Identification based Dynamic Equivalencing

X. Feng, Z. Lubośny, and J. W. Bialek

Abstract—Expected bulk connection of renewable energy sources to existing distribution networks may change dynamic properties of power systems and increase the size of power system models used for the analysis of power system operation and stability problems. To reduce the size and complexity of modelling, distribution networks could be replaced by their dynamic equivalents. This paper focuses on identification of dynamic equivalents of distribution network from measured disturbance data. The validity of derived state-space models has been confirmed by simulation.

Index Terms— Dynamic Equivalent, System Identification, Distribution Network

I. INTRODUCTION

Power system models are used for various types of power system operation analysis, e.g. stability analysis, designing of control systems, verification of designed controllers, etc. In practice, building, maintaining, and updating of such a model is an extremely difficult task. Traditionally, distribution networks tend to be replaced by their static equivalents in power system models used for dynamic system studies. However increased penetration of distribution networks by small generators, usually renewable ones, means that static equivalents cannot any longer represent correctly distribution networks. On the other hand, due to the increasing size and complexity of the whole transmission and distribution system, it is almost impossible to study the dynamics and stability problems using a full power system model. A solution for this is dynamic equivalencing.

Various methods for power systems static and dynamic equivalencing have been developed in the past. Node elimination method [1] relies on modelling loads by constant impedances and eliminating them by using the Ward equivalencing technique. Modal analysis method [2] relies on simplification of the system by eliminating modes, which have insignificant effects on system’s dynamic behaviour. Coherency-based method [3] relies on identification of coherent generators (generators that tend to swing together after a disturbance) and aggregation them into a single equivalent generator.

The methods mentioned above are model-based, i.e. a detailed information of network structure, its parameters and models of individual generators is required. However, in a real distribution network, such information may not be accessible. The measurement-based identification method proposed in this paper could solve this problem by regarding the system as a black box. It directly derives an equivalent model of a power system based on some observed Input/Output data from disturbances. Therefore, the detailed information of the system model (i.e. its configuration, parameters, machine models etc.) that needs to be reduced is not necessarily required.

The identification method proposed in this paper is the offline state-space identification. The whole system was modelled in PSS/E program. A disturbance at a bus connecting the distributed network to be equivalenced with the transmission network was simulated and time series of real power, reactive power, voltage and frequency were measured and imported into Matlab System Identification Toolbox to derive an equivalent state-space model. The equivalent was then inserted into PSS/E using user-defined models to replace the distribution network for verification purpose. The results confirmed good performance of the methodology.

II. THE DYNAMIC EQUIVALENCING PROBLEM

A. Definitions

For the purposes of this research, a complex interconnected power system can be divided into the study system and the external system. The study system is the part of the system which is of direct interests and where all the disturbances and configuration changes are assumed to happen. It should be retained in detail.

The external system is the rest of the system. It could be simplified to a reduced equivalent since most of the external systems have insignificant effects on the study system. And what we are interested in the external system are its effects on the study system.

The task of dynamic equivalencing is to eliminate the full model of the external system and replace it by an equivalent model, which has dynamic characteristics close enough to the full model.

B. Problems

1) Data Availability

For classical dynamic equivalencing methods, which are based on coherency or modal analysis, detailed information
about network structure, parameters, and dynamic models of individual elements (generators) is required from the external system, which needs to be reduced. However, in reality such data of power systems for dynamic equivalencing is not always accessible. The data of the local network and generators may not be possible to obtain in detail (e.g. the capability of power plants or the performance of loads) of their own network. For a complex multi-objects system with unknown parameters, the dynamic properties of the system can only be obtained from measurements.

2) Separation of system responses

In system identification methods, the parameters of equivalent model are derived by fitting the response of the system. But the external system and the study system are interconnected with each other so ideally the response of the external system (to be equivalenced) should be isolated from the response of the study system. It can easily done in simulation but such separation can not be done in practice. Hence, the system response, which is obtained after a disturbance, is the response of the whole system (a combined response of the external system and the study system). The equivalent derived using such a response, for this reason, is the equivalent of the full system instead of the equivalent of the external system only. Hence the main problem is how to choose a disturbance and the model so that the obtained equivalent models the external system only.

