Electric Power Systems Research 79 (2009) 878–887

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Dynamic REI equivalents for short circuit and transient stability analyses

Federico Milano[a,*], Kailash Srivastava[b]

[a] Dept. of Electrical Eng., Univ. of Castilla - La Mancha, 13071 Ciudad Real, Spain
[b] ABB AB Corporate Research, SE-721 78 Västerås, Sweden

ARTICLE INFO

Article history:
Received 18 April 2008
Received in revised form 16 October 2008
Accepted 18 November 2008
Available online 3 January 2009

Keywords:
Dynamic equivalents
REI (Radial, Equivalent and Independent) equivalents
Model aggregation
Power transfer distribution factors
Short circuit analysis
Transient stability

ABSTRACT

This paper proposes a systematic approach for dynamic power system equivalents based on power transfer distribution factors. The proposed method divides the original network into an internal interconnected system and an external one. Static equivalents are computed at frontier buses that separate the retained internal system from the external one. The equivalents are formed using REI (Radial, Equivalent and Independent) networks and generator model aggregation. Generator parameters are computed based on power transfer distribution factors of the generated active power. The equivalent models are able to accurately approximate the behavior of the original system for short circuit and transient stability analyses. Two test systems, namely the Kundur's 2-area test system and a 1213-bus network that model a real transmission system are used to illustrate and test the proposed technique.

1. Introduction

1.1. Motivation

Power systems all over the world have increased in size and complexity due to the rapid growth of widespread interconnections. Today interconnected power systems cover large geographical areas and comprise thousands of devices. For such large systems, it is neither practical nor necessary to perform studies such as the electromagnetic transient analysis, on-line dynamic security assessment, off-line stability studies and design of controls with the full detailed system model.

While analyzing a large system, the engineers are usually interested in the behavior of a certain part of the system. Such a part of the large system is called *internal* or *study* system and the rest of the system is referred to as *external* system. Static and dynamic reduction or equivalencing is the process of reducing the complexity of external system model while retaining its effect on the study system. The large electric power system models can be reduced significantly with this method while maintaining acceptable accuracy with respect to a specific phenomenon.

1.2. Literature review on static equivalents

Classical methods for computing static network equivalents are Ward equivalents and REI (Radial, Equivalent and Independent) equivalents. The interest on static equivalents is demonstrated by the large number of proposals and task forces dedicated to this topic [1–4].

Ward equivalents were initially proposed in [5] and then further discussed in [6–8]. The Ward equivalent is composed of a linear part and a nonlinear one. The issue of this equivalent is that the physical behavior of the internal system (which is accurate) and the behavior of the external system (which is approximated), cannot be simulated by the same algorithm process.

REI stands for Radial, Equivalent and Independent. This method was originally proposed in [9] and has been documented in great details in several publications [10–12]. Generally speaking REI equivalents is a loss-less network representation of a set of base case injections or, in other words, the so called *zero power balance network*. For its flexibility, the basic principle of REI equivalents is used in this paper for the static network reduction technique and is summarized in Section 2.

One important question when dealing with equivalent static networks is the nature of the equivalent buses of the reduced system. Typically, equivalent fictitious buses do not fall into one of the classical power flow buses (e.g. constant admittance, PQ, PV or slack bus), but are actually a composition of several bus types. In [13,14], sensitivities are used as an index of the impact of a change in the retained system. The external network is reduced based on sen-

---

* Corresponding author.
E-mail addresses: Federico.Milano@uclm.es (F. Milano), kailash.srivastava@se.abb.com (K. Srivastava).

0378-7796/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsr.2008.11.007

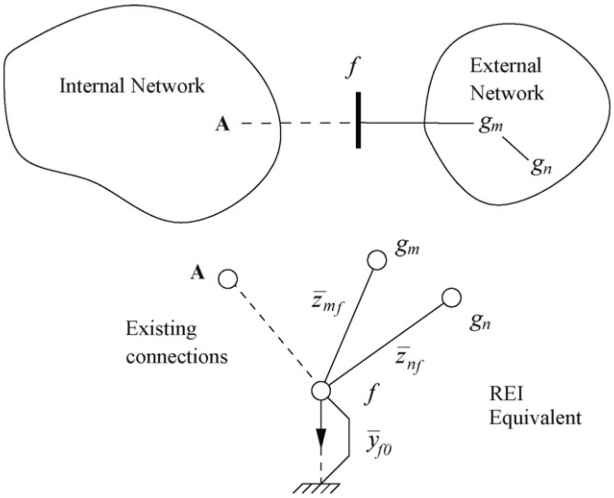

Fig. 1. REI equivalent.

sitivities and the nature of fictitious buses is determined based on sensitivity values. Ref. [15] provides an interesting application of the sensitivity approach similar to the one that is proposed in [13]. In [15], sensitivities are used within the framework of the probabilistic power flow analysis.

