Modeling, Tuning, and Validating System Dynamics in Synthetic Electric Grids

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***Abstract*—A synthetic network modeling methodology has been developed to generate completely fictitious power system models with capability to represent characteristic features of actual power grids. Without revealing any confidential information, synthetic network models can be shared freely for teaching, training, and research purposes. Additional complexities can be added into synthetic models to widen their applications. Thus, this paper aims to extend synthetic network base cases for transient stability studies. An automated algorithm is proposed to assign appropriate models and parameters to each synthetic generator, according to fuel type, generation capacity, and statistics summarized from actual system cases. A two-stage model tuning procedure is also proposed to improve synthetic dynamic models. Several transient stability metrics are developed to validate the created synthetic network dynamic cases. The construction and validation of dynamics for a 2000-bus synthetic test case is provided as an example. Simulation results are presented to verify that the created test case is able to satisfy the transient stability metrics and produce dynamic responses similar to those of actual system cases.**

***Index Terms*—Power system transient stability, synthetic networks, generator dynamics, model tuning and validation.**

I. Introduction

POWER system dynamic models are essential for power engineers and system operators to perform transient stability studies [1]–[3]. Six benchmark models with up to 16 (68) generators (buses) were presented in a technical report [4] and used for comparisons of different stabilizer tuning algorithms. Several IEEE test cases without dynamics were established in 1962 to represent a portion of the American Electric Power System (in the Midwestern US) [5], and have been extended with generator dynamic models appropriate for performing time-domain simulation. A list of power system cases, some of which contain dynamic models, are summarized in [6] and [7]. Actual large-scale network models can produce realistic, insightful simulation results, but access to those actual models is limited because of confidentiality concerns. A solution has been given in our previous work [8], [9], by developing an automated algorithm to build synthetic power system models that represent the complexity of today's electric grids. Those synthetic models are entirely fictitious and hence can be freely shared to the public. Once a synthetic network base case with buses, generators, loads, transformers, and transmission lines, has a feasible ac power flow solution, additional complexities can be added to improve the realism of the case and include data necessary for various types of studies. One application has been addressed in [10] to integrate generators' cost models and operational/physical constraints into a base case for energy economic studies. This paper will primarily focus on the construction of synthetic network dynamics cases for transient stability studies.

Compared to [11] that proposed a methodology for automatically synthesizing varied sets of medium voltage distribution feeders, this paper and our previous works [8]–[10] focus on large-scale high-voltage transmission systems. Bus type entropies and other metrics obtained using statistics from currently available cases were developed in [12] and [13] to improve the modeling of synthetic power grids. Paper [14] presented an algorithm for generating synthetic spatially embedded networks with structural properties similar to the North American grids. A bottom-up method used actual demand and generation data to build power network models on the footprint of Singapore [15]. Topological properties were used in [16] to develop synthetic network graphs. However, work [16] generated only a graph that matches the topological properties of actual grids, without considering any generation and demand data. Synthetic cases in [11]–[15], [17] were developed for steady-state power flow analysis. The research goal of this paper is to extend synthetic network base cases (for power flow studies) with appropriate generator dynamic models, that are able to reproduce similar responses as the actual grids. The synthetic network dynamic cases obtained using the proposed construction methodology are primarily for transient stability studies. Model selections, parameter determination, and model tuning and validation, are main challenges that need to be addressed to build such dynamic cases.

Previous work [18] performed detailed statistical analysis on GENROU (machine), TGOV1 (governor) and SEXS (exciter) for coal-fueled power plants, and determined parameters of those three models for all synthetic generators in a 200-bus case. Work [18] considered only one fuel type and one machine/governor/exciter combination in a small-scale case. This paper aims to produce large-scale synthetic network[1] dynamic cases in consideration of multiple fuel types and various

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Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

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[1]All synthetic network test cases are available for downloads at [19].

