Application of Large-Scale Synthetic Power System Models for Energy Economic Studies

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Abstract

Due to information confidentiality issues, there is limited access to actual power system models that represent features of actual power grids for teaching, training, and research purposes. The authors' previous work describes the process of creating synthetic transmission networks, with statistics similar to those of actual power grids. Thus, this paper outlines a systematic methodology to augment the synthetic network base case for energy economic studies. The key step is to determine generator cost models by fuel type and capacity. Based on statistics summarized from the actual grids, two approaches are proposed to assign coefficients to generator cost models. To illustrate the proposed creation procedure, we describe the construction of a synthetic model for Electric Reliability Council of Texas footprint. Simulation results are presented to verify that the created test system is able to represent the behavior of actual power systems.

1. Introduction

Regional Transmission Organizations (RTOs) and Independent System Operators (ISOs) are responsible for organizing and operating day-ahead and/or real-time energy markets and ancillary services markets [1], [2]. The first ISO established in United States was Electric Reliability Council of Texas (ERCOT), which oversees the regional wholesale electricity market in Texas as an impartial, third-party organization [3]. The European Union (EU) launched several market coupling projects to achieve a single EU market for electricity. For both RTOs and ISOs, power system models serve as the basis for a wide range of applications, including resource planning, production costing issues, environmental assessments, reliability and policy analysis. However, legitimate security concerns severely limit the disclosure of information about actual system models. Electricity market participants' information, such as offer data from generators and bid data from loads, are confidential as well. The lack of full public access to actual power system and energy market models limits the global power system community's ability to engage in research related to electricity markets and hinders commercial innovations in this area, too.

Several IEEE test cases were established in 1962 to represent a portion of the American Electric Power System (in the Midwestern US) [4]. An 8-zone test system proposed in [5] is based on structural attributes and data from the ISO - New England. Reference [6] developed an approximate model of the European interconnected system using actual transmission networks to study the effects of cross-border trades. Until recently, there was limited work focusing on the creation of synthetic large-scale power system models using publicly available data to mimic the full complexity of today's electricity grids for energy economic studies. Our previous works [7], [8], [9] presented a methodology to create entirely fictitious synthetic power system networks that capture structural and functional characteristics of actual power grids [1]. To enable greater innovation on electricity markets, this paper aims to augment the synthetic power system networks with generator cost data, and thus provides realistic test cases for energy economic studies without revealing any sensitive information.

We first briefly review the methods presented by [9] on creating the synthetic network base case. To augment the synthetic network base case for energy economic studies, two approaches are proposed to build generator production cost models. Except for the statistics observed in Eastern Interconnect (EI) case, all other data used to generate synthetic power system models are available to the public. For illustration purposes, a synthetic power system network on the ERCOT footprint is built. Specifically, we perform optimal power flow (OPF) simulations to compare the locational marginal costs produced using the synthetic model with those from the actual ERCOT market. To further illustrate the capabilities and applicabilities of the augmented synthetic network model for energy economic studies, we apply the augmented model to formulate a deterministic day-ahead unit commitment (DAUC) and look-ahead economic dispatch (LAED)

[1] The synthetic network models are available on the website: http://icseg.iti.illinois.edu/synthetic-power-cases

