

Dynamic System Equivalents using Integrated PSS/E and Python for Transient Stability Studies

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SUMMARY

Transient stability studies are required to be carried out for an efficient and secure operation of power systems. However, due to the limitations of computer memory and processing speed, handling a complete set of DAEs (differential-algebraic system of equations) that describe a large-scale interconnected power system is difficult and uneconomical. Hence, the transient stability of large power system is generally studied by dividing the system into internal and external areas. The internal area is also known as the study area in which transient studies are performed. Any areas outside the internal area are known as external areas, and the external areas are replaced with a dynamic equivalent circuit to reduce the calculation time. The research on dynamic equivalent circuit is still worth exploring. Therefore, this paper attempts to propose an approach to obtain a dynamic equivalent circuit for the external system.

In the proposed method, a dynamic equivalent circuit is obtained by adding equivalent generators to boundary buses of a static equivalent circuit. The static equivalent circuit of the external system can be constructed utilizing the static network reduction features available in PSS/E. If a complete set of dynamic parameters are not available or there are many generators in the external system, the optimization techniques based on minimizing the cost function are utilized to determine the model parameters of equivalent machines, where the cost function is defined as the sum of squares of the difference between equivalent system transient voltage results and the full system transient voltage results. The proposed method is validated with the New York and New England IEEE 68-bus system. The simulation has shown that the developed equivalent system is good at mimicking the dynamic features of the original system.

KEYWORDS

Coherency, dynamic reduction, generator aggregation, dynamic equivalent, heuristic optimization, Nelder-Mead method, Monte Carlo method, Powell method.

1. INTRODUCTION

Transient stability studies are required to be carried out by the utilities for successful planning, operation and control, and post-disturbance analysis of large interconnected power systems [1]. The complete power system model for transient stability analysis can be mathematically described by a very large set of differential equations modelling generation stations which are coupled by the algebraic equations describing the transmission network and loads [2]. With the increasing scale of power systems, handling a complete set of differential and algebraic equations that describe the entire interconnected system becomes difficult and uneconomical due to its huge computation burden. Therefore, it is necessary to divide the interconnected power system into a study system and one or more external systems. In transient studies, the study system is of specific interest and represented by a detailed model. The external system can be represented by a dynamic equivalent circuit to reflect the influence of the external system on the study system. The development of dynamic equivalent circuits has existed for decades, and there are three main approaches reported in literature:

1. Model methods: describe the external system by an approximate linear model [3]-[5].
2. Coherency methods: identify coherent groups of generators and then replace the coherent generators with equivalent generators [6]-[9].
3. Measurement or simulation-based methods: obtain the external system response to applied disturbance by measurements or simulations, and determine model parameters through curve fitting techniques [10]-[13].

Due to the fact that the linear state equations of the equivalent model cannot reflect the characteristics of real physical power system components, the dynamic equivalent circuit generated by the Model methods cannot be directly used for transient stability studies. In comparison, Coherency methods and measurement or simulation-based methods can be directly used for transient stability studies. However, the Coherency methods are proposed on the condition that the structure and parameters of the external system are available, which cannot always be satisfied, especially the dynamic parameters of the generators.

This project aims to develop a generalized method to obtain a dynamic equivalent circuit for external power system. Specifically, when the parameters of external generators are not available or there are many generators in the external system, the simulation-based method can be applied to determine equivalent dynamic parameters. As the development of a good dynamic equivalent circuit is a time-consuming task, this paper thus provides a much easier way to do this using integrated commercial software PSS/E and Python.

2. METHODOLOGY

2.1 STATIC EQUIVALENCING

A static equivalent circuit of external system is constructed by performing a static reduction [14]-[17] on the admittance matrix of the external system, which is given by:

$$\begin{bmatrix} I_R \\ I_D \end{bmatrix} = \begin{bmatrix} Y_{RR} & Y_{RD} \\ Y_{DR} & Y_{DD} \end{bmatrix} \begin{bmatrix} V_R \\ V_D \end{bmatrix} \quad (1)$$

where I_R and V_R represent node current and voltage at the nodes to be retained, and I_D and V_D are node current and voltage at the nodes to be deleted.

