

U.S. Eastern Interconnection (EI) Model Reductions Using A Measurement-based Approach

Xuemeng Zhang¹, *Student Member, IEEE*, Yaosuo Xue², *Senior Member, IEEE*, Shutang You¹, *Student Member, IEEE*, Yong Liu¹, *Member, IEEE*, Yilu Liu^{1,2}, *Fellow, IEEE*

¹University of Tennessee,
Knoxville, TN

²Oak Ridge National Laboratory,
Oak Ridge, TN
xzhan103@vols.utk.edu

Abstract—Interconnected power systems experienced a significant increase in size and complexity. It is computationally burdensome to represent the entire system in detail to conduct power system analysis. To derive reduced models of large power systems, this paper proposes a measurement-based dynamic equivalent, which uses a set of measurements at the boundary nodes between the study area and external area for model parameter identification. Case studies on the U.S. Eastern Interconnection (EI) demonstrate that the measurement-based equivalent technique can capture the external system behaviors accurately and improve computation efficiency.

Index Terms—Dynamic equivalent, model reduction, power system dynamic simulation, system identification, system transfer function.

I. INTRODUCTION

Due to the expansion of widespread interconnections and increasing penetration of distributed resources, today's power grids increase in size and complexity. As power systems expand to larger geographical areas and comprise more devices, the dimensions of the models can easily reach or even exceed millions of state variables. For such large-scale power systems, it is computationally intensive to perform dynamic studies with a very accurate full-order dynamic system model. Thus, dynamic model reduction techniques are required to accommodate limited computational capabilities while ensuring accuracy requirements. In most cases, the behavior of a certain part of the system, called the internal or study area, is the major study focus, while the rest of the system can be reduced. Therefore, system dynamic model reduction aims to provide a representation of the reduced system, while preserving, with reasonable accuracy, the aggregated steady-state and dynamic characteristics of the full-order network.

The bulk of model reduction techniques in power systems are tailored for the tasks of control design and transient/small signal stability analysis [1]. Concepts like:

- Coherency based method [2]-[7]
- Singular perturbation analysis (SPA) [8]-[10]
- Modal analysis (MA) [11]-[18]
- Identification [19]-[24]

form the basis for a wide variety of model reduction tools. Typical software tools for model equivalence include DIgSILENT, DYNRED and PSS/E [25].

A popular and widely accepted approach for dynamic of power system is the coherency-based method, introduced by Podmore [4]. The coherency-based method is able to give a physical picture of the reduced system. This method starts with identifying coherent generators, and in the second stage it proceeds with system dynamic reduction and generator aggregation. The idea of coherency is widely adopted in commercial software, e.g. DYNRED program and DIgSILENT software. Although coherency-based method has been accepted as the most reliable for power system dynamic equivalence, the major drawback is that the quality of the reduced model depends on the perturbation chosen for coherency identification and system operating conditions, and the coherency has to be re-evaluated, thereby becoming time-consuming for large-scale interconnected power systems and inappropriate for online analysis. Another well-known concept for dynamic equivalence of power systems is slow coherency, which clusters generators based on a priori assumption that the equivalent should retain only slowest system modes. By modifying impedance, aggregated generator terminal buses are not connected by infinite admittances, otherwise it would "stiffen" the system [6].

Singular perturbation analysis (SPA) and modal analysis (MA) are commonly used in control theory. The SPA is based on the assumption that the system equations can be separated into two parts, fast mode and slow mode, thus this method is most conveniently used on two time-scale systems in the explicit form. By identifying singular perturbation parameters and formulating physical transformations to obtain slow and

Notice: This manuscript has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (<http://energy.gov/downloads/doe-public-access-plan>).

fast variables, two subsystems can be used for separated time-scale analyses. One is the slow subsystem by setting singular perturbation parameters to zero; the other one is the fast subsystem obtained by modeling the fast transients of fast variables from its quasi-steady state. The PSA has been proven efficient in power system modelling at both the device and system level, yet the stability of reduced model remains an unresolved question. The MA method [18] simplifies the system by linear equations and preserves dominant modals. After eigenvalue analysis, generators in the external system that have little impact on the internal system are eliminated using controllability, observability and participation factors. However, this method requires detailed information of system parameters, which may be inaccurate and difficult to update in real time.

