mathbf{i}_i]^T = [i_{ra1}\ \ i_{rb1}\ i_{rc1}\ i_{rn1}\ i_{rg1}\ \ldots\ i_{rqj}\ \ldots\ i_{ram}\ i_{rbm}\ i_{rcm}\ i_{rnm}\ i_{rgm}, i_{ia1}\ i_{ib1}\ i_{ic1}\ i_{in1}\ i_{ig1}\ \ldots\ i_{iqj}\ \ldots\ i_{iam}\ i_{ibm}\ i_{icm}\ i_{inm}\ i_{igm}]^T$

Finally, $\mathbf{TRX}$ is the system impedance matrix of $10\,m\times 10\,\mathrm{m}$ dimension, in which the entries are determined according to topology and network structure for all phases, neutral and ground. $\mathbf{i}$ is a vector with nodal currents. These currents should be calculated depending on the load and/or distributed generation model adopted.

2.1. Network structure: the ***TRX*** matrix

The distribution system model comprises three elements to be clearly specified: (1) network structure definition, (2) reference voltages and angles at substation specification, and (3) nodal current model setup depending on load/generation type.

The nature of the distribution line requires an exact model in order to identify the self an mutual impedances of the conductor taking into account the ground path for the unbalanced currents.

Download English Version:

https://daneshyari.com/en/article/7112065

Download Persian Version:

https://daneshyari.com/article/7112065

Daneshyari.com