Dynamic Model Reduction of Large Power Systems Based On Coherency Aggregation Techniques and Black-Box Optimization

Mahmoud Matar, Nilkamal Fernandopulle, and Ahmed Maria

Abstract-- **This paper presents the dynamic model reduction methodology developed by Ontario IESO (Independent Electricity System Operator) to obtain reduced-order dynamic network equivalents for large interconnected power systems. This methodology is based on electrical-proximity progressive reduction and utilizes: (i) coherency aggregation techniques, (ii) static network reduction, and (iii) black-box nonlinear optimization, to develop the reduced-order equivalent.**

This paper provides validation and evaluation of the performance of the model reduction methodology. As a case study, the paper presents the reduction of Ontario's external system from 58,173 buses to 1,757 buses without compromising the accuracy of the results. The accuracy combined with the significant reduction in CPU time makes the use of this reduced-order model for real-time (On-line) security limits derivation highly beneficial.

***Keywords*: On-line dynamic security assessment, dynamic equivalents, coherent generators, optimization.**

I. INTRODUCTION

A power system is reliable if it is able to supply the energy requirements of the loads and is able to withstand disturbances, e.g., the loss of a transmission element. The latter is achieved by deriving a set of operating security limits (OSLs) that limit power flows across the transmission system and ensuring that generation is dispatched in such a way that those limits are not violated. As such, power system operation is constrained by OSLs since these OSLs often cause congestions and thereby alter energy prices. OSLs are determined through power system studies and are generally a function of several power system parameters such as the status of generating units, the status of shunt compensators, the load level and the power flows across transmission elements.

The process of deriving OSLs involves conducting both steady-state power flow analysis as well as dynamic simulations for hundreds of scenarios. As such, this process is computationally demanding and time consuming.

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Traditionally, OSLs are determined off-line based on selected pre-specified operating conditions and contingencies. Necessarily, these limited scenarios do not reflect the real-time operating conditions of the system and may result in conservative OSLs which lead to uneconomical operation. Hence, to fully utilize the capacity of the transmission system, without compromising the reliability, it is of paramount importance to be able to accurately and automatically derive OSLs based on real-time or near real-time operating conditions using live telemetered data, especially in the context of the deregulated energy markets, the smart grid initiatives, and the large scale integration of intermittent renewable energy resources.

Benefiting from the vast processing powers of today's computers and the sophisticated dynamic security assessment (DSA) tools, many control centers have started to derive OSLs on-line. Typically, the DSA tools are integrated into the energy management system (EMS) and the same model of the power system is used for both dynamic security assessments and power system operations, e.g. dispatching generation. The success of on-line OSLs derivation relies not only on making use of advances in information technology, but also on using a system model that is:

(a) accurate enough to preserve vital characteristics of the actual system,
(b) small enough to accelerate voltage and transient simulations, and to meet any size restrictions imposed by the EMS, and
(c) robust enough to withstand all realistic adjustments in operating states and still enables a solution to be reached both in steady-state and dynamic simulations.

The size and complexity of modern interconnected power systems hinder the use of the detailed system model for real-time applications. Further, given that dynamic models are more prone to numerical lapses compared to steady-state models, achieving robustness is a challenge. However, due to the fact that the impact of most power system problems, except rare wide-spread black-outs and inter-area modes, are usually confined to a limited area makes it unnecessary to always use detailed models. As such, it is a common practice, to reduce the size and complexity of the power system, to divide the system into two main subsystems (i) the study subsystem and (ii) the external subsystem. The transient phenomenon of interest occurs and is primarily experienced in the study subsystem. The study subsystem comprises those components that are highly influenced by the transient phenomenon. The study subsystem has to be modeled accurately and in detail. On the other hand, the external subsystem represents the remainder of the full system and is represented by a reduced-order equivalent model that accurately mimics the effects of the detailed external subsystem on the study subsystem.