Recently, a well-established solution for the reduction of large-scale power system dynamic models is based on parametric identification techniques. The objective is to estimate a set of parameters of a model that is assumed to represent a part of a power system, based on measurements of important signals. This method can utilize the real-time measurement from phasor measurement units (PMUs) and Frequency Disturbance Recorders (FDRs) to reflect the actual system condition and to derive the faithful dynamic system model. However, the key issue is the parametrization of the target equivalent model without information on the configuration, parameters, or operating state of the external system. As illustrated in [22], the autoregressive model (ARX) is employed to reduce the external system. However, only the zero-order ARX model is studied, which is unable to represent the whole dynamic performance of the external system.

To meet both the model accuracy and simulation time requirements, this paper introduces a new equivalent model development method based on the transfer function, which directly utilizes the measured data such as the bus frequency, bus voltage, active and reactive power and then identifies model parameters using system identification techniques. The derived equivalents are integrated with a study system using a new user-defined model. Dynamic simulations are performed and corresponding results are evaluated.

The rest of this paper is organized as follows. Section II introduced model reduction approach. The model reduction accuracy test in the EI system is presented in Section III. In Section IV, the integrated simulation in power system dynamic software is shown and results are compared. Conclusions are drawn in Section V.

II. PROBLEM FORMULATION AND SOLUTION APPROACH

A. Problem Formulation

A power system can be divided into a study area and an external area. The interface between the study area and the external area is defined by their n tie-lines and the corresponding power flow (P_i and Q_i) from the external area to the study area are shown in Fig. 1. V_i and f_i are the voltage magnitude and frequency of the border buses in study area.

In power system dynamic simulation, the purpose is to determine the dynamic response of generators and control

systems in a study area due to disturbances inside the region. The external area is reduced to a less detailed model. In this paper, a transfer function model, which injects active power P_i and reactive power Q_i to study area, is defined to replace the external area.

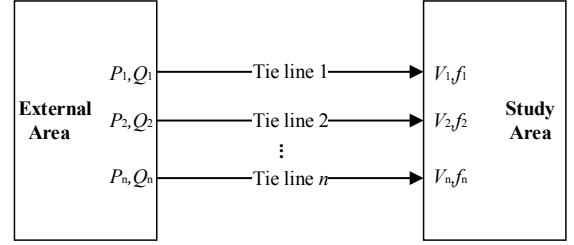


Figure 1. External and study areas of the power system.

B. Transfer Function Method

Consider a linear time-invariant (LTI) system, for continuous-time input signal $u(t)$ and output $y(t)$, the transfer function is the linear mapping of the Laplace transform of the input, $U(s) = L\{u(t)\}$, to the Laplace transform of the output $Y(s) = L\{y(t)\}$:

$$G(s) = \frac{Y(s)}{U(s)}. \quad (1)$$

If the inputs and outputs of the system are determined, the system model can be represented as

$$\begin{bmatrix} y_1(s) \\ y_2(s) \\ \vdots \\ y_q(s) \end{bmatrix} = \begin{bmatrix} G_{11}(s) & \dots & G_{1p}(s) \\ G_{21}(s) & \dots & G_{2p}(s) \\ \vdots & \dots & \vdots \\ G_{q1}(s) & \dots & G_{qp}(s) \end{bmatrix} \begin{bmatrix} u_1(s) \\ u_2(s) \\ \vdots \\ u_p(s) \end{bmatrix}, \quad (2)$$

where $G_{ij}(s)$ is the transfer function representing the relationship between input signal $u_j(s)$ and output signal $y_i(s)$.

C. System Identification

Generally, a transfer function can be used to determine important system response characteristics with selected inputs and outputs. The models only represent the mathematical relationship of the input signals and output data, instead of based on the physics of power system components represented by differential-algebraic equations.

Two important features for the equivalent model are the order of the transfer function and the mathematical structure. To identify the transfer function of dynamic systems from measured input-output data, this paper uses the following steps as shown in Fig. 2.