C. Methodology

The dynamic equivalencing method presented in this paper is based on system identification, which identifies parameters of a selected model structure based on measurements from a chosen point of the system only. It contains three steps:

1) Data Collection

PSS/E program is initially used to simulate dynamic responses of the power system after various disturbances. Measurements are taken at the connecting bus between the external system model and the study system model (see Fig.1a). Time series of voltage and frequency are chosen as inputs and those of real power and reactive power are used as outputs.

2) Offline Identification

In this step, the collected input and output data are imported to Matlab for parameter identifications. The equivalents are derived in a form of mathematical model structures (e.g. discrete state-space model) using System Identification toolbox. The subspace algorithm used to derive the state-space models shown in this paper is described in Appendix.

3) Model Verification

The derived dynamic equivalent model, which has good performance in fitting the measurements, is then implemented as PSS/E user-defined models to replace the external system in the original power system model - see Fig. 1b. Verification is done by comparing responses to system disturbances (short-circuits) of the full model (Fig. 1a) and the reduced model (Fig.1b).

III. IDENTIFICATION OF DYNAMIC SYSTEM

A. Model Structure

Identification of a dynamic system is not an ideal and easy method, especially for a non-linear system such as the power system. Different disturbances applied to the considered power system may possibly lead to different equivalents with good fitting to the measured time series.

The selection of model structure results in different model performances. It is very difficult to say which model is the best in general. Therefore a wide choice of model structures with different orders has been tested to search for acceptably accurate equivalents.

B. Inputs to the Model

For a power system, the static and the dynamic characteristics should both be considered.

1) Static characteristics

a) Loads have static frequency characteristics close to linear and voltage characteristics closer defined by square function; b) Small synchronous generators and wind generators produce power, which does not depend on frequency. Their voltage characteristics are linear; c) Bigger generating units usually have frequency dependent and voltage independent (due to voltage control) characteristics.

2) Dynamic characteristics

Dynamic characteristics of the system are complex. a) The responses of loads and generating units depend on both frequency and voltage; b) Synchronous machines are poorly damped objects whilst asynchronous machines are better damped. In general dynamic properties of the power system are mainly influenced by synchronous machines and the structure of a given power system.

In this project, the measurements of voltage and frequency at the connecting bus between transmission network and distribution network are used as input signals. However, there are problems in measuring frequency due to the noise. Especially when the disturbance applied to the system is relatively small, the measured signal variation in magnitude could be close to the noise. For this reason, using single input
The results suggested that both factors have effects on the state of the system.

C. Disturbances

The disturbances used to derive equivalents should be practical (e.g., line fault or tripping, load rejection etc.) and disturbances like bus faults are not suitable for this reason. The disturbances could be grouped into three categories depending on their locations: a) disturbances in the study system; b) disturbances in the external system; c) and disturbances at the connecting bus.

The object system to be replaced by equivalents is the external system. In real life, the external system cannot be disconnected from the study system for testing and measuring purpose. Hence, the measurements obtained at the connecting bus actually include the response of not only the external system but also the study system.

A key point is to find out disturbances, which have minor effects on the study system so that the dynamic responses of the system are mainly the responses of the external system. If we choose disturbances in the study system, the generator oscillations in the study system cannot be neglected. The models that we derive using these measurements are the equivalents of the full system (the study system and the external system) rather than the external system only. Some disturbances in the external system may have small effects on the study system. But the disadvantage of adding disturbances in the external system is that it could change the topology of the object system during the fault time. This will either more or less affect the accuracy of the equivalents. Also, these equivalents are highly dependent on the locations of disturbances. The third option is to add disturbances at the connecting bus between the study system and the external system.

Among these disturbances that could be added at the connecting bus, changing loads may have relatively small effects on the study system. Disconnection and reconnection of loads could keep the post-fault steady state the same as the initial steady state. On the other hand, the sole load disconnection would change the steady state operating point. In this case, the dynamic response of the network is the combination of the response to the load change and a step response. Besides, from the practical point of view, load disconnection and reconnection could be tested in the real power system without affecting the network operation very much, if the disconnection time is short enough. Therefore the load disconnection and reconnection disturbances are of the main interests for the dynamic equivalencing method presented in this paper.