Dynamic reduction techniques reported in the literature can be divided into two categories: (a) Coherency-based techniques [1] - [6], and (b) modal-based techniques [6] - [9]. In coherency-based techniques, a disturbance is simulated and the acceleration of generators is monitored to identify generators that accelerate at the same rate, thereby maintaining their initial angular difference with respect to each other. These groups are said to be coherent and are replaced by one equivalent unit. On the other hand, in the modal approach first the equations are linearized and then the eigenvalues and eigenvectors are calculated. Generators in the external system that have no impact on study system are eliminated based on controllability, observability and participation factors.

This paper presents the model reduction methodology developed by Ontario's IESO to obtain the reduced-order dynamic equivalent for Ontario's external system. Today, this equivalent is being successfully used by the IESO for on-line OSLs derivation (OLLD). The methodology is based on utilizing: (i) MATLAB and PSS/E to identify generators in the external system model that swing coherently for a disturbance in Ontario, (ii) PSS/E to reduce number of buses in the external system model, and (iii) MATLAB black-box nonlinear optimization and PSS/E to determine dynamic model parameters of external equivalent generators. The rest of this paper is organized as follows. Section II presents the reduction methodology and the steps to develop the reduced model. Section III presents the study system. Section IV provides validation of the developed model. Conclusions are stated in Section V.

II. Reduction Methodology

The adopted reduction methodology is based on the electrical-proximity progressive reduction approach. The main idea is to first classify the control areas within the external system based on their electrical proximity to the study system and then based on their closeness to the study system, the level of details being preserved is determined. The further the control area is, the lesser details are being preserved and vice versa. In other words, control areas within the external area are subjected to different levels of reduction depending on their influence on study system.

The electrical proximity of different control areas within the external system can be evaluated based on a combination of the following factors:

- The system topology and geographical proximity.
- The power transfer distribution factors (PTDFs), where the PTDFs are calculated for the tie-lines, connecting the study system to the external system, subject to the loss of external system generators [9].
- The acceleration of generators present in the external system subject to major disturbances in the study system [4], [10].

Generally, the control areas within the external system can thus be categorized into four main groups; (i) neighbouring areas, (ii) intermediate areas, (iii) remote areas, and (iv) asynchronous areas, i.e., areas connected to the rest of the system solely via HVDC links.

Neighbouring areas are considered as buffer zones and are subject only to static reduction of the passive network at the 115 kV level and below. All the generators, controlling equipment, controlled buses, and the transmission system above 115 kV, are fully retained.

For the intermediate areas, the level of reduction is increased. Coherent generators are aggregated into equivalent generators; where a single machine is used to represent each coherent set of generators. The ratings of the equivalent generator are scaled up to match the group totals. The detailed dynamic model of the largest generator in a coherent group, with all the control equipment, e.g., the exciter and the governor, is used to model the aggregate generator [4]. The entire passive network at the 230 kV and below is subject to static reduction.

For remote areas, a coarser generator aggregation approach is adopted, with major generating stations aggregated into equivalent generators that are scaled up to represent the total generation in those areas. The aggregate generators are modeled using the classical generator model GENCLS and the simple governor model GAST. The parameters for the GENCLS and GAST dynamic models are determined based on least square minimization.

For the asynchronous areas, they are completely removed from the system since the HVDC lines decouple the dynamics of those areas from the rest of the system. If necessary, only the HVDC link model is included.

In vision of the aforementioned discussion, to develop the equivalent, it is required to perform the following steps:

A. Coherency Identification and Generators Aggregation

The whole idea is to reduce the number of generators in the external system while retaining their impact on the study system. Generators that have similar dynamic response can be aggregated into a single equivalent unit.