Step 1: Collect measurement data from the full-order system model. To estimate all model parameters, the dynamic response of the system (P, Q, V, f) is recorded for a disturbance.

Step 2: Define model inputs and outputs. Output signals are usually power flow of tie lines from external area to study area. Inputs can be any measurable signal in the study area.

Step 3: Train the model with selected inputs and outputs. Firstly, the number of zeros and poles should be defined. Initialization applies the instrument variable (IV) method. The numerical search uses the Gauss-Newton least squares method. The termination condition is set to 0.01 error, or 20 iterations.

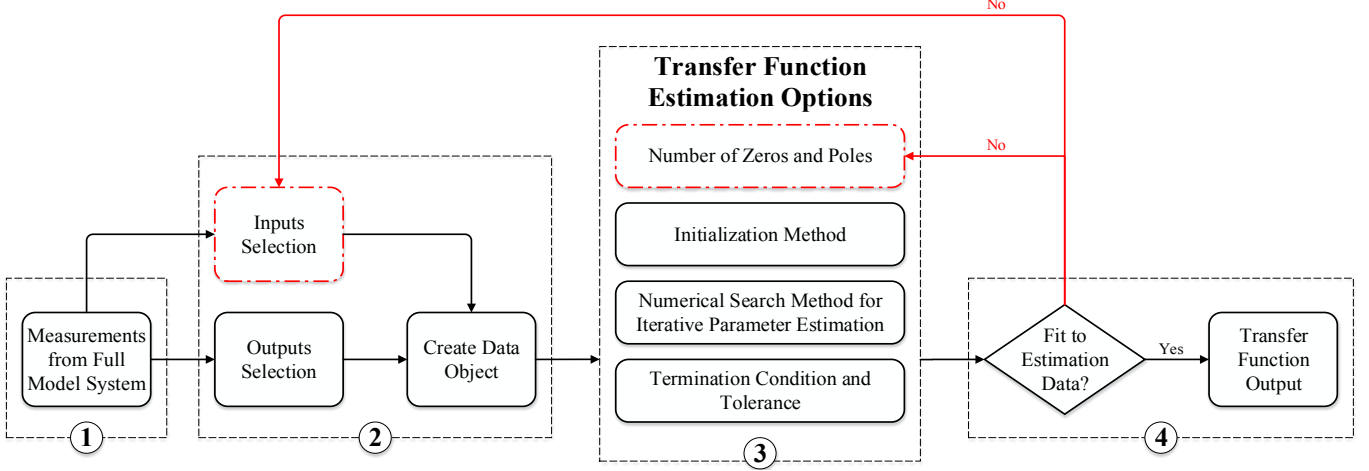


Figure 2. Procedure of system identification

Step 4: Output the model parameters for validation.

D. Evaluation of the Model Accuracy

The general idea of model accuracy evaluation is shown in Fig. 3. Area 1 is the study area and Area 2 is the external area to be reduced. A tie line exists between Area 1 and Area 2. For example, the voltage and frequency of the border bus in the study area are used as inputs: active power and reactive power of the tie line are outputs. After training the transfer function with those inputs and outputs, a function $(P, Q) = G(f, V)$ in (2) can be obtained as the equivalent of the external system. The derived model is then used to predict results of the test events and its accuracy is evaluated by comparing its responses with that of the full model.

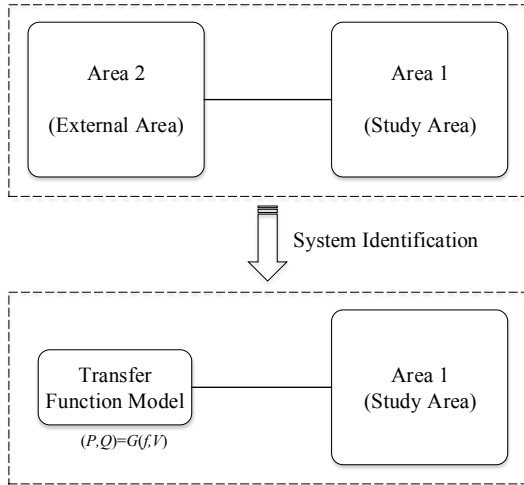


Figure 3. Approach of model reduction.