Other interesting techniques based on static equivalencing are as follows:

(1) In [16,17], the topology of the external system is not known. The equivalents are determined based on measurement and state estimation techniques.
(2) In [18], equivalent are computed based on an expert system. The bigger the data base, the better the estimation of the equivalent at frontier buses.
(3) Ref. [19] proposes a method to evaluate static equivalents so that the resulting reduced network minimize the error of participation factors with respect to the original system. The application of this kind of equivalents is intended for transmission cost allocations and electricity markets.

1.3. Literature review on dynamic equivalents

Like static equivalents, dynamic equivalent methods have also had a key role in power systems research. The typical problem of dynamic equivalents is to define equivalent synchronous machines so that the reduced network transient stability features are as close as possible to the original system [20]. Another topic, although less exploited in the literature, is to determine dynamic equivalents of loads. This problem is typically solved through identification techniques (for example, see [21]).

Several methods such as heuristic approach, modal analysis approach, coherency approach have been developed to determine static and dynamic equivalents of power systems.

The heuristic approach dates back to 1950s and has been used with AC network analyzer [22]. The procedure was extended to digital computers in 1969 by Brown et al. [23]. It has been widely used for many years but the practice was not based on any solid theory. This may provide reasonable results when the stability problem is local to the study system with dynamics of external areas having only secondary effect.

The modal analysis approach to dynamic equivalencing was introduced in the seventies by Price et al. [24]. This approach suffers from two major drawbacks: it is very time consuming, and equivalents do not have structural identity.

Off late coherency approach has found favor amongst researchers. It involves coherency identification based on rotor angle swings and aggregating each coherent group. Several methods have been proposed for coherency identification based on linearized models. They include inspection of time responses [25–30], pattern recognition [31], closest unstable equilibrium point [32], Liapounov function [33], weakly coupled subsystems [34], modes of low frequency oscillations [35]. Coherency identification without linearization has also been attempted [36]. Some of the recent developments in this area are discussed in references [37–39]. In [40], the authors proposes a method for aggregating not only synchronous machines, but also machine AVRs.

Although coherency methods are recognized as the most reliable for dynamic equivalencing, these have the drawback that it is not always possible to reduce a given part of the network, since the coherency impose the regions into which the network can be divided. Approaches that are able to retain a given part of the network are [41–43]. Other relevant approaches include: dynamic Ward equivalents for transient stability [44], and dynamic identification using artificial neural networks [45].

In this paper we use the main concepts of coherency methods to aggregate several machines into an equivalent one, and to compute the parameters of the equivalent machine.

1.4. Overview of existing software tools for network equivalencing

Few production-grade tools that meet requirements of modern power system exist. Some of the requirements of equivalencing software are described below.

(1) Retention of key system characteristics impacting on specific aspects of stability.
(2) Validity over the expected range of system operating conditions.
(3) Adequate modeling capability.
(4) Compatibility with programs used for analysis of different aspects of stability.

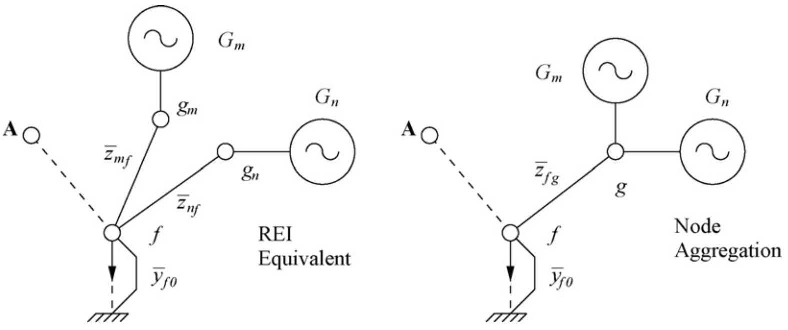

Fig. 2. Node aggregation.