Several techniques are available in the technical literature to identify coherent generators [1]-[6]. Among those, the non-linear time-domain simulation method is simple and effective. In this method, severe disturbances are applied in the study system and the rotor angle deviations of the external system generators are monitored. Two generators are considered coherent if their rotors swing together, i.e., if the maximum difference between their angular deviation remains less than a certain tolerance for entire simulation, or mathematically:

$$\max\left|\Delta\theta_i(t) - \Delta\theta_j(t)\right| < \xi \qquad (1)$$
$$\Delta\theta(t) = \theta(\mathrm{t}) - \theta(0)$$

After the identification of coherent generator sets, each coherent set is then replaced with a single aggregate generator. In this work, the terminal bus aggregation method is adopted [3]-[5]. For a given coherent generator set, the terminal buses of the coherent generators are connected to the terminal bus of the aggregate generator using ideal phase shifters to maintain the power flow unchanged at the terminal buses of the coherent generators after their removal [4].

B. Static Network Reduction

Static network reduction is the process of eliminating some buses from the original network to reduce its size. One approach to perform static network reduction is based on Gauss elimination. In this work, PSS/E capabilities to conduct static network reduction are utilized [11].

C. Black-Box Optimization

A vital step in the process of creating dynamic equivalents is to optimally determine the parameters for the dynamic models of the aggregate generators such that the dynamic responses of the study system equipment can be accurately replicated using the reduced-order model. This can be achieved based on the use of optimization techniques with the objective of minimizing the error between the dynamic responses obtained from the full case and the corresponding ones obtained from the reduced case. Mathematically, the objective function is defined as

$$\min_{x} f(x) = \sum_{i=1}^{N} \left\| \frac{\theta_i^f - \theta_i^r(x)}{\theta_i^f} \right\| + \sum_{k=1}^{M} \left\| \frac{P_k^f - P_k^r(x)}{P_i^f} \right\| \tag{2}$$

Subject to : $x_{low} \leq x \leq x_{high}$

where θ_i^f is the rotor angle of the i^{th} generator obtained from the full case, θ_i^r is the rotor angle of the i^{th} generator obtained from the reduced case, P_k^f is the active power flow over the k^{th} tie-line obtained from the full case, and P_k^r is the active power flow over the k^{th} tie-line obtained from the reduced case.

The principle challenge, in this optimization problem, is the lack of a closed form mathematical model that relates the outputs, i.e., the dynamic responses of the study system equipment, to the inputs, i.e., the dynamic model parameters of the aggregate generators. The use of time-domain simulation tools is the only practical option to find the system outputs for a specific set of system inputs. As such, the system can be considered as a black-box system and a black-box optimization technique has to be adopted in order to minimize (2).

The process of determining the dynamic model parameters of the reduced system can be summarized as follows. First, the dynamic responses of critical machines within the study system and power flows over the tie-lines connecting the study system to the external system are obtained using the full system and stored to be used as the benchmark results. Second, the black-box optimization algorithm is started. The optimization algorithm and the time-domain simulation tool, PSS/E in this work, are closely coupled. The whole process is running in a closed-loop iterative manner. In each iteration, the optimization algorithm sends a set of parameters for the dynamic model, automatically runs the PSS/E software to obtain the dynamic responses based on the reduced-order system, evaluates the objective function, and then generates an enhanced set of parameters for the dynamic model [12]. In this work, the sequential quadratic programming (SQP) in conjunction with the finite difference method, which is used to construct the gradients, are adopted for the black-box optimization [13].

III. Study System

The North American bulk-power system consists of four asynchronous systems; the Eastern interconnect, the Western interconnect, Texas, and Quebec. The Eastern and Western systems are interconnected by six back-to-back DC links where five of them are located in USA and one is located in Canada. The Eastern system is connected to Texas by two DC links. Similar to Texas, Quebec also remains asynchronous with the rest via six DC links. The Eastern system has the highest energy consumption and thus, administratively divided into six regions (NPCC, RFC, SERC, MRO, FRCC, SPP) as shown in Fig. 1 [14]. Each region consists of many states and provinces where each may include many independent electricity suppliers, equipment owners and operators. Ontario is part of NPCC and the IESO manages Ontario's bulk power system and electricity market.

