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A methodology for computing robust dynamic equivalents of large power systems

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ABSTRACT

This paper presents a simple and computationally efficient methodology for computing robust dynamic equivalents. While simple to implement, the methodology involves many factors, and these are discussed, explained and justified throughout the paper. It classifies clusters of generators to be equivalenced by their electrical distances, and identifies second order reduced models for them. It maps them into classical synchronous machine models and aggregates them. Reduction of the network is based on the Ward PV method. The quality of the dynamic equivalent, in terms of flexibility and reduced dependence on disturbances, is automatically verified by performance indices. The methodology can easily be embedded in time domain simulation packages. Two large real power system networks are used for testing the performance of the approach.

1. Introduction

Forming the reduced dynamic equivalent of parts of a power system is frequently desirable and/or necessary in power system analysis. In online applications, the reduced equivalent can dynamically represent the (unobserved) network external to the "internal" system of main interest. In all applications, not least in planning studies, such an equivalent can substantially speed up the computation-intensive simulation of large interconnected networks. Such model reductions are also expected to play increasingly important roles with the spread of distributed generation.

Several decades of research in this area have produced significant progress in the related methodologies [1] and specialized software [2]. Nevertheless, dynamic equivalents have received limited practical application, as observed long ago [3], and this is still the case. The obstacles to application include: the use of different, non-standard models by commercial dynamic simulation packages; lack of dynamic model reduction in most such packages; cumbersome and time consuming handling of data and validation of reduced models. Clearly, therefore, it becomes highly advantageous for any time domain simulation program to have a reliable dynamic model reduction feature embedded within it.

In general, dynamic network equivalents have three applications: (i) reducing very large systems for planning studies; (ii) model sizing for a real-time simulator; and (iii) computing external models for online dynamic security assessment. The proposed methodology is suitable for these applications. Here, for model portability reasons, only methods that produce dynamic equivalents in standard power system model form are considered. The general procedure for computing dynamic equivalents is as follows: (i) define the groups of external generators that are coherent; (ii) aggregate each group into an equivalent generator; (iii) perform reduction of the network interconnecting them.

The concept behind aggregating groups of external generators is that each group oscillates almost as a single rotating mass against the other groups, and in particular against the area of interest. That is, each group is coherent with respect to inter-area electromechanical oscillation modes. The generators in each area or group are electrically close to each other, and the ties between groups are relatively weak [4–6]. One of the first approaches to identify coherent generators was based on angle trajectory similarity when the internal system is perturbed by contingencies [7,8]. To speed up the time domain simulations of these perturbations, the generators were represented by linear models. As already reported (e.g., [3]), this approach can lead to coherent groups that differ depending on fault location, and it can erroneously group generators that are quite electrically distant from each other.

Another approach is based on modal analysis [4,5]. Second order synchronous machine models are used to simplify the computa-

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tion of eigenvalues and eigenvectors. The principle is that coherent generators share the same mode shape related to slow (inter-area) modes. The associated computational effort can be significant for large systems. This is mitigated by methods based on electrical proximity/weak links [9], which measure the coupling factors between machines, clustering them via nonsingular perturbation. This type of method has been successfully used in practical applications [10]. The coupling factors are derived from off-diagonal elements of the system Jacobian matrix reduced to the dynamic state variables. The drawback is that such matrices are dense and very large for real-life interconnected systems. A simpler approach to derive such coupling factors is proposed here.

Once the coherent groups have been found, the respective buses and dynamic models are aggregated. These buses have different voltage magnitudes and angles. The use of ideal phase-shifting transformers allows the connection of the nodes [11], preserving the contour conditions. Alternatively, the Zhukov method [12] presents some advantages, since it maintains network symmetry, and it is adopted in this work. For the dynamic model aggregation itself, several approaches have been suggested. The simplest is the use of the classical synchronous machine model [12] with original reactance and inertia parameters. More complex proposals include the weighted frequency response aggregation of detail models [11,13,14]. The proposal here is to use classical synchronous machine model, but with fitted parameters, which significantly simplifies the aggregation, renders portability and provides quite good accuracy as shown by tests.

For the network reduction, the Ward [15–17] and REI [18,19] methods have been used. In the case of steady-state analysis, it has been shown that the performance of some of the Ward method variants (e.g., PV) can be superior [15–17].

The main contributions are summarized as follows: (i) electrical proximity is simplified by using few elements of the $\mathbf{Z}_{\text{bus}}$ matrix to identify electrical proximity; (ii) medoid concept is used in the clustering of generators; (iii) external generators are represented by the synchronous machine classical model, but with parameters identified from the original detailed models; (iv) the buffer zone concept [20], originally applied to static network reduction, has also been used for dynamic equivalents (e.g., [21]) and is revisited here: a well-defined buffer zone retains the explicit models of those quantities that have high sensitivity to the area of interest.