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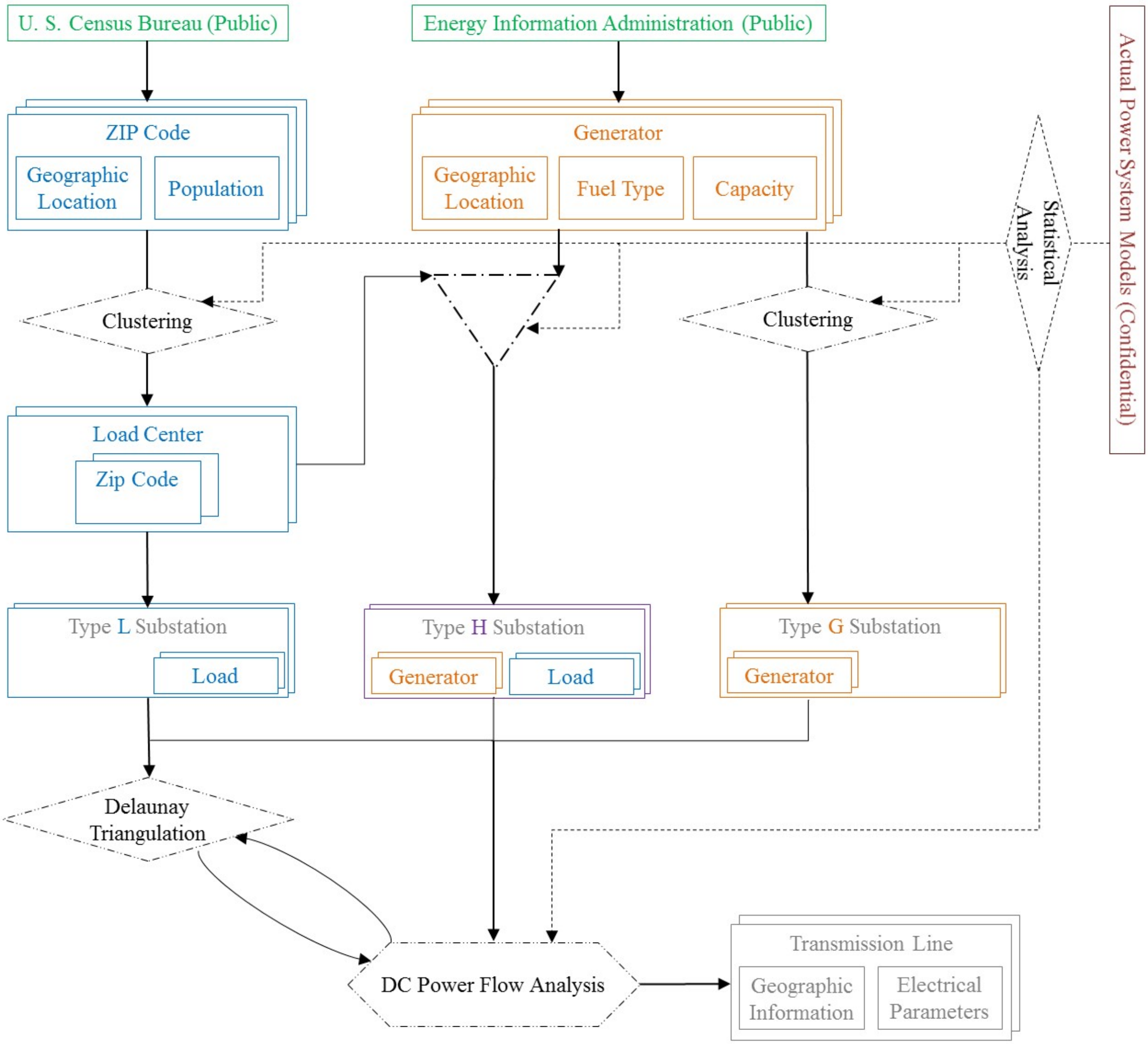

Figure 1: Geographic substation placement and transmission line topology building procedure

framework, which is used to study the impacts of various reserve requirements on market clearing results.

There are four more sections in this paper. In Section II, we describe the method for geographic substation placement and transmission line topology design. Generator cost assignment approaches are discussed in Section III. Section IV presents illustrative simulation results and, in Section V, we conclude our work and provide directions for future work.

2. Reviews of the Creation of Synthetic Transmission Networks

In this section, we briefly introduce the creation procedure of a synthetic transmission network. Works [7], [8], [9] provide readers more details on geographic substation placement, synthetic transmission line topology design and line parameter determination. As summarized in Fig.1, the network construction process is based on the statistics summarized from EI case, geographic relations, location-dependent load levels and generation capacities.

First, public data [10], [11] are used to site and size power plants and loads. A modified version of the hierarchical clustering algorithm is applied to group load and generation buses into electric substations. Three types of substations are considered in the created synthetic network: Type L purely containing load, Type G purely containing generators and Type H containing both. Each individual substation in the synthetic network is assumed to contain multiple buses, each of which is connected to at most either a load or a generator.