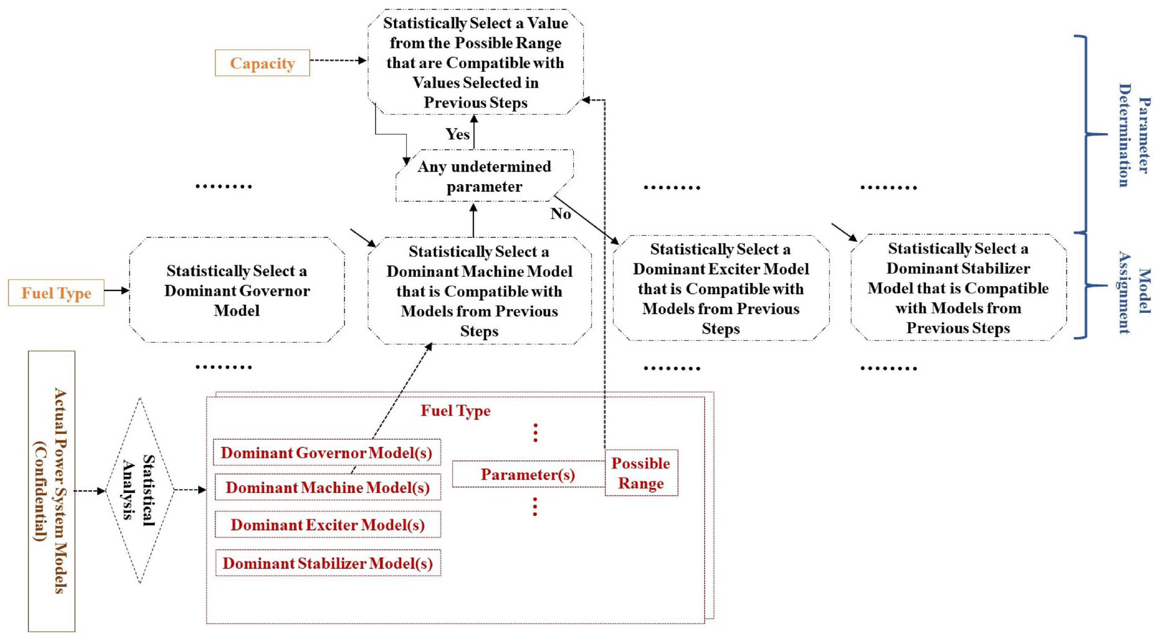

Fig. 1. Extension process to include generator dynamic models.

machine/governor/exciter/stabilizer models for each fuel type. We build such dynamic cases using publicly available data and statistics summarized from actual system cases [18]. Detailed statistical analysis on actual system cases is performed individually for each fuel type. Commonly-used dynamic models are identified and then assigned to synthetic generators. For each parameter of every commonly-used model, a value will be drawn from its typical distribution observed in actual system cases and then assigned to a synthetic generator. Statistical and physical relations among parameters are used to facilitate the parameter determination process. Several transient stability metrics are adopted for validating the created cases. Those generator dynamic models are then improved and validated by a two-stage model tuning procedure such that the created cases have satisfactory and realistic dynamic performances. This paper presents dynamics for a 2000-bus case on the region of the Electric Reliability Council of Texas (ERCOT) as an example. We perform dynamic simulations with selected $N-1$ contingency events to verify that synthetic network dynamic cases are able to reproduce satisfactory dynamic responses similar to those of actual system cases. In summary, contributions of this paper are threefold:

- Extension of large-scale synthetic network base cases with generator dynamics in consideration of multiple fuel types and various machine/governor/exciter/stabilizer model types;
- Tuning model parameters to obtain satisfactory and reasonable dynamic responses;
- Development of proper performance indices to validate the synthetic network dynamic cases.

The extension, tuning and validation steps together build synthetic network dynamic cases that are statistically and functionally similar to actual system cases.

Four more sections come as follows. In Section II, an algorithm is proposed to automatically complete the model assignment and parameter determination for adding dynamics to each synthetic generator. Transient stability validation metrics are discussed in Section III. A model tuning process is presented in Section IV. Section V provides simulation results using a 2000-bus test case for illustration, and Section VI presents concluding remarks and directions for future work.

II. Extension of Synthetic Network Base Cases With Generator Dynamics

In order to create a synthetic network cases that could reproduce similar dynamic responses as actual grids, generator dynamic model selection/assignment and parameter determination should generate synthetic network dynamic cases that match statistics summarized from actual system cases. In this section, an algorithm is developed to statistically choose appropriate dynamic models and parameters for each synthetic generator.

A. *Overview of the Proposed Statistical Extension Algorithm*

For simplicity, different fuel types or technologies are combined into five major categories: natural gas, coal, wind, nuclear and hydro. By doing so, the synthetic network creation process focuses on modeling generators that compose the majority of total installed generation capacity.

Fig. 1 generalizes the steps to determine generator dynamic models with their associated parameters. Generation capacity and fuel type of each synthetic generator are defined in the network building process. These two parameters and statistical analysis results obtained from actual system cases are bases to add dynamic models and set parameters for each synthetic

TABLE I
STATISTICS ON GAS UNITS' GOVERNOR TYPES IN THE EI CASE

Governor Type	GAST	GGOV1	GAST2A	GASTWD
Percentage (%)	50.15	33.41	15.47	0.97
Dominant		√	√	
Relative Percentage (%)		68.35	31.65	

TABLE II
STATISTICS ON GAS UNITS' MACHINE TYPES IN THE EI CASE

Machine Type	GENROU	Other
Percentage (%)	98.61	1.39
Dominant	√	
Relative Percentage (%)	100	

TABLE III
STATISTICS ON GAS UNITS' EXCITER TYPES IN THE EI CASE

Exciter Type	ESST4B	EXST1	EXPIC1	EXAC2	...
Percentage (%)	36.84	11.03	7.94	5.78	...
Dominant	√	√	√	√	...
Relative Percentage (%)	59.79	17.92	12.89	9.40	... ...