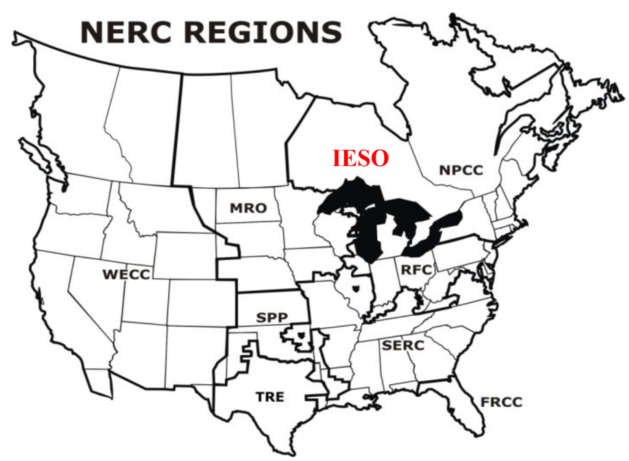

Fig. 1. NERC Interconnections [14].

The IESO uses the full model for its off-line studies. Currently, this model has over 63,000 buses and the Ontario portion is only about 5% of the total size. Due to this large external size, the use of the full model to perform on-line studies is neither possible nor recommended due to real-time limitations. Thus, it is required to develop a reduced-order external model to be used in OLLD applications. The OLLD uses the DSA software developed by Power-Tech Lab to derive security limits that are based on voltage stability (VSAT) and transient stability (TSAT). The power-flow is obtained from the state-estimator, solved and used in VSAT and TSAT that runs every 15 minutes.

Based on the presented system reduction methodology, a reduced-order external model was developed. Table I compares the sizes of the detailed external model and the reduced-order external model and highlights the percentage reduction in size.

TABLE I
SUMMARY OF FULL AND REDUCED MODELS

Component	External Model			Ontario Model
	Full	Reduced	% Reduction	
Buses	58,173	1,757	97	3,857
Branches	74,880	5,001	93.3	4,839
Generators	7,843	798	89.8	431

IV. VALIDATION

To validate the accuracy of the generated equivalent, various tests were carried out to compare the original full case with the reduced-order case. In all cases, the study zone, i.e., Ontario's system is identical in both the full and reduced cases. While validations were done extensively, only a sample of the results are presented in this paper. The following subsections present the results of the validation tests. The first subsection presents the comparison between the dynamic responses for one of the severest contingencies whereas the second subsection presents the comparison between the distribution factors for various contingencies.

A. Transient Stability

The contingency simulated is one of the most critical contingencies for Ontario. Two 500 kV lines are tripped due to LG fault in each line. These circuits supply power to transformer stations at major supply points in Ontario. In order to secure the post-fault system, 2 nuclear units are tripped.

Figures 2 to 7 compare the transient responses obtained from the full case and the corresponding ones obtained from the reduced case. These figures show a set of selected variables that include the rotor angle of one of the nuclear generators, the frequency and voltage at one of the 500 kV buses, the power flow over one of the major transmission lines originating from the nuclear station, the collective performance of Ontario's system as a total through monitoring the total Ontario acceleration power, and the total power flow across the tie-lines to New York.

The close agreement of the presented dynamic simulation results verifies the validity of the reduced model to conduct studies involving disturbances within Ontario.