Then, about 10-20% of substations are assigned to a higher system voltage with probabilities proportional to load and large Type H/G substations are more likely to be at a higher voltage level. Within each substation, loads are usually connected to the lowest voltage level, and generators are often connected to the highest voltage level through a generator step up transformer. In addition, transformers are added in each substation to connect multiple nominal voltage levels.

Furthermore, in order to connect substations with synthetic transmission lines at multiple nominal voltage levels, an automated line placement process is developed, which considers some characteristic network properties, such as networks' graph topology, geometry, and power flow solution. Similar to actual power grids, the majority of transmission lines in the synthetic cases are overhead lines, while some underground transmission lines are used in urban areas where overhead lines are infeasible or more costly. Line parameters are determined according to available datasheets and reference manuals [12]-[17], line lengths estimated from the geographic substation coordinates and their assigned voltage levels, for both overhead lines and underground cables.

Last, an iterative, penalty-based algorithm is used to add lines for all voltage level networks at the same time until there are approximately $1.22N_s'$ lines at each nominal voltage level with N_s' buses. Since Delaunay triangulation (see [18], [19]) matches some basic properties observed in actual power grids, Delaunay triangulation is integrated into the penalty-based iterative line placement algorithm by setting a quota of lines which may be added from each category: minimum spanning tree, Delaunay, Delaunay 2 neighbor, and so forth. In addition, the dc power flow solution is adopted to aid the iterative line placement algorithm. At each iteration, we update the system bus susceptance matrix and compute the dc power flow solutions. Negative penalties are given to unused Delaunay segments with the largest expected power flows. Eventually, the penalty-based algorithm adds approximately $1.22N_s$ lines in total for a synthetic network with N_s substations.

3. Extension of Synthetic Transmission Networks for OPF Studies

Given a synthetic network base case, the key step to perform OPF studies is to add energy economic data. In this section, we propose two approaches based on statistics summarized from actual grids to determine generator cost models by fuel type and capacity.

For simplicity, more than 15 different fuel types/technologies in the actual ERCOT generation mix are combined into five major categories: Natural Gas, Coal, Wind, Nuclear and Hydro. By doing so, the synthetic network creation process avoids relatively complicated modeling for a very small portion of total installed generation capacity. As shown in Fig.2, the simplified generation mix in the synthetic network still represents similar system-wide generation mix features of the actual ERCOT system.

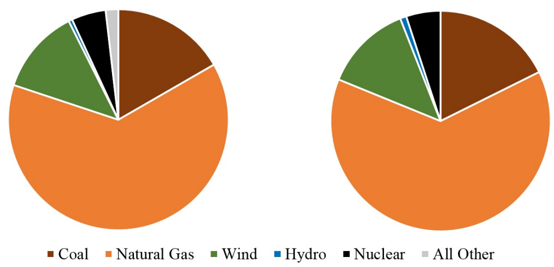

Figure 2: Comparison of generation capacities of the actual ERCOT system (left) and the synthetic network (right) by fuel type

3.1. Cost Assignment Process

The core of economically efficient and reliable power market operation is an OPF problem, which was first formulated in the 1960's [20], [21]. An ACOPF algorithm involves the minimization of an objective function subject to a number of equality and inequality con-

Table 1: Cost Model Coefficients by Fuel Type and Capacity

			Approach A		Approach B		
Fuel Type	Capacity(MW)	a_0 (\$/h)	a_1(\$/MWh)	a_2(\$/MWh^2)	c_f(\$/MBtu)	b_1(MBtu/MWh)	b_2(MBtu/MWh^2)
Coal	0 - 75	0 - 238	19	0.001	2.16	9.43 - 18.53	0
Coal	75 - 150	238 - 745					
Coal	150 - 350	745 - 1213					
Coal	> 350	1213 - 3043					
Natural Gas	0 - 400	0 - 600	23.13 - 57.03	0.002-0.008	2.59	6.5 - 17.5	0
Natural Gas	> 400	600 - 3859					
Nuclear	$---$	1000 - 1500	5 - 11	0.00015-0.00023	0.85	10.46	0
Hydro/Wind	$---$	0	0	0	0	0	0