generator's machine, turbine-governor, exciter, and/or stabilizer. Given a synthetic generator, we first select a typical governor model according to its fuel type and statistical analysis results on governor model types for that fuel type. Model parameters are determined according to its capacity and statistical analysis results on parameters of the selected governor model types for its fuel type. Upon the completion of governor model selection and parameter determination, similar operations are carried out to sequentially determine the type and parameter values of machine/exciter/stabilizer models. The extension process is interested in those models and parameter values that appear much more frequently than others in actual system cases. In each model category (machine, governor, exciter and stabilizer) of every fuel category, we define one dynamic model as "dominant" if power plants adopting that dynamic model have a relative total capacity over 5%. By doing so, several dominant types are selected for each model category and each fuel category. Similarly, possible ranges for model parameters are used to set model parameter values for each synthetic generator.

In the remaining of this section, we will discuss how to select dominant model types and assign them to synthetic generators, and then describe how to determine corresponding model parameters. Here, we use gas-fueled power plants as an illustrative example.

B. Model Selection and Assignment

1) Governor: Since governors are strongly dependent on fuel types, we start model selection and assignment process with governor models. As shown in Table I, gas-fueled generation units in an Eastern Interconnect (EI) case [20] have four governor models, among which three of them have a combined percentage over 99%. Each of the GAST, GGOV1 and GAST2A models has a percentage over 5%. Those three models may be defined as dominant governor types for gas-fueled units and assigned to synthetic gas-fueled generators. The NERC reported that GAST is an obsolete model that should not be used in interconnection-wide dynamics cases [21]. Thus, the GAST is not considered for assignment to synthetic generators.

Those two dominant governor types - GGOV1 and GAST2A - are then assigned to gas units in the created synthetic network, with the same probabilities as their relative percentages. For instance, the percentage of gas-fueled generators with the GGOV1 governor model among all synthetic gas units is 68.35%.

2) Machine: Table II shows that the GENROU machine model is used for the majority of gas-fueled units in the EI case. Thus, the only dominant machine model is GENROU, which will be assigned to all gas-fired generators in the synthetic network.

3) Exciter: In the EI case, there are 38 exciters models adopted for natural gas power plants. However, except for ESST4B, EXST1, EXPIC1 and EXAC2, each of the remaining exciter models appears in less than 5% of gas-fueled plants (in terms of unit generation capacity). As shown in Table III, relative percentages of gas units with ESST4B, EXST1, EXPIC1 or EXAC2 are 59.79%, 17.92%, 12.89% and 9.4%, respectively.

4) Stabilizer: Since there is no stabilizer model used in the EI case, we assign the IEEEST model to all synthetic generators of each fuel type but wind in the synthetic network. The WT3P1 model is assigned to wind power plants in the synthetic network.

5) Additional Constraint: Some combinations of machine, governor, exciter and/or stabilizer models are not allowed. For instance, WT3G1 and WT3G2 are the dominant wind turbine machine models, while WT12T1 and WT3T1 are the dominant wind turbine governor models. However, WT12T1 is not compatible with WT3G1 or WT3G2. This is because WT3G1 and WT3G2 are machine models for type 3 wind generators, which are not compatible with WT12T1 - a governor model for type 1 and type 2 wind generators. Thus, only the WT3T1 is selected as the governor model for wind turbines in the synthetic network dynamic case. During the model assignment process, such incompatibility of one dominant model with another is essential to exclude some physically infeasible combinations of machine, governor, exciter and/or stabilizer models.

6) Model Selection and Assignment Summary: As such, similar analysis and model selection/assignment are repeated for each fuel type. Table IV summarizes the dynamic model candidates for synthetic generators by fuel type.

Here, we note that Table IV simply provides a set of dominant dynamic models obtained from the EI case. Other factors may be taken into consideration such that only a subset of those dominant models are used to build synthetic network dynamic cases. For instance, to build a case in PowerWorld, PSSE and PSLF formats, we only use generator dynamic models compatible with all three software packages.

TABLE IV
SUMMARY ON GENERATOR DYNAMIC MODEL CANDIDATES IN THE SYNTHETIC NETWORK

	Machine	Governor	Exciter	Stabilizer
Coal	GENROU GENSAL	IEEEG1 IEEEG0 IEEEG2	ESST1A, IEEET1 AC7B, ESST4B ESAC6A, ESAC1A EXAC1, ESDC1A EXST1	IEEEST
Gas	GENROU	GGOV1 GAST2A	ESST4B, EXPIC1 EXST1, EXAC2	IEEEST
Nuclear	GENROU	IEEEG1	ESST1A	IEEEST
Hydro	GENSAL	HYGOV HYGOV2	ESST1A, IEEET1 SCRX, EXST1 ESDC1A, ESDC2A	IEEEST
Wind	WT3G1 WT3G2	WT3T1	WT3E1	WT3P1

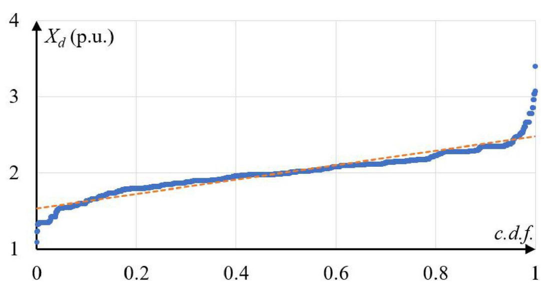

Fig. 2. The *c.d.f.* of X_d for the GENROU model of gas units in the EI case.