After identifying the transfer function model, it is necessary to validate whether the model is effective to represent dynamic response of the reduced area. The response of the identified model is compared with actual response.

$$MSE = \frac{1}{N} \sum_{k=1}^N (y(t_k) - y^{est}(t_k))^2, \quad (3)$$

MSE is the Mean Squared Error between $y(t_k)$, the actual measured outputs, and $y^{est}(t_k)$, the simulated outputs, at time t_k . N is the number of sampling points. The smaller MSE is, the better the response of the reduced model matches actual response.

III. CASE STUDY

To demonstrate the effectiveness of the proposed approach, a case study was performed on the Eastern Interconnection (EI) system. The baseline model of the EI system used in this study is a detailed dynamic model with 70,000 buses and 9,000 machines. The total generation capacity of this model is about 590 GW. Fig. 4 shows its geographical map with major transmission lines reflected.

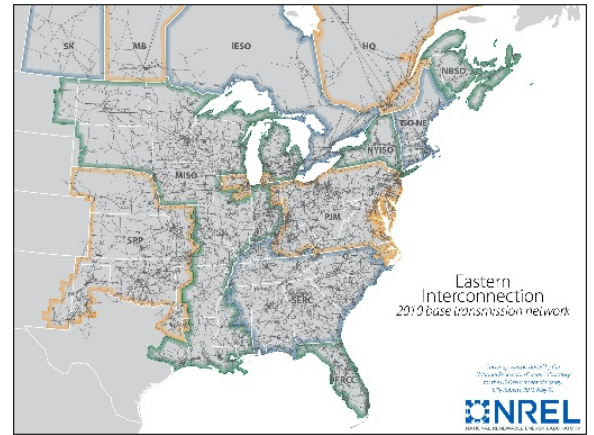


Figure 4. EI system map

In our study, the Florida Reliability Coordinating Council (FRCC) is the study system, as shown in Fig. 5, which is connected to SERC Reliability Corporation by two tie lines (denoted in yellow solid lines: Bus No. 1 to Bus No. 3 and Bus No. 2 to Bus No. 3). Besides FRCC, the rest of the EI system, which has 66,000 buses and 8,300 machines, is reduced using proposed transfer function model.

A generation trip (red dot) at the study area (Bus No. 4) is used for model training. The inputs of the transfer function are voltage (V) and frequency (f) from the border bus (Bus No. 3) of tie lines. The outputs are active power (P_1/P_2) and reactive power (Q_1/Q_2) of two tie lines. Theoretically, more measurement signals would improve model accuracy but, unfavorably, increase complexity. To reduce model complexity, input signals with low correlation with output signals can be omitted. In this paper, since the transfer function represent dynamic response of power flow at tie lines, frequency and voltage are selected as inputs since they are typical inputs of controllers, such as governors and exciters.

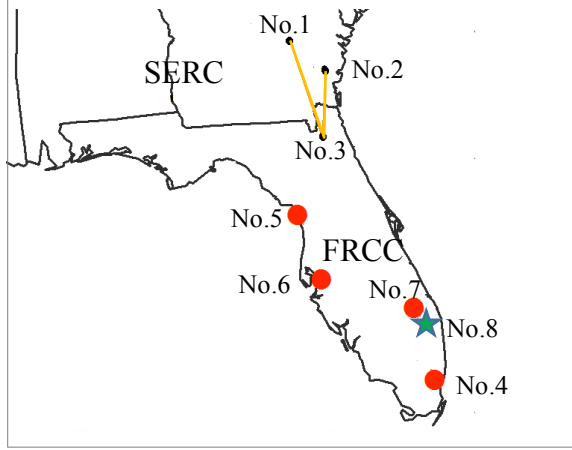


Figure 5. FRCC geographical map

Another important feature of a transfer function is its order. Generally, a higher order is more complex but may not demonstrate higher accuracy. A comparison of transfer functions with different orders is shown in Fig. 6.