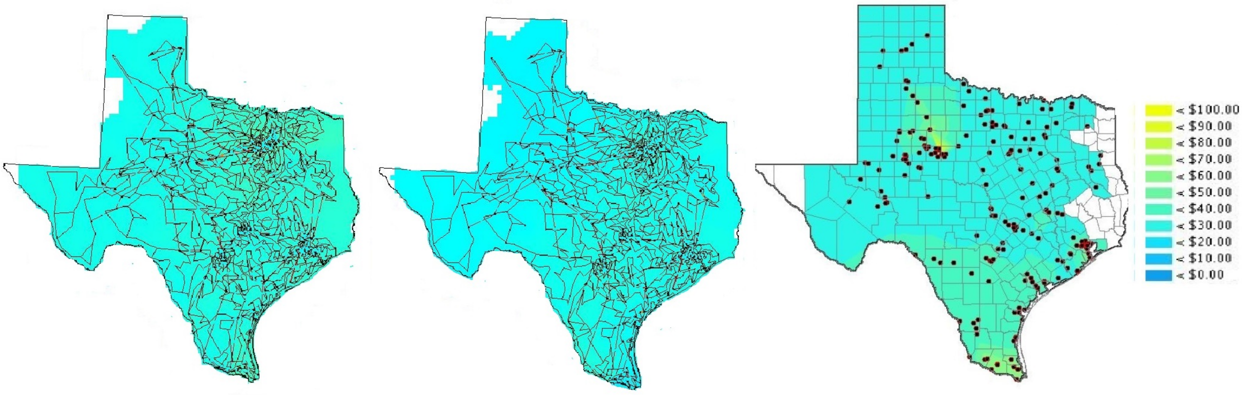

Figure 3: Comparison of marginal generation costs of synthetic networks (Approach A: left; Approach B: middle) and the actual ERCOT system (right)

straints:

$$\begin{aligned} \min \quad & C(\mathbf{x}, \mathbf{u}) \\ s.t. \quad & \mathbf{g}(\mathbf{x}, \mathbf{u}) = \mathbf{0} \\ & \mathbf{h}(\mathbf{x}, \mathbf{u}) \leq \mathbf{0} \end{aligned} \tag{1}$$

where $\mathbf{x}$ is a vector of dependent variables (such as bus voltage magnitudes and angles), $\mathbf{u}$ is a vector of control variables (such as real and reactive power outputs of generators), $C(\cdot, \cdot)$ is the scalar objective function (for instance, the system production costs), $\mathbf{g}(\cdot, \cdot)$ is the set of equality constraints (e.g., the power flow equations), and $\mathbf{h}(\cdot, \cdot)$ is the set of inequality constraints (e.g., upper and lower bounds of each generator's output).

We can use the transmission network model created in the previous section to formulate corresponding OPF constraints $\mathbf{g}(\cdot, \cdot)$ and $\mathbf{h}(\cdot, \cdot)$. The essential component to perform energy economic studies, such as OPF problems, is to determine generator cost models and their associated coefficients in $C(\cdot, \cdot)$. In this section, we adopt a quadratic cost model, and propose two approaches to assign no-load and production costs to each generator:

$$costs = \begin{cases} a_0 + a_1 P + a_2 P^2 \rightarrow \text{Approach A} \\ a_0 + c_f(b_1 P + b_2 P^2) \rightarrow \text{Approach B} \end{cases}$$

where $\{a_i : i = 0, 1, 2\}$, $\{b_i : i = 1, 2\}$ denote the fuel-dependent cost model coefficients, c_f refers to fuel cost and P is generator output.

The no-load cost (a_0) for each generator is estimated by its fuel type and capacity. This paper adopts no-load cost data summarized in [5]. No-load costs for wind and hydro power plants are set to zero [22]. Similar to the determination of no-load costs, the first approach (A) adopts a quadratic cost model with two coefficients summarized in [5]. For comparison, we compute the average heat rate b_1 using data from [11] and [23], with b_2 set to zero for each generator in ERCOT. The fuel costs are also obtained from EIA [11]. Table 1 summarizes the cost model coefficients derived using the two different approaches.