C. Model Parameter Determination

Upon the completion of dynamic model selection and assignment, corresponding parameters are determined individually for each model of every synthetic generator. Here, we use a synthetic gas unit equipped with the GENROU model as an example.

Statistics obtained from actual system cases present us a possible range of values for each model parameter. For any model m with a parameter c, values are statistically selected from c's possible range and assigned to synthetic generators equipped with model m. For instance, as shown in Fig. 2, the cumulative distribution function (*c.d.f.*) of parameter X_d can be approximated by a linear function[2] with R-squared value to be 0.95. Therefore, values can be drawn from the range [1.4, 2.6] and assigned to the GENROU model of synthetic gas-fueled units.

However, parameter assignment performed independently for each parameter may be oversimplified. As such, we also consider the statistical and physical relations among model parameters during the parameter determination process.

1) Correlation Analysis: Some parameters are depending on fuel type and/or generator capacity, and some other parameters have strong correlations. Given any model m with two strongly correlated parameters c_1 and c_2, one value for c_1 is statistically determined first and the remaining one c_2 is assigned with a value computed using c_1 value and their relation observed in actual system cases.

[2]We did not limit our statistical analysis to be linear. We adopt linear regression only for parameters with a relatively high correlation coefficient or R-squared value.

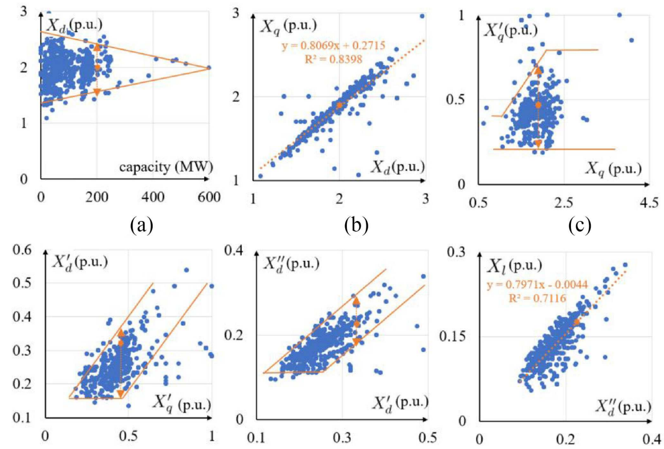

Fig. 3. Statistics on X_d, X_q, X_d', X_q', X_d'' and X_l in the GENROU model for gas units.

2) Additional Constraint: There are also some physical limitations on assigning values to model parameters. Those limitations are used to exclude impossible combination of model parameters. For example, in the GENROU model, $X_d'' < X_d'$ and $X_d' > X_l$ should be enforced as hard constraints.

3) Example: Statistical analysis among X_d, X_q, X_d', X_q', X_d'' and X_l indicates two well-fit linear regressions, as shown in Fig. 3(b) and (f) for X_d and X_q, and X_d'' and X_l, respectively. Fig. 3(c)–(e) also show the dependence of X_q' on X_q, X_d' on X_q', and X_d'' on X_d'. Till now, with two linear relations and three statistical dependences, only one value among X_d, X_q, X_d', X_q', X_d'' and X_l is needed to determine all their values. Here, the dependence of X_d on generator capacity for gas units [as displayed in Fig. 3(a)] is the starting point to determine the values of X_d, X_q, X_d', X_q', X_d'' and X_l.

In this way, a set of machine/governor/exciter/stabilizer models and their parameters can be statistically assigned to each synthetic generator in every fuel type. This section uses gas units for illustration. However, the proposed extension algorithm is general enough for generators of other fuel types.

The proposed statistical extension process could generalize to other system dynamics. Here, we use load dynamics as an example. This first step is to perform statistical analysis on load dynamic models in available actual system cases. Model selection and parameter determination process similar to that in this paper is then applied to assign proper load model types and parameters to each load. One of our current research projects [22] uses public data to determine residential, commercial, and industrial ratios of each synthetic load bus. Those information can also assist in assigning load models since different load sectors may have distinct load dynamic model compositions. Constant impedance loads are still quite typical for dynamic studies and thus adopted in this paper. The remaining of this paper will focus on generator dynamics, and extending the process to more complex load models is a subject for future work.

III. Transient Stability Validation Metrics

The previous section develops a statistical approach to extend synthetic network base cases with generator dynamics. Such cases are statistically validated, but should also be functionally validated. Therefore, this section discusses several transient stability validation metrics adopted in our paper.