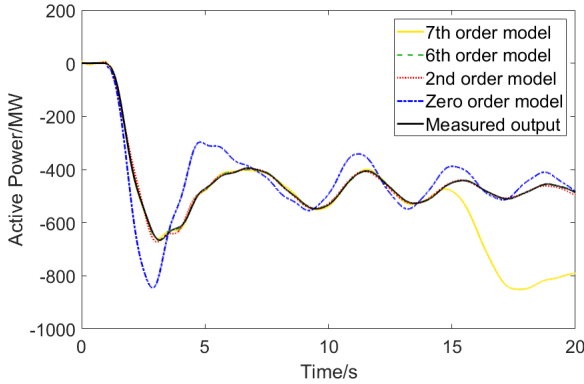


Figure 6. Comparison of different order transfer function

The result show that a higher order model generally has higher accuracy. However, there is no significant improvement in accuracy when the model order increases from second to sixth. The seventh order model even results in over fitting. In this study case, the two-order model is adequate in accuracy and thus considered the appropriate reduced model of the external system. For general applications, the optimal number of model orders depends on system characteristics, accuracy requirements, computation resources, and the model

implementation constraint in simulation environments (for example, high-order user-defined models are difficult to incorporate in PSS/E).

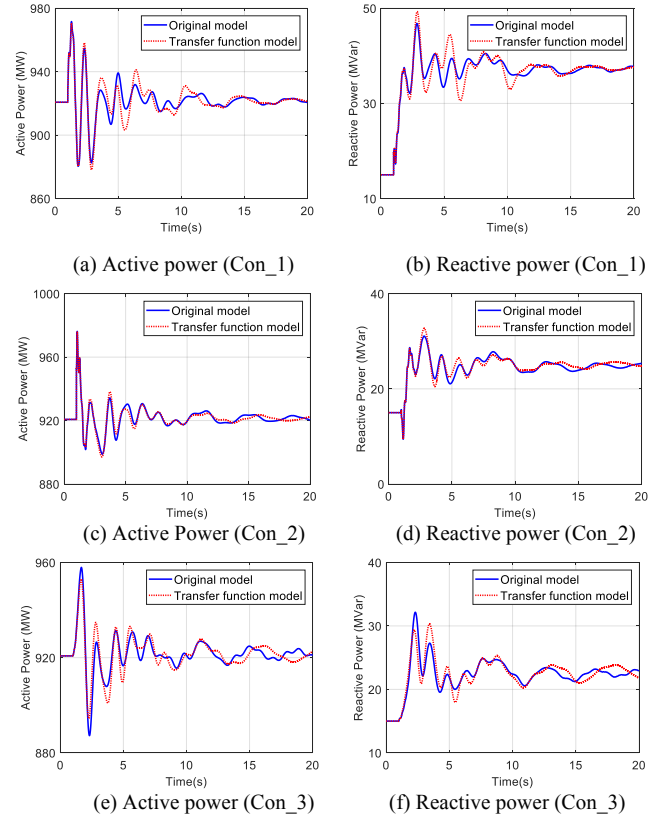
IV. INTEGRATED SIMULATION IN POWER SYSTEM DYNAMIC SIMULATION SOFTWARE

In order to implement the transfer function in power system analysis software, a user-defined model is written in Fortran and integrated in PSS/E to control active and reactive power outputs according to the trained model.

Using the procedure in Fig. 2, the influence of each tie line (between the study area and the external area) on the study area bus in the study area (Bus No. 3). To validate the performance of the transfer function model, four different generation trips as listed in Table I are applied. Active power and reactive power at the observation location (indicated by the green star in Fig. 5) following four contingencies are shown in Fig. 7. The similarity between responses of the reduced model and those of the original model shows that transfer function can effectively capture the behavior of the full system.