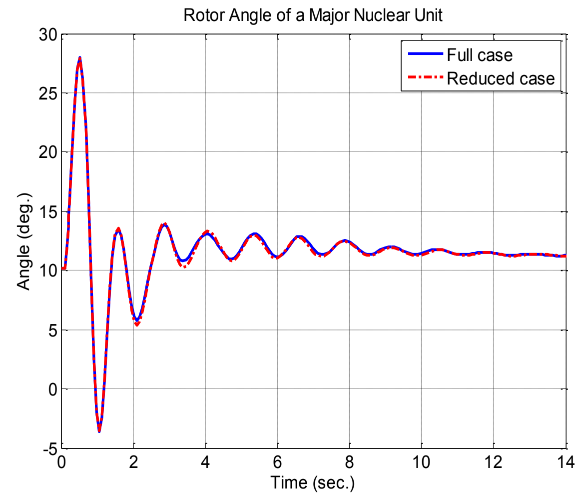

Fig. 2. Comparison between the rotor angle of a nuclear unit obtained from the full case and the reduced case.

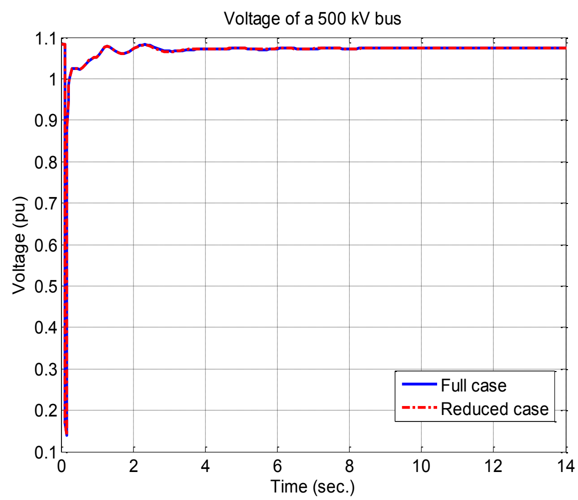

Fig. 3. Comparison between the voltage of a 500 kV bus obtained from the full case and the reduced case.

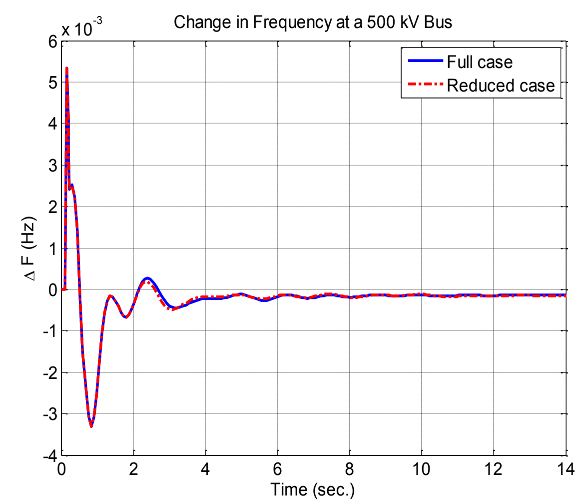

Fig. 4. Comparison between the change in frequency of a 500 kV bus obtained from the full case and the reduced case.

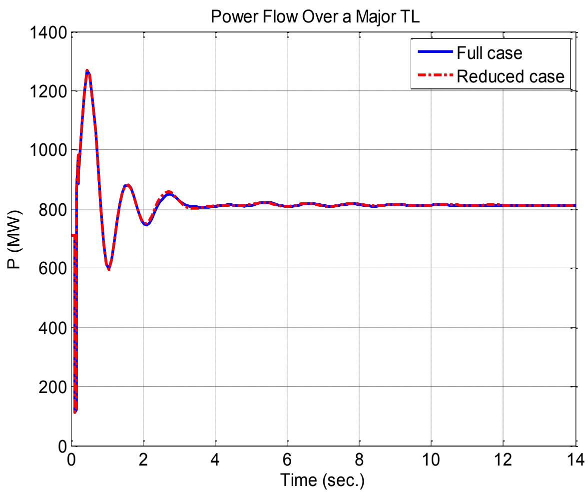

Fig. 5. Comparison between the power flow over a major transmission line obtained from the full case and the reduced case.