A. Transient Stability Definition and Classification

Report [23] defines and classifies power system stability into three primary categories: rotor angle stability, frequency stability and voltage stability.

1) Rotor angle stability refers to the ability of synchronous machines in an interconnected power system to remain in synchronism after being subjected to a disturbance. Instability occurs when machine rotor angles exhibit poor-damped or growing oscillations. The Southwest Power Pool computes the *Successive Positive Peak Ratio* (SPPR) using the peak rotor angle $\theta_{\max,k}$ of the k_{th} positive peak and the minimum rotor angle, as a direct rotor angle stability measure:

$$SPPR_1 = \frac{\theta_{\max,2} - \theta_{\min}}{\theta_{\max,1} - \theta_{\min}} \leq 0.950 \tag{1}$$

$$SPPR_5 = \frac{\theta_{\max,6} - \theta_{\min}}{\theta_{\max,1} - \theta_{\min}} \leq 0.774 \tag{2}$$

Damping ratio - an indirect rotor angle stability measure - determined by modal analysis methods is also used to quantify machine rotor angle stability. For example, angular oscillations are defined by Southwest Power Pool as well-damped if its damping ratio is larger than 0.8163% [24].

2) Frequency stability is defined as the ability of an interconnected power system to maintain steady frequency following a contingency event that results in a significant imbalance between generation and load. Severe frequency deviation may result in load shedding, generator tripping, equipment damage or even system collapse. The minimum/maximum rate of change of frequency (RoCoF) and the minimum/maximum frequency during the first several seconds after disturbances are commonly used to assess system frequency stability. For instance, the Eastern Interconnection and the Western Electricity Coordinating Council set 59.7 Hz and 59.5 Hz, respectively, as their low frequency limit[3] [25]. The maximum RoCoF magnitude of 0.5 Hz/s is defined in the Grid Code in Ireland.

3) Voltage stability refers to the ability of a power system to maintain steady voltages at all buses. Voltage instability implies an uncontrolled decrease in voltage, which may lead to voltage collapse and even system blackout. Take the ERCOT as an example. Except from the time of fault inception to the time the fault is cleared, voltage drop is required be above 75% and 70% of pre-disturbance value for load and non-load buses, respectively.

[3]The highest setpoint in the interconnection for regionally approved under frequency load shedding systems.

TABLE V
Impacts of Increases in Gains on Control Responses and Recommended Performance Indices

Indices	Rise Time (s)	Overshoot (%)	Settling Time (s)	Steady-State Error (%)
Proportional K_p	decrease	increase	trivial	decrease
Integral K_i	decrease	increase	increase	zero
Derivative K_d	trivial	decrease	decrease	trivial
Governor	1 - 25	0 - 40	2 - 100	
Exciter	0.025 - 2.5	0 - 40	0.2 - 10	0 - 1

B. Transient Stability Validation Metrics

This paper considers N-1 contingencies - both large (e.g., generator outages) and small (e.g., three-phase bus fault) disturbances - to determine transient stability metrics, which includes:

- M_r - the minimum generator rotor angle damping ratio;
- M_f - the minimum/maximum bus frequency values;
- M_v - the minimum ratio of bus minimum voltage to pre-contingency voltage level.

In addition to aforementioned transient stability requirements, each power grid has characteristic dynamic performances. Available reports provide dynamic simulation results on several interconnected power grids. For example, report [26] presents frequency responses of three U.S. Interconnections. Those existing simulation results can also be used as references to verify whether synthetic dynamic models are able to reproduce similar responses as actual system cases.

This section adopts several transient stability metrics to quantify frequency, voltage and angular stability. Those metrics are used to describe whether a synthetic network case has stable, well-damped dynamic responses. We refer to industrial and academic documents for defining each metric and determining its acceptable values. With different tuning and validation targets, the proposed construction methodology can consider different metric formulations and other stability indices.

IV. Model Tuning Procedure

In order to achieve desirable dynamic performances and satisfactory transient stability metrics, a tuning procedure is proposed in this section to properly modify the model parameters obtained in Section II.

A. Governors and Exciters of Fossil Fuel Generators

Governors and exciters often use proportional-integral-derivative (PID) controllers. As shown in Table V, different values of each gain have varying impacts on four key characteristics of control responses - rise time, overshoot, settling time and steady-state errors. Reports [27] and [28] established typical ranges of values of performance indices for speed-governing and excitation control systems, respectively, which are also presented in Table V.