3.2. Numerical Example

Here we perform ACOPF studies using the created synthetic network at the load level of 49,775 MW, which is close to the load in ERCOT region around 14:00, on June 6, 2016. Assuming hydro and wind plants are not dispatchable, we randomly set hydro units operating at 50% - 100% of their capacities and wind resources run at 0% - 80% of their capacities. Since not all units are committed to supply demand in a actual power system, one preliminary ACOPF was run to determine the marginal cost of each generator. We decommit generators in the decreasing order of their marginal costs until the system reserves are around 16% level.

The contour plots of the marginal generation costs of the synthetic network and the actual case are shown in Fig.3 [24], [25]. The results verify the capability

Table 3: Typical Generator Ramp Rates and Start-up/Shut-down Costs

Fuel Type	ramp rate (% of the rated capacity per min)	start-up costs ($/MW/start)	shut-down costs ($/MW/shutdown)	starting-up time (hour)	shutting-down time (hour)	minimum on time (hour)	minimum off time (hour)
Coal	0.6-8	100-250	10-25	4-9	2-9	0-12	0-12
Natural Gas	0.8-30	20-150	2-15	2-4	1-4	0-2	0-1
Nuclear	0-5	1000	1000	24	24	days	days
Hydro	15-25	0-5	0-0.5	0-1	0-1	0-1	0-1
Wind	Non-dispatchable						

Table 2: Statistics of the ACOPF Results

	Approach A	Approach B	Real Case
Average($/MWh)	28.90	23.87	27.41
S.Deviation ($/MWh)	3.32	2.69	8.85

of the created synthetic network using both cost assignment approaches to reproduce the realistic locational marginal cost pattern over the ERCOT region. For example, all three contour plots indicate relatively low marginal costs in the western area. This is due to a lot of non-thermal, cheap generation units - hydro and wind - in that area. Similar to those in the actual case, one high-marginal-cost area (southern corner) is also captured in the synthetic networks. We also notice some differences between the marginal costs of the synthetic network and the actual case in the northern region, particularly for Approach A, due to denser population and higher electricity demands. Furthermore, as shown in Table 2, compared to results using Approach B, those using Approach A are closer to the actual case results in the sense of statistics. This is reasonable because, for Approach B, assuming a zero value for each quadratic term over-simplifies the generator cost functions.

4. Illustrative Application of the Synthetic Network for Energy Economic Studies

In this section, we further extend our synthetic network to construct a comprehensive DAUC and LAED simulation framework, which is applied to investigate the impacts of reserve levels on total system production costs, considering the uncertainty nature of renewable energy outputs and demand. A system-wide reserve requirement with no zonal reserve constraints is considered. Readers are encouraged to refer to [26], [27], [28] for further information on DAUC and LAED formulation. We only use cost models determined using Approach A in this section.

4.1. Generator Operational Constraints

The power plant outputs are usually adjusted smoothly, restricted by their ramp rate limits. The start-up/shut-down and minimum on/off times are also enforced to guarantee secure operation of generation units. Furthermore, the start-up and shut-down operations of power plants result in additional costs, which need to be taken into account for optimal resource planning. Hence, the unit operational constraints, summarized in Table 3, are used to achieve more a realistic operation of the power system [29], [30], [31], [32]. Hydro units are assumed to be dispatchable in the DAUC and LAED of this section.

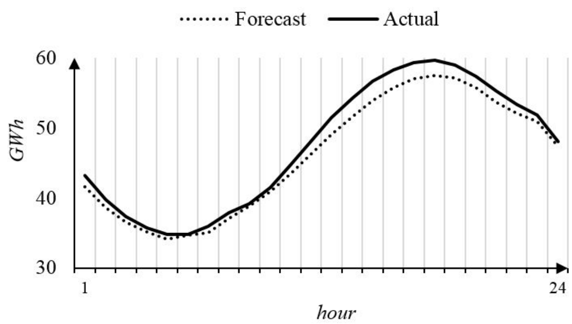

Figure 4: DA forecast and actual load data in the ERCOT region [33]