In this research we have concentrated on disconnection and reconnection of a reactive load. Real load and complex load disconnection have also been tested as disturbances but disconnecting reactive loads is more practical in real power systems since it could be done by just disconnecting a capacitor bank. Disconnecting a real load means disconnecting a customer which is unacceptable. Additionally, the real component of loads may have some effects on frequency. If the frequency has relatively small effects on the accuracy of the equivalent, the effects of real power on frequency could be neglected.

Disturbances like three-phases short-circuit fault, tripping branch and closing branch etc. have also been simulated in either the study system or the external system for testing.

D. Modal Analysis

A disturbance which leads to electromechanical oscillations (of generators) can be analysed using modal (eigenvector) analysis. The modes could be illustrated in a tree structure (Fig. 2):

1) System modes: The root modes of the tree are system modes. System modes are non-oscillatory (real) modes. They are the most basic modes, which involve all the generators in the system. The close-to-zero system modes correspond to the angle state. The real-negative system modes correspond to the speed state (system frequency).

2) Inter-area modes: Inter-area mode oscillations are associated with generators in one area swinging coherently against generators in another area. These modes have lower frequencies and are within the range of 0.05 to 1Hz.

3) Local modes: Local modes, or machine modes, oscillations are associated with single generators. Their frequencies are typically in a range of 0.5 to 2.5Hz.

The areas could be divided into sub-areas till individual generators are obtained. The modal tree structure shown in Fig. 2 is simplified for clearer illustration.

In order to understand better how the derived equivalent worked, we have undertaken eigenvalue analysis of the full and the reduced power system models. For dynamic equivalencing, any modes that involve any machine in the study system should be kept and all the other modes can be discarded and replaced by the equivalent. That means we could cut off the branch of the external system modes at the point shown in Fig. 2. The retained modes should be the system modes, the area modes and study system machine modes. In other words, the external system machine modes can be discarded.

IV. CASE STUDY

The test system used for this project was a part of the Scottish power system shown in Fig. 3. The study system is the...
transmission network (partly shown at the top pf the diagram)

TABLE I

<table>
<thead>
<tr>
<th>Bus</th>
<th>Unit type</th>
<th>Sn[MVA]</th>
<th>Pg[MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>STRD3R</td>
<td>Steam</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>PENP3-</td>
<td>Steam</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>CARG3R</td>
<td>Diesel</td>
<td>2.5</td>
<td>2</td>
</tr>
<tr>
<td>LOCH3Q</td>
<td>Diesel</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>HEHA5-</td>
<td>Hydro</td>
<td>20</td>
<td>18</td>
</tr>
<tr>
<td>PENP5-</td>
<td>Hydro</td>
<td>14</td>
<td>12</td>
</tr>
</tbody>
</table>

while the external system is the distribution network shown below the 132/33 kV transformer with generating units listed in Table 1.

After applying a disturbance consisting of disconnecting a 2 Mvar reactive load at the connecting bus, oscillations in both transmission and distribution networks were observed. However the amplitude of real power oscillations in transmission network was in the range of $10^{-5}$ p.u., which means the oscillations of the generators were really small, just a noise. However, in the distribution network the generators have relatively large oscillations, in the range of $10^{-3}$ p.u. Hence we concluded that such disturbances, which have really small effects on transmission network, could be used to derive a dynamic equivalent that represents only (or rather mainly) the distribution network.

The whole system was modelled in PSS/E program. Disturbances were introduced into either distribution network or connecting bus. Time series of real power, reactive power, voltage and frequency were measured at the connecting bus. These time series were then imported into Matlab System Identification Toolbox to derive equivalent models, which were later introduced into PSS/E to replace the distribution network for verification purpose. We will refer to two models:

(i) The original model (T+D):
Transmission network is connected with the distribution network. All the generators in the system are represented by the sixth or fifth sub-transient models. Loads are composed of constant real and reactive power.