The Ziegler-Nichols (ZN) tuning method is a heuristic method of tuning a PID controller [29]. Several other tuning methods derived from the ZN method were presented in [30]. Those tuning methods set K_p, K_i and K_d, using the ultimate gain K_u

TABLE VI
SUMMARY OF TUNING RULES

Methods \ Gain	Proportional K_p	Integral K_i	Derivative K_d
P	$0.5K_u$	0	0
PI	$0.45K_u$	$1.2K_p/T_u$	0
PD	$0.8K_u$	0	$0.125K_pT_u$
ZN	$0.6K_u$	$2K_p/T_u$	$0.125K_pT_u$
Pessen Integral Rule	$0.7K_u$	$2.5K_p/T_u$	$0.15K_pT_u$
Some Overshoot	$0.33K_u$	$2K_p/T_u$	$0.33K_pT_u$
No Overshoot	$0.2K_u$	$2K_p/T_u$	$0.33K_pT_u$

TABLE VII
HYDROELECTRIC SPEED-GOVERNING SYSTEM SETTING [31], [32]

Parameters	Value
K_p	$0.8T_M/T_W$
K_i	$0.24T_M/T_W^2$
K_d	$0.27T_M$
Temporary Droop R_T	$[2.3 - 0.15(T_W - 1)]T_W/T_M$
T_R	$[5 - 0.5(T_W - 1)]T_W$

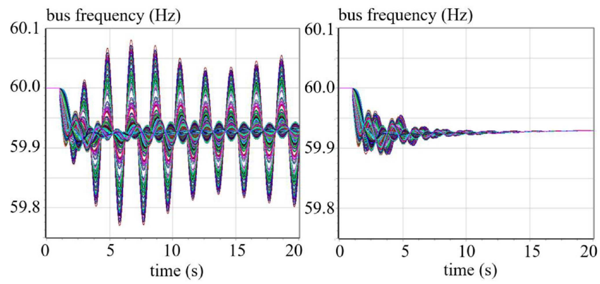

Fig. 4. Frequency responses without (left) and with (right) tuning stabilizers.

and the associated oscillation period T_u[4]. Table VI summarizes tuning rules of different methods. Those rules simply provide initial tuned parameters, on which further adjustments are based to obtain a set of coefficients so as to have satisfactory control responses. The initial dynamic case may have some unstable responses caused by some generators, of which exciter or governor gains are set too high or too low. We adjust exciter and/or governor gains to stabilize this generator in both its single machine infinite bus(SMIB) model and the full case. Such adjustments are done by first applying methods in Table VI as initial value guess and further changes according to Table V. For instance, given a control system with significant overshoot issue, the last two tuning rules in Table VI may be used and further adjustments can be done by decreasing K_p, K_i or increasing K_d, according to Table V.

B. Hydroelectric Speed-Governing System

Hydro turbines have a peculiar response due to water inertia: when gate position is suddenly changed, the flow does not change immediately due to water inertia, but the pressure across the turbine is reduced, causing the power to reduce. This process is determined by a time constant T_W [1]. For stable control performances, a large temporary droop R_T with an appropriate resetting time T_R is required. As such, we consider tuning rules designed for hydroelectric speed-governing systems [31], [32]. Specifically, as shown in Table VII, T_W and $T_M = 2H$ (H is the machine inertia) are used to set parameters of PID coefficients, temporary droop R_T and its resetting time T_R.

[4]With $K_i = K_d = 0$, K_p is increased from zero until it reaches the ultimate gain K_u, at which the output of the control system has stable and consistent oscillation with an oscillatory period T_u.

TABLE VIII
SUMMARY ON BUILDING SYNTHETIC NETWORK DYNAMIC CASES

Step	Description
	Statistical Extension Process
Step 1	Section II: Apply statistics obtained from actual system cases to determine dynamic models and parameters for each synthetic generator;
	Model Tuning with a Full Model
Step 2.1	Set proper generation/load levels so that the synthetic case have a feasible ac power flow solution with all units on;
Step 2.2	Section IV.B: tune hydroelectric governors;
Step 2.3	Perform dynamic simulations with each of selected contingencies;
Step 2.4	Identify synthetic generators $g \in \mathcal{G}$ causing: a) non-flat start; b) poor-damped oscillation modes; c) unstable system responses;
Step 2.5	Section IV.A&C: tune governor, exciter and/or stabilizer models for each synthetic generator $g \in \mathcal{G}$ until the case has a flat-start and stable dynamic responses with well-damped oscillations;
	Model Tuning for a Specific Case
Step 3.1	Dispatch and/or decommit units in a full model to build a desired synthetic case with a feasible ac power flow solution at a specified load level;
Step 3.2	Repeat Steps 2.3-2.5.

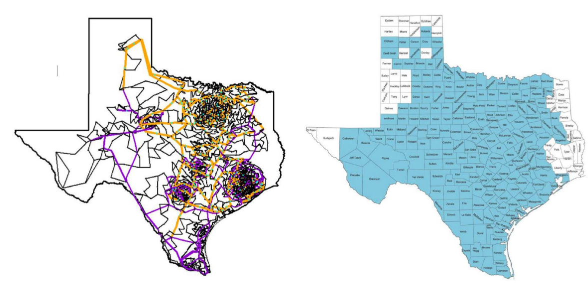

Fig. 5. Geographic footprint and one-line diagram of the 2000-bus model.