Table I. Test contingencies

Contingency	Generation Trip Bus	Trip Amount (MW)	MSE	
			P	Q
Con_1	4	1237	19.4812	3.0804
Con_2	5	1078	3.2192	0.5184
Con_3	6	1078	11.7651	1.3455
Con_4	7	1078	4.7960	0.3777



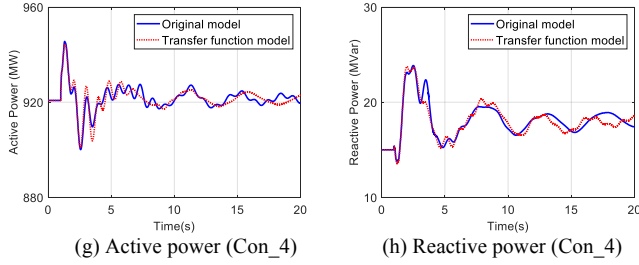


Figure 7. Integrated simulation results of the EI system

Table I also listed the MSE values, indicating that the measurement-based equivalent model has relatively high accuracy in representing the external system. With the external system reduced, to the measurement-based model, the complexity scale of the new model is around 5% of that of the full-order system model, substantially increasing the simulation speed.

V. CONCLUSION

Measurement-based system reduction can overcome the disadvantages of traditional model-based techniques and it is more suitable for online update with the increasing availability and quality of wide-area measurement data. In this paper, a measurement-based transfer function model is proposed for model reduction and multiple tie lines between the study area and the external area can be replaced by the reduced model. Transfer functions with different orders are compared and the model accuracy is tested on the EI system. A PSS/E user-defined model is developed to integrate the reduced model to the study area. Results show that the transfer function is accurate in presenting the dynamics of the external system.

ACKNOWLEDGMENTS

This work is supported by the U.S. Department of Energy, Grid Modernization Initiative, Grid Modernization Laboratory Consortium Extreme Event Modeling project, and partially supported by NSF under award number 1509624. This work also made use of the Engineering Research Center Shared Facilities supported by the Engineering Research Center Program of the National Science Foundation and DOE under NSF Award Number EEC-1041877 and the CURENT Industry Partnership Program.

REFERENCES

- [1] D. Chaniotis and M. A. Pai, "Model reduction in power systems using Krylov subspace methods," *IEEE Trans. Power Syst.*, vol. 20, no. 2, pp. 888-894, May 2005.
- [2] R. W. deMello, R. Podmore, and K. N. Stanton, "Coherency-based dynamic equivalents: Applications in transient stability studies," in *PICA Conference Proceedings*, pp. 23-31, 1975.
- [3] A. J. Germond, R. Podmore, "Dynamic Aggregation of Generating Unit Models," *IEEE Trans. Power App. Syst.*, vol. 97, no. 4, pp. 1060-1069, July 1978.

