Steady-State Scenario Development for Synthetic Transmission Systems

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***Abstract*—The development of synthetic transmission networks has equipped the power system research community with public test cases that can be used and shared freely. As the synthetic electric grid power flow model only represents a one-time snapshot of the system, this paper proposes a methodology of developing scenarios that can reflect a wide spectrum of system operating conditions. The general process of determining load and generation levels, planning scheduled outages, and dispatching generators is discussed. Techniques that are commonly used to aid the convergence of power flow of scenario case are also provided.**

***Index Terms*—Synthetic transmission networks, time series, power system test cases, power system scenarios, power flow analysis**

I. INTRODUCTION

POWER system steady-state scenarios are complete system models with power flow solutions that can be adapted to represent a broad range of system operating conditions. These system models typically include the dispatch outputs of generators, values of electric load, parameters of transmission lines and transformers, tie-line interchange schedules, and the status of other system elements [1]. Each scenario constructs a snapshot of the power system to reflect the system during a specific period of interest with respect to the intention of the study. Scenarios are used for real-time operation analysis, and short- and long-term system planning procedures. The represented system condition can be at a normal operating point that system operators often experience, or may represent the system under unusual conditions for some eventful scenarios [2].

The development of steady-state scenarios is critical for the operation and planning in power systems. Various tests such as contingency analysis, deliverability analysis, reliability assessment, and voltage stability studies need to be simulated using different scenarios to deploy operation actions, and make planning decisions [3]. The knowledge of power system's limit and expected event response under specific operating conditions ensures that the grid can be operated in an effective and reliable manner, and the needs of future system improvements can be identified [2]-[4].

In the power industry, the development and maintenance of scenario cases are often managed by steady-state working groups and regional modeling working groups of entities like Western Electricity Coordinating Council (WECC), Eastern Interconnection Planning Collaborative (EIPC) and Independent System Operators (ISOs) [5], [6], [7]. Each scenario will have assumptions such as load and generation levels, expected outages, and area interchange schedules. Those assumptions are then translated into parameters and settings of a power flow model [3], [8].

However, because in many locations worldwide the distribution of real power system topologies and scenarios is restricted (such as in the United States where such information is considered to be critical energy infrastructure information [CEII]), they are confidential and protected by non-disclosure agreements.

Recent efforts have been made to create synthetic electric power transmission networks that are statistically and functionally similar to real power system topologies. Those synthetic system networks are developed based on public data of the actual grid and have geographic coordinates so that their characteristics and functions follow the statistics of the actual power systems [9]–[13]. The reactive power planning is also studied so that synthetic transmission network can converge to an initial AC power flow solution, representing the one-time snapshot of the system at its peak demand [10].

Time series data for bus-level load and renewable energy generation are also synthesized from public data set [14], [15]. It lays the fundamental work of scenario development, which enables a wider range of applications for the synthetic transmission networks.

This paper proposes a method of generating realistic power system steady-state scenarios using synthetic transmission network and time series developed at Texas A&M University (TAMU). The general procedure used to determine the load and generation level, scheduled outages, as well as unit commitment and dispatch is discussed. The techniques needed for the designed scenario to converge to an initial power flow solution are also introduced.

This paper primarily focuses on the creation of operating

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scenarios for the ACTIVSg2000 synthetic transmission model, a 2000-bus system on the footprint of Electric Reliability Council of Texas (ERCOT). However, the proposed methodology is generally enough to produce scenarios representing any system conditions for any other power system models.

II. BACKGROUND

A. *TAMU Synthetic Transmission Models*

TAMU synthetic electric transmission models are fictitious power grids with a detailed modeling of generators, loads, transmission lines, and other power system elements. Those models were created using the methodology outlined in [9], [10], and can capture structural and functional characteristics of actual power grids. Model sizes of current synthetic networks range from 200 buses (on the footprint of Central Illinois), to 70,000 buses on footprint of eastern United States. All synthetic electric network models are available for download at [16]. One key feature of those synthetic network models is the availability of geographic information of system elements. The geographic information is explicitly used in this paper to develop scenarios with various system operating conditions.

Figure 1 shows the one-line diagram of the ACTIVSg2000 synthetic transmission system. It has 1250 substations and 2000 buses. The total load is 67 GW and the total generation capacity is 100 GW. The orange, purple and green lines in the one-line diagram represent the 500-kV 230-kV and 115-kV network in the synthetic system respectively. This paper refers it as the base case, and it is the foundation from which the operational scenarios are created.