The desired form of an equivalent circuit only contains I_R and V_R , with variables I_D and V_D assumed to be linearly dependent on variables I_R and V_R . The second row of (1) is rearranged as:

$$V_D = Y_{DD}^{-1}(I_D - Y_{DR}V_R) \quad (2)$$

Substituting (2) into the first row of (1), the current equation of I_R can be written as

$$I_R = (Y_{RR} - Y_{RD}Y_{DD}^{-1}Y_{DR})V_R + Y_{RD}Y_{DD}^{-1}I_D \quad (3)$$

Due to the fact that all boundary buses are retained, the first term of (3) can be regarded as new equivalent transmission lines between the boundary buses and static shunts connecting the boundary buses. The second term represents a set of equivalent currents injected at boundary buses. These equivalent currents reproduce the effect of load currents at the deleted nodes, which can be transformed to equivalent constant real and reactive power loads at boundary buses. To perform the operation discussed above in PSS/E, the BUILD ELECTRICAL EQUIVALENT (EEQV) activity is used.

2.2 DYNAMIC EQUIVALENCING

The static network equivalent obtained through PSS/E is only capable of providing the interconnections between the boundary buses and does not provide the equivalent voltage source. The dynamics of the power system is mainly affected by the generators. Thus, it is important to take into account the effect of external generators on the internal system. The dynamic equivalent circuit for the external systems is constructed by adding equivalent generators at boundary buses of the static equivalent circuit.

The proposed fitting process determines the parameters of equivalent generators in an iterative way. The dynamic parameters of equivalent generators are identified by fitting the response of the equivalent system with the original system. The optimal parameters of equivalent generators are obtained by minimizing the error between the dynamic response of the original system and the equivalent system. The transient voltage recovery waveforms are used to as the error criterion for the fitting process. To investigate the effect of the external system on the dynamic performance of the internal system, the voltage recovery characteristics at the buses in the internal system are studied. The transient voltage recovery waveform is obtained by performing transient simulation. Thus, voltage values at each simulation time instant are chosen to form an objective function for the fitting process, given by

$$\min f(x) = \sum_{i=0}^n [V_f(i) - V_e(x, i)]^2 \quad (4)$$

where the subscripts f and e denote the full system and the equivalent system, respectively. The voltage values are given by points on the transient voltage recovery waveform and n is the total number of points over the simulation period. $V_f(i)$ is the voltage value (known in advance) at point i obtained from the full system, $V_e(x, i)$ is the voltage value at point i obtained from the equivalent system. Here, x denotes the parameter to be identified by the fitting process. The voltage value of the equivalent system at point i varies as a function of the parameter x . The basic principle of the objective function is to search for optimal parameters so that the dynamic responses of the reduced system can be roughly close to the dynamic responses of the full system. The fitting process is depicted in Figure 1.

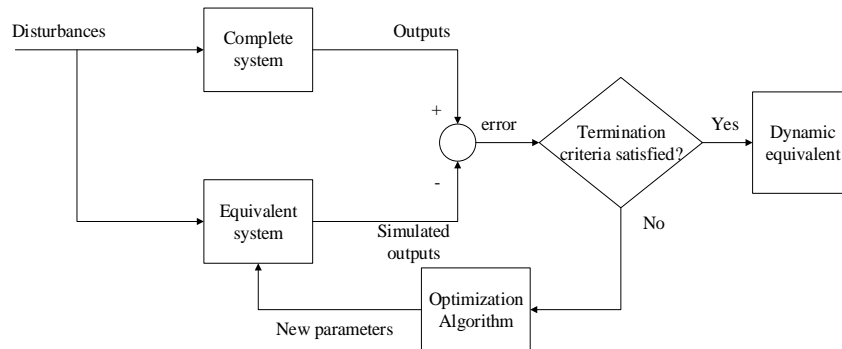


Figure 1. Process of determining dynamic model parameters

The proposed algorithm is iteratively executed in the Python environment based on the PSS/E Application Program Interface (API). Each iteration of the algorithm automatically:

- a. Run dynamic simulation of equivalent system in PSS/E
- b. Export dynamic response of equivalent system to Python
- c. Evaluate the objective function $f(x)$ for simulation time period
- d. Adjust parameters according to the optimization algorithms
- e. Feedback the adjusted values to PSS/E

The iteration between Python and PSS/E is illustrated in the following flowchart (of Figure 2).