- [4] R. Podmore, "Identification of coherent generators for dynamic equivalents," *IEEE Trans. Power App. Syst.*, vol. 97, no. 4, pp. 1344-1354, 1978.
- [5] R. Nath, S. S. Lamba and K. S. P. Rao, "Coherency Based System Decomposition Into Study and External Areas Using Weak Coupling," in *IEEE Power Engineering Review*, vol. PER-5, no. 6, pp. 52-53, June 1985.
- [6] J. H. Chow, R. Galarza, P. Accari and W. W. Price, "Inertial and slow coherency aggregation algorithms for power system dynamic model reduction," *IEEE Trans. Power Syst.*, vol. 10, no. 2, pp. 680-685, May 1995.
- [7] Sung-Kwan Joo, Chen-Ching Liu, L. E. Jones and Jong-Woong Choe, "Coherency and aggregation techniques incorporating rotor and voltage dynamics," *IEEE Trans. Power Syst.*, vol. 19, no. 2, pp. 1068-1075, May 2004.
- [8] J. H. Chow, J. R. Winkelman, M. A. Pai, P. W. Sauer, "Singular perturbation analysis of large-scale power systems," in *International Journal of Electrical Power & Energy Systems*, vol. 12, no. 2, pp. 117-126, 1990.
- [9] P. V. Kokotovic, R. E. O'Malley, P. Sannuti, "Singular Perturbation and Order Reduction in Control Theory - An Overview," in *Automatica*, vol. 12, no. 2, pp. 123-132, March 1976.
- [10] V. R. Saksena, J. O'Reilly, P. V. Kokotovic, "Singular Perturbation and Time-scale Methods in Control Theory - Survey," in *Automatica*, vol. 20, no. 3, pp. 273-293, May 1984.
- [11] N. Martins, L. T. G. Lima and H. J. C. P. Pinto, "Computing dominant poles of power system transfer functions," *IEEE Trans. Power Syst.*, vol. 11, no. 1, pp. 162-170, Feb 1996.
- [12] N. Martins and P. E. M. Quintao, "Computing dominant poles of power system multivariable transfer functions," *IEEE Trans. Power Syst.*, vol. 18, no. 1, pp. 152-159, Feb 2003.
- [13] R. A. Schlueter, H. Akhtar, H. Modir, "An RMS Coherency Measure: A Basis for Unification of Coherency and Modal Analysis Model Aggregation Techniques," in *IEEE PES Summer Power Meeting*, Los Angeles, CA, USA, 16-21, July 1978.
- [14] R. A. Schlueter, U. Ahn, "Modal Analysis Equivalents Derived Based on the RMS Coherency Measure," in *IEEE PES Winter Power Meeting*, New York, USA, 1979.
- [15] J. Lawler, R. A. Schlueter, P. Rusche, D. L. Hackett, "Modal-coherent Equivalents Derived from an RMS Coherency Measure," *IEEE Trans. Power App. Syst.*, vol. 99, no. 4, pp. 1415-1425, July 1980.
- [16] J. Lawler, R. A. Schlueter, "Computational Algorithms for Constructing Modal-coherent Dynamic Equivalents," *IEEE Trans. Power App. Syst.*, vol. 101, no. 5, pp. 1070-1080, May 1982.
- [17] G. C. Verghese, I. J. Perez-arriaga and F. C. Schweppe, "Selective Modal Analysis With Applications to Electric Power Systems, Part II: The Dynamic Stability Problem," *IEEE Trans. Power App. and Syst.*, vol. PAS-101, no. 9, pp. 3126-3134, Sept. 1982.
- [18] S. E. M. de Oliveira and J. F. de Queiroz, "Modal dynamic equivalent for electric power systems. I. Theory," *IEEE Trans. Power Syst.*, vol. 3, no. 4, pp. 1723-1730, Nov 1988.
- [19] A. Chakraborty, J. H. Chow and A. Salazar, "A Measurement-Based Framework for Dynamic Equivalent of Large Power Systems Using Wide-Area Phasor Measurements," *IEEE Trans. on Smart Grid*, vol. 2, no. 1, pp. 68-81, March 2011.
- [20] S. Wang, S. Lu, N. Zhou, G. Lin, M. Elizondo and M. A. Pai, "Dynamic-Feature Extraction, Attribution, and Reconstruction (DEAR) Method for Power System Model Reduction," *IEEE Trans. Power Syst.*, vol. 29, no. 5, pp. 2049-2059, Sept. 2014.
- [21] H. Liu, *et al.*, "ARMAX-Based Transfer Function Model Identification Using Wide-Area Measurement for Adaptive and Coordinated Damping Control," *IEEE Trans. on Smart Grid*, vol. 8, no. 3, pp. 1105-1115, May 2017.
- [22] J. Chai, Y. Liu, Y. Liu, N. Bhatt, A. D. Rosso and E. Farantatos, "Measurement-based system reduction using autoregressive model," in *2016 IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*, Dallas, TX, 2016, pp. 1-5.
- [23] F. Ma and V. Vittal, "A Hybrid Dynamic Equivalent Using ANN-Based Boundary Matching Technique," *IEEE Trans. Power Syst.*, vol. 27, no. 3, pp. 1494-1502, Aug. 2012.
- [24] X. Zhang, *et al.*, "Measurement-based Power System Dynamic Model Reductions," in *2017 North Amer. Power Symp.*, to be published.
- [25] F. Milano, K. Srivastava, "Dynamic REI Equivalents for Short Circuit and Transient Stability Analyses," in *Electric Power Systems Research*, vol. 79, no. 6, pp. 878-887, June 2009.