Such novelties render a simpler and computationally more efficient method. The resulting model is portable to most commercial simulation packages. In conjunction, the paper discusses other relevant aspects of the general methodology. It is assumed that the full system model is known and that the reduced part must consist of standard network and dynamic models. The area of interest, or internal system, is fully preserved and the external system is reduced.

The proposed methodology is tested in two real power systems: the Brazilian network and the North American Eastern power grid.

2. Generator clustering

Once the area of interest has been defined, the coherent groups (clusters) of generators in the external system must be identified, as follows.

2.1. Electrical proximity

The system model can be represented by a set of ordinary differential equations and algebraic equations as.

$$\dot{\mathbf{x}} = f(\boldsymbol{x}, \boldsymbol{v}) \tag{1}$$

$$\mathbf{0} = g(\mathbf{x}, \mathbf{v}) \tag{2}$$

where $\mathbf{x} \in R^m$ is the vector of system differential variables, $\mathbf{v} \in R^{2n}$ is the vector of bus voltages (real and imaginary), and n is the number of buses.

The corresponding linearized model is given by

$$\Delta\dot{\mathbf{x}} = \mathbf{A}_1\Delta\mathbf{x} + \mathbf{A}_2\Delta v \tag{3}$$

$$\mathbf{0} = \mathbf{A}_3\Delta\mathbf{x} + \mathbf{A}_4\Delta v \tag{4}$$

By eliminating the voltages in the above equations one gets

$$\Delta\dot{\mathbf{x}} = \mathbf{A}_r\Delta\mathbf{x} \tag{5}$$

where

$$\mathbf{A}_r = \mathbf{A}_1 + \mathbf{A}_2\mathbf{A}_4^{-1}\mathbf{A}_3 \tag{6}$$

In the weak-links method [9], the strong and weak couplings of the generators are identified by the off-diagonal elements of matrix $\mathbf{A}_r$. This has the computational disadvantage that $\mathbf{A}_r$ is dense. For the classical synchronous machine models, $\mathbf{A}_1$ is 2×2 block diagonal. Consequently, the coupling is affected mainly by $\mathbf{A}_2\mathbf{A}_4^{-1}\mathbf{A}_3$, and in particular by $\mathbf{A}_4^{-1}$, which is the $\mathbf{Z}_{\text{bus}}$ matrix (i.e., the inverse of the $\mathbf{Y}_{\text{bus}}$ matrix).

Another view of the effect of $\mathbf{Z}_{\text{bus}}$ is the following. Its elements $z_{ij} = \Delta V_i/\Delta I_j$ are the sensitivities that can be used as proximity indices. The injection of a current at bus j will change voltages throughout the system [22]. The closer the bus is to bus j, the larger will be its voltage change. Thus, these elements provide a measure of bus electrical proximity. The $\mathbf{Z}_{\text{bus}}$ matrix is dense and consequently it is inefficient to fully compute and store it. This is avoided by careful implementation of the clustering algorithm, as explained in the following.

2.2. Clustering

In addition to the electrical proximity of generators, the clustering strategy takes into account the sizes of the generators. The concept is that the generators with larger inertia tend to dominate the angular motion of surrounding generators in interarea oscillations. Thus, the larger generators are candidates to be selected as "medoids". A medoid is a central object around which the cluster is formed [23].

The proximities between the other generators and the medoid are measured by the respective voltage sensitivities for a current injection at the medoid generator that produces 1 pu (per unit) of voltage change at its own bus. A sensitivity threshold establishes a ray of proximity to the medoids, i.e., if the sensitivity is greater than the threshold the generator is added to the cluster.

The clustering algorithm is then:

- i Construct the $\mathbf{Y}_{\text{bus}}$ matrix with the inverse of the reactance of each generator added to the respective row, and factorize it;
- ii Sort all generators by size, either MVA or inertia referred to the system base;
- iii Select the largest generator j not already belonging to a cluster as the medoid of a new cluster;
- iv Compute the voltage sensitivities with respect to the medoid, which corresponds to the row elements in the column j of the $\mathbf{Z}_{\text{bus}}$ matrix relative to the generators terminal buses;
- v Scale the sensitivities so that the sensitivity to the medoid bus is 1;
- vi Add to the cluster all generators whose sensitivities are greater than a specified threshold. If the generator already belongs to another cluster, decide whether to leave it there or transfer it to this cluster by comparing the sensitivities in both clusters;
- vii Store only the sensitivities of the clustered generators;
- viii If all generators have been classified into clusters, terminate the clustering process. If not, return to step (iii).