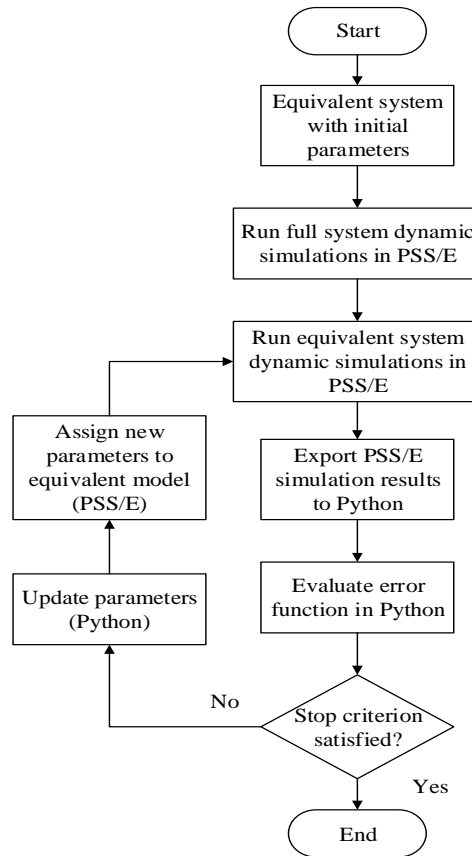


Figure 2. Interface between PSS/E and Python

In this optimization problem, voltage values at each time instant obtained from equivalent system are compared to that of the full system. However, there is no mathematical function that can be used to express the relationship between the inputs (i.e., equivalent model parameters) and the outputs (i.e., voltage responses). The system output corresponding to the specific set of system inputs can only be obtained by using time domain simulation tools. As such, the objective function which relates the outputs, i.e., the transient voltage responses, to the inputs, i.e., the parameters of equivalent models, cannot take derivatives. Three optimization algorithms, namely Monte Carlo method, Nelder-Mead method and Powell method, are adopted here to determine the equivalent parameters by minimizing the objective function. These three optimization methods are chosen because they do not require any derivative information.

3. VALIDATION

The proposed method is applied to a 16-generator, 68-bus system that is representative of the New England/New York interconnected system [18]. A single line diagram of this system is shown in Figure 3.

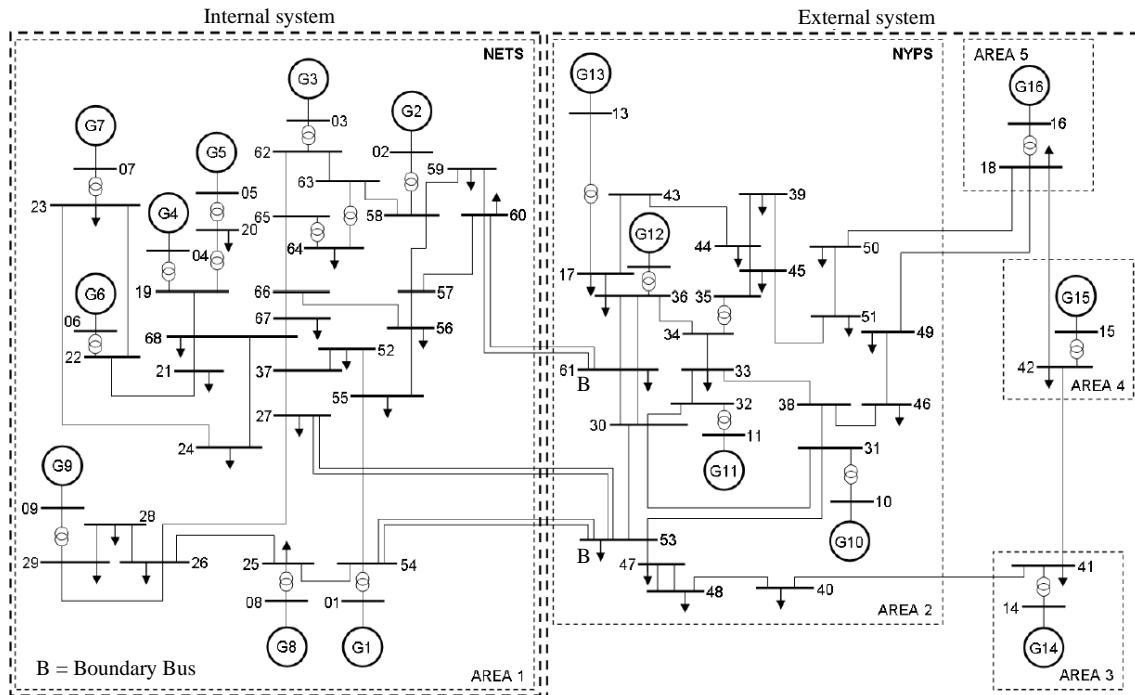


Figure 3. Single-line diagram of IEEE 68-bus power system

3.1 VALIDATION OF STATIC EQUIVALENT RESULTS

Based on the presented system reduction method, a static equivalent network of external system was developed. Table 1 compares the original system and the reduced system and highlights the percentage reduction in size. To validate the performance of the static equivalent circuit, bus voltages, power transfer and faults levels at retained buses were compared with that of the original system and found satisfactorily matching.