(ii) The equivalent model (T+Eq):
All the generators in transmission network are represented by the sixth or fifth sub-transient model. Loads are composed of constant real and reactive power. The distribution network is represented by the derived equivalent (in the state-space form).

$$
\begin{align*}
\dot{x}(t+1) &= Ax(t) + Bu(t) + Ke(t) \\
y(t) &= Cx(t) + Du(t) + e(t)
\end{align*}
$$

State-space model relates the current output $y(t)$ and the next state $x(t+1)$ to current state variables $x(t)$ and input $u(t)$. $e(t)$ is a white noise.

V. RESULTS AND DISCUSSION

Fig.5 shows the eigenvalues of the power system on s-plane. The squares represent the modes of the whole (T+D) power system. The diamonds represent the modes of the transmission system only which were obtained by representing the whole distribution network by a constant load. By comparing those modes in the plot we could find the modes associated with distribution system - the diamonds that are not covered by the transmission system modes.

The oscillation modes of the distribution system could be grouped into two groups: a) Group B is close to the real axis and has frequencies lower than 0.5Hz, which suggests that they are inter-area modes; b) Group A has frequencies higher than 1Hz, which is within the typical local mode frequency range.

The modes transferred to the z-plane using sampling time as 0.05s (the time step of discrete model) are shown in the left plot of Fig.6. The crosses and the circles represent the modes of the whole system and the transmission system respectively. We can see that the distribution system modes are distributed at real axis, close to unit circle 0°, and around 30°. As we can see from the polar plot, local modes of the system are around 30°. The distribution system local modes are mixed with transmission
system local modes. Hence, it is hard to extract the distribution modes.

The right plot in Fig. 6 shows the modes of the dynamic equivalent of the distribution network identified by the 5th order model (called n4s5) and the 6th order model (called n4s6) which were derived using the same data set. The 5th order model n4s5 has identified the poles at the position corresponding to the system modes and area modes only. The 6th order model n4s6 has also identified a pair of complex poles, which corresponded to the local machines.

As discussed earlier, since we cannot disconnect distribution system from the transmission system, the data sets of system response we use to derive the model is a combined response of both the transmission system and the distribution system. Although we could choose a proper disturbance (close to distribution network) to excite the response of the distribution system more, the response of the transmission network cannot be totally ignored, especially the response of generators near the transmission network. Model n4s6 model contained the modes of local machines, which also included generators in the transmission system. This could have doubled the response of those generators in transmission system when the model is connected with the transmission system, and cause larger oscillations in the system.

The two equivalent models were implemented into the power system model to replace the original distribution system with their outputs as shown in Fig.7. Clearly the response of the new system with n4s5 fits the response of original system well. On the contrary, n4s6 significantly increases the oscillation amplitude. The likely reason is that n4s6 model contained the modes of local machines, which also included generators in the transmission system. This could have doubled the response of those generators in transmission system when the model is connected with the transmission system, and cause larger oscillations in the system.

Fig.8 shows the system response spectra obtained from the original system (solid line), system with n4s5 equivalent (dashed thick line) and system with n4s6 equivalent (dotted line). The upper plot shows real power P flowing from distribution side to bus TON1. The lower plot shows the voltage at bus TON1.

The plots in Fig.8 confirm that model n4s5 seems to offer a better performance than n4s6. The power plots (upper diagram) show a good agreement between the original system and n4s5 while the plot of n4s6 is distinctly different. The voltage plots show that n4s6 model keeps the peak value at around 1Hz rather than around 2 Hz as in the original system. The plot of n4s5 is again much closer to that of the original system. on transmission network. Model n4s5 has a different initial value than the
original model probably due to different mean values caused by output errors.

Fig. 9 compares the response of the original (T+D) model with (T+eq) model when a three phase line fault was applied in the transmission network near the distribution network. The original and the equivalent models have the same maximum clearing time for this fault and the result shows a close resemblance of their voltage and rotor angles transients.

The study that concerns the angle stability of generators in distribution networks has also been carried out. The results suggested that disturbances within the distribution network are required to derive the equivalent for such study.

VI. CONCLUSIONS

Increasing penetration of generators embedded in distribution networks makes it necessary to represent them by dynamic equivalents in power system stability studies. As often the exact model of the distribution network with embedded generators is not known, the aim of this project was to produce a measurement-based, rather than a model-based, dynamic equivalent of a distribution network with embedded generation.