TABLE IX
TRANSIENT STABILITY METRIC REQUIREMENTS

Metric	M_r	M_f	M_v
Requirement	3%	$[59.5, 60.5]$ Hz	75%

C. Stabilizer

Without properly tuned stabilizers, the synthetic network dynamic models may have poor-damped oscillation under some

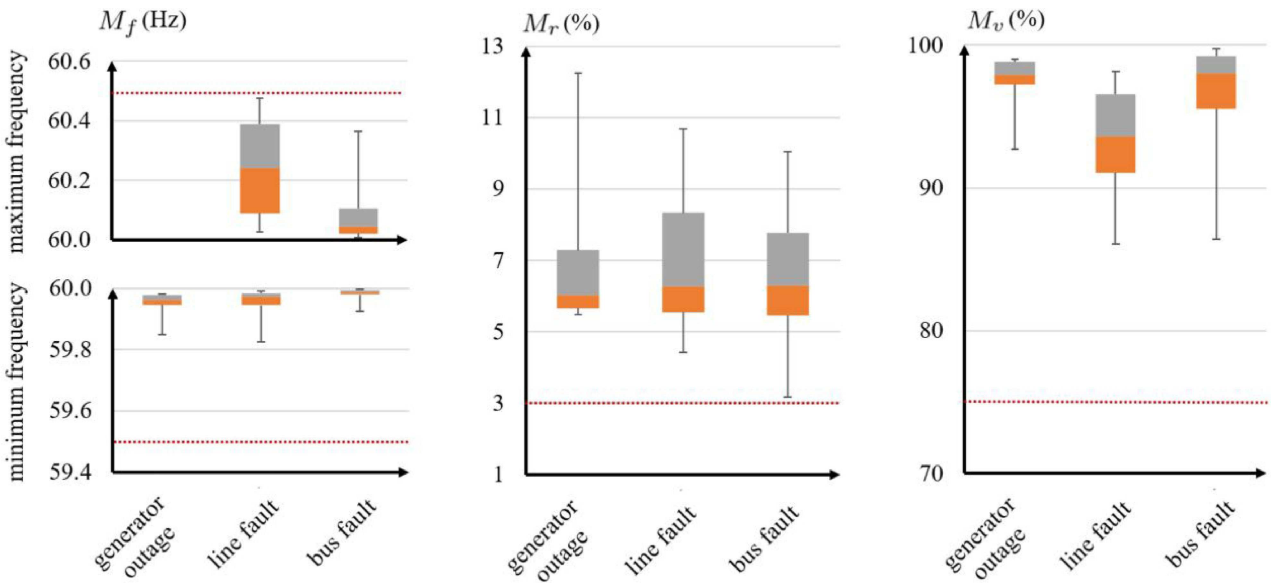

Fig. 6. Computed transient stability metrics using the 2000-bus case after being subjected to N-1 contingency events.

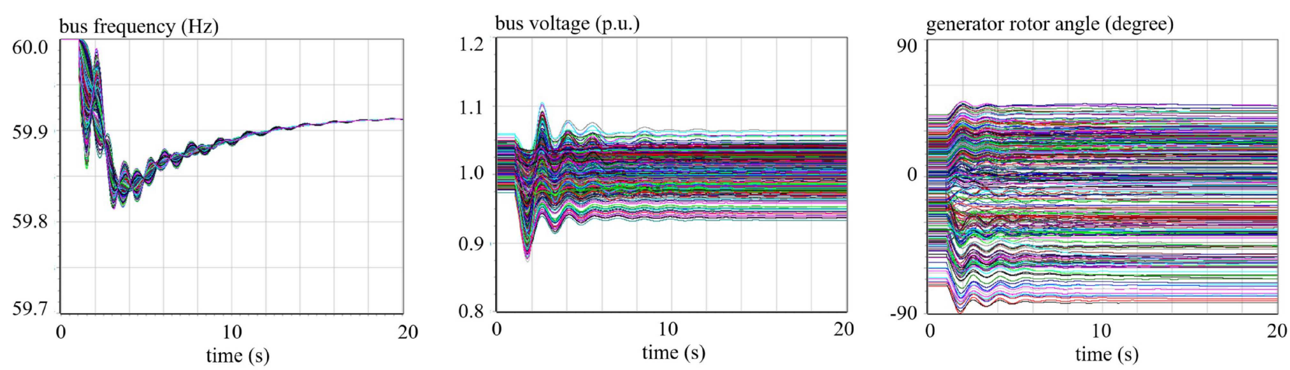

Fig. 7. Simulation results using the 2000-bus case after a N-2 contingency event—loss of 2425 MW generation.

contingencies. The first step is to locate the oscillation source. A SMIB model is built to tune the stabilizer of each generator that causes oscillations. Then, we run simulations using the full case to carry out additional tuning operations if oscillations are not still well damped. Tuning is very case-dependent. Any theoretic method may or may not directly give a good solution. If not, we use those solutions as initial guess and continue to tune parameters with some manual adjustments. In this paper, we perform N-1 contingency simulations and apply a practical stabilizer tuning method [1], [2], [33]–[36] to appropriately adjust stabilizer parameters for eliminating all observed poor-damped oscillations. For illustrations, Fig. 4 presents dynamic simulation results without and with tuning stabilizers.[5]