Table 1. Comparison between Original and Static Equivalent System

Component	Original system	Static equivalent system	% Reduction
Buses	68	38	44
Branches	69	38	45
Generators	16	9	43.75
Loads	36	22	38.9

3.2 VALIDATION OF DYNAMIC EQUIVALENT RESULTS

The proposed curve fitting method is validated by identifying optimal parameters of equivalent generators. The original transient voltage response is obtained from the full New England & New York 68-bus system. The reduced 68-bus system consists of an unchanged internal system and a dynamic equivalent external system, where generators in the external area (generators 10-16) are replaced by two equivalent generators at boundary buses 53 and 61. To investigate the influence of external system on the dynamic performance of internal system, a fault is applied in the internal system and the dynamic responses of buses in the internal system are analyzed. Here, we only take two main parameters (H: inertia and D: damping coefficient) of each equivalent generator as an example to validate the proposed fitting process.

These two parameters for each equivalent generator must be determined such that the objective function is minimized. For both the full system and the reduced system, a three phase fault was applied at bus 37 at 1 second and cleared after six cycles (100ms). The transient voltage response of bus 27, which is one bus away from bus 37 and close to the external system, is monitored. Therefore, the accuracy of the proposed fitting process using optimization algorithms is examined by how well the terminal voltage at bus 27 of the reduced system match with that of the full system.

I. VALIDATION OF THE MONTE CARLO METHOD

To validate the Monte Carlo method, the corresponding ranges of four parameters were given. The best fitting curve is plotted, as shown in Figure 4. It is seen that the transient voltage recovery waveforms of the dynamic equivalent system match well with that of the full system. It turns out that the proposed curve fitting technique using Monte Carlo method provides good performance in determining dynamic parameters.

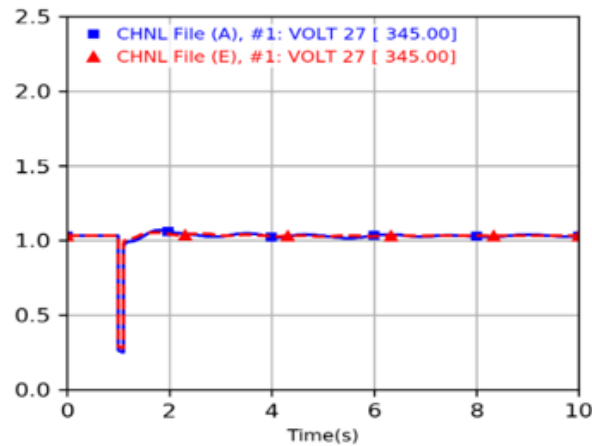


Figure I. Best case obtained by Monte Carlo method

II. VALIDATION OF NELDER-MEAD METHOD

Equivalent parameters H and D were set to random values (e.g., $H_1=0.5$, $D_1=0.2$, $H_2=0.5$, $D_2=0.2$), which can be regarded as bad initial values to begin the optimization process. Comparison of full system and dynamic equivalent system voltage reconverge waveforms obtained with this setting (on the left) and its corresponding optimal result (on the right) are shown in Figure 5. It is seen that the Nelder-Mead method fails to converge to a critical point of objective function in the case that the choice of initial values is not good. That is, the proposed curve fitting technique using Nelder-Mead Method fails to find optimal values for parameters H and D of equivalent generators.