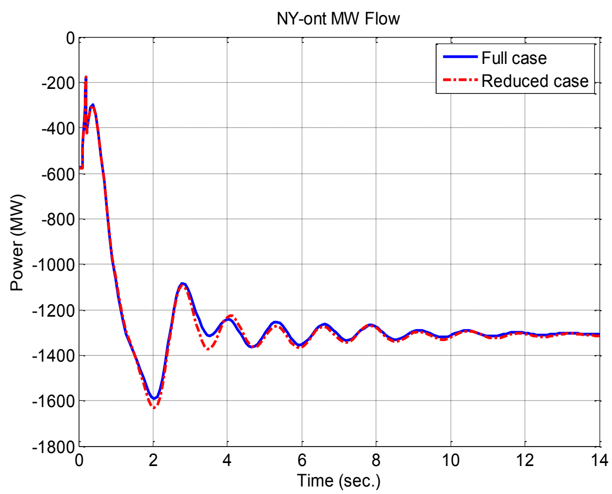

Fig. 6. Comparison between the power flow over the tie-lines between Ontario and New York obtained from the full case and the reduced case.

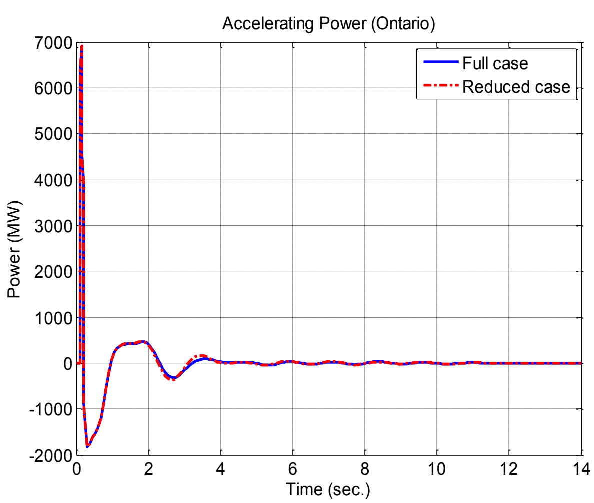

Fig. 7. Comparison between the total accelerating power obtained from the full case and the reduced case.

Based on the use of the reduced-order external model, the CPU time is drastically reduced from the 562 sec required by the full model to only 26.5 sec with the reduced order model. This is more than 95% reduction in the CPU time.

B. Power Transfer Distribution Factors

The relative change in power flow over the tie-lines to New York, Michigan, and Manitoba & Minnesota due to various outages within Ontario are calculated from both the full case and the reduced one. Table II shows a sample of the distribution factors obtained from both cases. As seen from Table II, the distribution factors obtained from the reduced case closely match the corresponding ones obtained from the full case.

TABLE II
DISTRIBUTION FACTORS

	New York Ties		Michigan Ties		Man+Minn Ties	
Contingency	Full	Reduce	Full	Reduce	Full	Reduce
L4D	10.8	10.7	-11.7	-11.6	0.8	0.8
J5D	20.4	20.3	-21.9	-21.8	1.5	1.5
B3N	11.4	11.2	-12.3	-12.1	0.8	0.8
L33P	-14.2	-14.1	13.1	13.1	1	1
PA302	-4.5	-4.5	4.3	4.2	0.3	0.3
F3M	15.5	15.3	17.8	17.8	-33.3	-33
K21W	7.8	7.7	9	8.9	-16.8	-16.7

V. CONCLUSIONS

This paper presents the steps to develop dynamic network equivalents for large power systems. Based on the use of coherency aggregation techniques and nonlinear black-box optimization, the external system can be drastically reduced to a small fraction of its size without compromising the accuracy of the simulation results.

The reduction methodology has been used to reduce Ontario's external system to about 3% of its original size resulting in a more than 95% reduction in the CPU time for most transient simulations. The accuracy of the model has been extensively validated.

The accuracy combined with the drastic reduction in the simulation time make the use of this reduced model for on-line dynamic security assessment highly beneficial.

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