A dynamic equivalencing approach using system identification has been presented in this paper. Following a disturbance consisting of disconnecting a capacitor in the transmission network, a dynamic equivalent has been created. Eigenvalue analysis and time-domain simulations have confirmed a good performance of the equivalent.

VII. APPENDIX

Subspace methods to estimate state-space models are explained in detail in [5].

The state space model structure is

$$\begin{align*}
x(t + 1) &= Ax(t) + Bu(t) + w(t) \\
y(t) &= Cx(t) + Du(t) + v(t)
\end{align*}$$

(A1)

w(t) and v(t) are assumed to be white, have zero mean and a covariance matrix of the form

$$E \left[ \begin{bmatrix} w^T \\ v^T \end{bmatrix} \begin{bmatrix} w \\ v \end{bmatrix} \right] = \begin{bmatrix} Q & S \\ S^T & R \end{bmatrix} \delta_{YY}$$

(A2)

Based on a finite set of collected data{ut, yt},t=0,..., N-1, N4sid algorithms are concerned to find an estimate for the model order n of the system, estimates for the matrices A, B, C, D to a similar transformation , and the noise covariance matrices Q, S and R.

Block Hankel matrices play an important role in these algorithms. The input data are arranged in Hankel matrix as

$$U = \begin{bmatrix}
u_0 & u_1 & \ldots & u_{j-1} \\
u_1 & u_2 & \ldots & u_j \\
\vdots & \vdots & \ddots & \vdots \\
u_{n-1} & \ldots & u_{j,n-j-1}
\end{bmatrix} = \begin{bmatrix}U_1 \\ U_2 \end{bmatrix}$$

(A3)

This matrix is divided into two halves, which represent the past U1 and the future U2 with respect to a reference t=i

The output Hankel matrix Y, the past input/output block Hankel matrix and the extended observability matrix of the form

$$\begin{bmatrix}Y_1 \\ Y_2 \end{bmatrix} \quad W_p = \begin{bmatrix}U_1 \\ Y_1 \end{bmatrix} \quad \Gamma_i = \begin{bmatrix}C \\
CA \\
\vdots \\
CA^{i-1} \end{bmatrix}$$

(A4)

The state sequence can be obtained from

$$O_i = \Gamma_i \tilde{X}_i,$$

where Oi is the oblique projection of Y2 onto Wp along the U2:

$$O_i = \begin{bmatrix}Y_1 \\ Y_2 \end{bmatrix} W_p$$

(A5)

The steps of the algorithm are as follows:

1. Calculate the oblique projections of the future outputs along the future inputs onto the past. This can be implemented using the least squares algorithm.
2. Calculate the Singular Value Decomposition (SVD) of the oblique projection Oi and determine the order.
3. Determine the extended observability matrix.
4. Derive estimates for the state sequences.
5. Derive estimates for A, B, C and D.
6. Determine Q, S and R.

VIII. REFERENCES


IX. BIOGRAPHIES

Xiaodan Feng holds B.Sc. (2001) degree in Control Theory from Beijing Institute of Technology (China) and M.Sc. (2004) degree in Electrical Engineering from the University of Edinburgh. She is currently a PhD student at Institute of Energy System of Edinburgh University. Her interests are in electricity market pricing and in power system dynamics.

Zbigniew Lubosnky graduated from the Gdańsk University of Technology (Poland) in 1985. He received his Ph.D. degree in 1991 and D.Sc. degree in 1999 from the same university. He is currently full Professor (since 2004) at the Gdańsk University of Technology and Research Fellow at the University of Edinburgh, UK. His fields of interests include mathematical modeling, power system stability and control, artificial intelligence utilization to power system control, wind turbines modeling and control.

Janusz W. Bialek obtained his M.Sc. (1977) and Ph.D. (1981) degrees in Electrical Engineering from Warsaw University of Technology (Poland), where he worked from 1981 to 1989. From 1989 to 2002 he was with University of Durham, UK, and since 2003 he has held Bert Whittington Chair of Electrical Engineering at the University of Edinburgh, Scotland. His research interests are in liberalism of the electricity power industry and in power system dynamics.