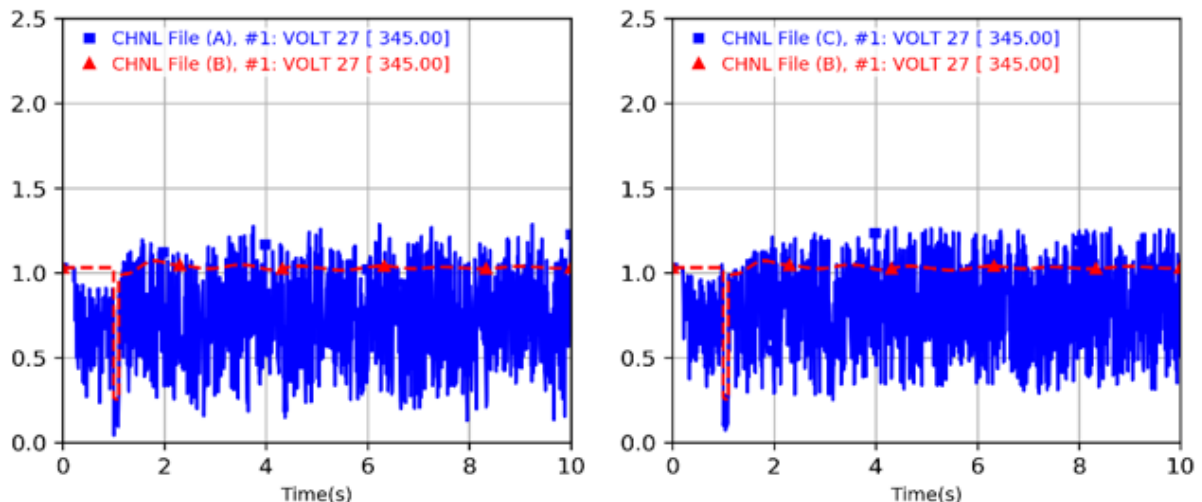


Figure 5. Comparison between the bad initial scenario and its corresponding optimal scenario using Nelder-Mead method

III. VALIDATION OF POWELL METHOD

Similar to the procedures of validating the Nelder Mead method, the comparison of the bad initial scenario (on the left) and its optimal scenario (on the right) resulted from Powell method is shown in

Figure 6. By comparison, Powell method is efficient in finding optimal parameters for H and D to match the full system voltage responses, even if the starting guessing values are bad.

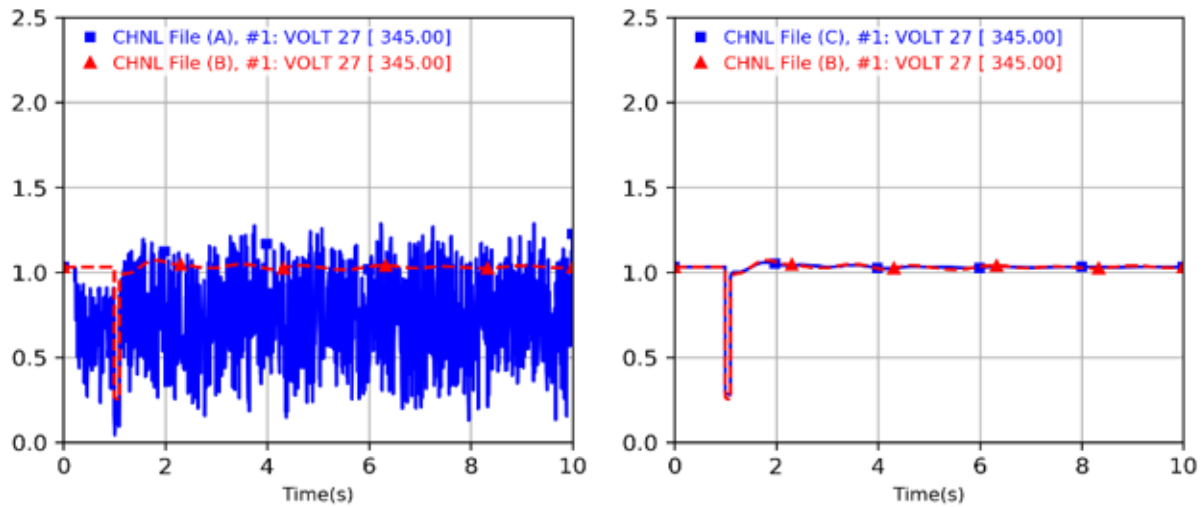


Figure 6. Comparison between the bad initial scenario and its corresponding optimal scenario using Powell method

4. CONCLUSION

This paper presented an approach to develop a dynamic equivalent circuit for the external system while remaining its effects on the study system. The main feature of this approach is the use of a nonlinear optimization based fitting process to determine the model parameters of equivalent generators. New England and New York IEEE 68 bus system has been used for validating the effectiveness of the proposed method in constructing a dynamic equivalent circuit. The developed approach using integrated commercial software PSS/E and Python is easier and more automated, thus repeatable. Validations proved that the proposed approach based on Monte Carlo and Powell methods were effective to search optimal equivalent generator parameters, whereas, the Nelder-Mead algorithm failed to provide an optimal solution.

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