D. From A Full Model to Synthetic Network Dynamic Cases

Table VIII briefly overviews the overall procedure to build a synthetic network dynamic case. Given a synthetic network base case, the statistical extension process determines appropriate generator dynamic models with their associated parameters. A two-stage process is adopted to tune speed-governing and excitation control systems, as well as stabilizer models. The first stage uses a full model with all units on, while the second stage tunes models for one specific case built from the tuned full system model. Therefore, the proposed method outputs a statistically and functionally validated and well-tuned synthetic network dynamic case.

In this section, we focus on model tuning and parameter verification methods for uses in this paper, but the construction of synthetic network dynamic cases is general enough to consider other methods. The goal of statistical and functional validation is to have a system model that can reasonably reproduce similar dynamic responses as actual system cases. Any modeling activity necessitates certain assumptions and compromises, which are determined by a thorough understanding of the process how the model is built and the purpose for which the model is to be used. As such, the eventual validity of a model requires both engineering judgments and those commonly-used criteria [37].

[5]Simulation results are obtained by applying a generation-loss contingency on the full model developed in Section V.

The overall tuning and validation process considers both aforementioned methods and reasonable manual adjustments.

V. Illustrative Example

In this paper, we apply the proposed method to model dynamics for a synthetic network model - ACTIVSg2000 - on the ERCOT region, as shown in Fig. 5. The 2000-bus model has four voltage levels (500/230/161/115 kV) and a total generation capacity of nearly 100 GW, a portion of which is committed to supply a load of 67 GW and 19 GVar. There are 544 generators and 2345 transmission lines modeled in the ACTIVSg2000. All synthetic network cases are available for download at [19].

Table IX presents transient stability metric requirements specified in reports [25], [38]. To determine whether this case has satisfactory transient stability metrics, three types of N-1 contingency events are selected and applied to disturb this case:

- generator outage;
- three-phase transmission line fault, followed by line tripping in 0.01 s;
- three-phase bus fault (cleared in 0.01 s).

First, we run simulation without any contingency event for a time period over 100 s to verify that this case has a flat start. Then, for each $N-1$ contingency event, we perform full dynamic simulations using the ACTIVSg2000 case, and compute transient stability metrics. Fig. 6 summarizes the computed transient stability metrics of all contingency events. In the boxplot, the upper and the lower bars correspond to the maximum and the minimum values for each metric, and two filled boxes cover each metric ranging from 90% to median, and median to 10%, respectively. Simulation results verify that the created synthetic network dynamic case has satisfactory transient stability performances after being subjected to the given contingency events. As an example, simulated generator rotor angles, bus frequencies and voltages for a $N-2$ contingency event - loss of 2425-MW generation - are displayed in Fig. 7. We observe that this case has stable dynamic responses with well-damped oscillations and acceptable voltage/frequency levels.

Therefore, simulation results demonstrate that the proposed methodology can generate publicly available synthetic network dynamic cases that are able to produce satisfactory dynamic responses.

VI. Conclusion

In this paper, we use publicly available data and statistics summarized from an actual system case to produce a large-scale synthetic network dynamic case. A detailed statistical analysis performed on selected machine / governor / exciter / stabilizer models is presented to illustrate the statistical extension process to include generator dynamic models. Three transient stability metrics are used to validate the synthetic network dynamic cases. A two-stage model tuning process is introduced to adjust model parameters such that the created dynamic cases satisfy transient stability metric requirements.

The application and direct benefit of the concept in this paper are twofold. On the one hand, this paper discusses in detail about the construction framework, consisting of modeling, tuning and validation steps, for building synthetic network cases with dynamics. Our construction framework is general enough for direct applications by experts in academic and industrial areas with their own modeling targets. Additional tuning and validation goals can also be implemented. On the other hand, the proposed construction framework generates synthetic network dynamic cases that are statistically and functionally similar to the actual grid, and contain no confidential data. Experts in both academic and industrial areas are free to download those cases that reproduce realistic, insightful dynamic performances. Although this section uses the ERCOT case to illustrate the synthetic network creation process, the proposed methodology is general enough for applications to other footprints of interest. For instance, experts from a different region may use the statistics obtained from actual system models for that region or those similar ones to build synthetic network cases. They could freely share those cases with other researchers that can provide insights into current system conditions and offer useful operation/investment advices, based on simulation results using their own synthetic cases.

The large-scale synthetic networks with generator dynamics can be used for power system planning, generator siting and some other applications related to power system transient stability. The proposed methodology is able to consider other tuning methods and additional transient stability metrics. Comparison among simulation results by different software is of interest, as well [39]. We will report these studies in future work.

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