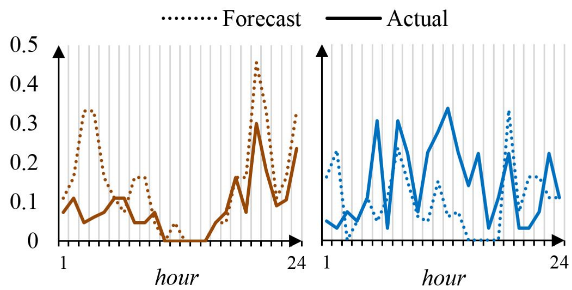

Figure 5: Day-ahead forecast and actual wind farm output realization (% out of its capacity) at two sites in the ERCOT region [34]

4.2. Simulation Setup

The generation outputs scheduled in DA market are used to supply demand in both DA and RT markets. A portion of generation capacities is reserved in DA market and deployed in RT market to compensate the energy output/consumption deviation of uncertain sources from their forecast values. One source of uncertainty in DAUC and LAED comes from the demand side. As shown in Fig.4 [33], the actual system load realizations deviate from the forecast values, particularly around 18:00, which may result in deployment of reserve services and wind output curtailment. In this work, the load data in the synthetic network is proportionally scaled to achieve the same daily load pattern as shown in Fig.4 with a peak load of 59,335 MW. Similarly, renewable energy also brings uncertainty into DAUC and LAED. Fig.5 shows that the day-ahead forecast results may over- or under-estimate the wind farm outputs. Therefore, location-varying wind farm output profiles over the ERCOT region [34] are represented in the simulation framework. We perform simulations over a day, using an internal of one hour.

4.3. Simulation Results

We consider a fixed down-spinning reserve of 3% and a fixed non-spinning reserve of 5%. Up-spinning reserve level varies from 4% to 15% and simulation results are summarized in Fig.6. The total system

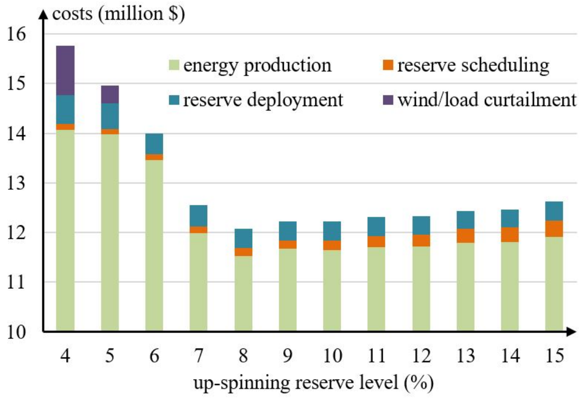

Figure 6: Simulation results with varying up-spinning reserve levels

costs are decomposed into four categories: energy production, reserve scheduling, reserve deployment and wind/load curtailment penalty. As the up-spinning reserve level increases from 4%, the total system costs decline because there is more reserved capacity available to be deployed for avoiding massive wind/load curtailment and starting up of expensive power plants. However, when the up-spinning reserve level reaches 8%, stricter reserve requirements cannot further reduce the total system costs. This is because additional reserve costs more and requires unnecessary starting-up of expensive power plants. Thus, in realistic system planning and operations, an appropriate up-spinning reserve level requirement is needed to achieve a relatively low total system cost. The simulation results illustrate one possible application of the created synthetic network for energy economic studies. Another potential application of synthetic large-scale power system models in the energy economics area is to help develop complementing multi-system operations and one robust, non-discriminatory wholesale electricity market [35].

5. Conclusion and Future Work

This paper presented the development and testing of a synthetic power system model for energy economic studies. We reviewed and summarized previous work for the process of building a synthetic network and, in this paper, augmented that network with cost data for OPF and DAUC/LAED studies. For illustration purposes, some simulation results were shown to demonstrate the usefulness of our work and the capability of the created synthetic network for planning, investment decisions, regulatory filing, and policy analysis applications in the energy economics area. Simulation results using the synthetic case matches similar economic properties of the actual ERCOT grid. Although this paper uses the ERCOT case to illustrate the synthetic network creation process, the proposed methodology is general enough for applications to other footprints of interest, starting with a synthetic network base case of that footprint, and then updating the input data such as cost data in Table 1 and Table 3.

Apart from the energy economics application shown here, synthetic networks could be applied for studies such as transient stability. In addition, voltage regulation, reactive power support and some other research topics are also of interest. We will report on such efforts in future publications.

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