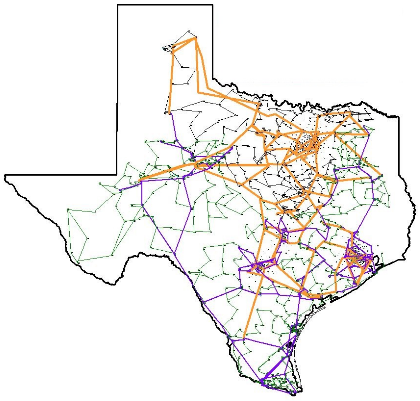

Fig. 1. One-line diagram of the ACTIVSg2000 synthetic transmission model

B. *Synthetic Load and Renewable Generation Time Series*

Hourly time series of bus-level load and renewable generation for a typical year are created for the TAMU synthetic transmission models [14]-[15]. For the load time series, the geographic coordinates of each bus are used to determine a unique electricity consumption profile at that location. An iterative aggregation approach is then taken to integrate publicly available building- and facility-level load time series to the bus-level. The synthetic load time series were also validated using time series from the actual power systems [15]. The system-level load time series for the ACTIVSg2000 synthetic system is shown in figure 2.

As for renewable generation time series, the geographic coordinates of each bus for wind and solar units in the synthetic system are used to identify the closest renewable sites in the actual grid. The National Renewable Energy Laboratory (NREL) 5-minute resolution data of real power generation from Wind Integration National Data Set (WIND) and Solar Resource Data Set (SOLAR) [17]-[18] are upsampled to hourly resolution time series. Then, they are synthesized considering the Texas wind and solar generations' unique patterns that are created by their regional features and seasonal variation of weather and temperature. The synthetic renewable time series that have public access to the bus-level are also validated using time series from the actual power systems [15]. The system-level ACTIVSg2000 synthetic renewable generation time series as well as the actual system are presented in Figure 3 and Figure 4. The bus-level load and renewable generation time series are used as the benchmarks of typical profiles to develop scenarios.

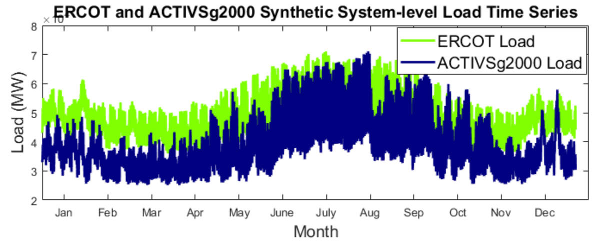

Fig. 2. System-level load time series for the ERCOT and ACTIVSg2000 synthetic system

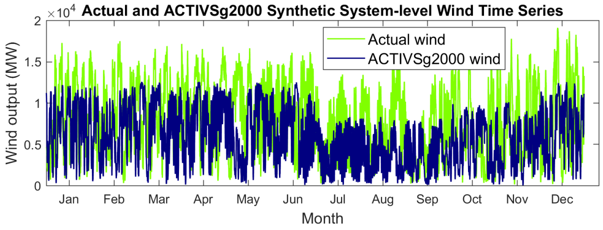

Fig. 3. System-level wind time series for the Actual and ACTIVSg2000 synthetic system

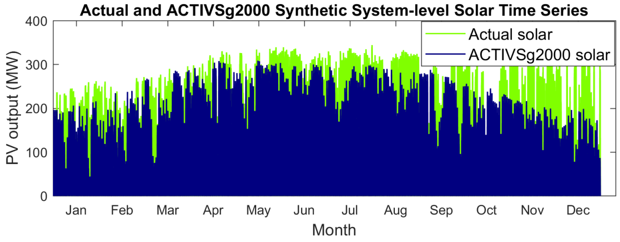

Fig. 4. System-level solar time series for the Actual and ACTIVSg2000 synthetic system

III. METHODOLOGY

The detailed methodology of developing a scenario is dependent on many factors such as the specific operating condition that needs to be reflected, the duration of the event, the intended applications of the scenario, et cetera. This paper provides a general procedure of creating scenarios for the synthetic power system, which includes the determination of load and generation level, scheduled outages, unit commitment, and unit dispatch. The general method is developed based on the existing synthetic transmission models and time series, and takes advantage of the geographic information associated with the synthetic systems.

Since the ACTIVSg2000 synthetic system and the ERCOT system share the same geographic footprint, ERCOT's steady-state working group procedure is used as a reference to choose the set of scenarios to be developed [19]. Eight operation scenarios, including the maximum and minimum load for the four seasons are created and discussed in this paper.

A. Load Level

Under normal system operating conditions, electric loads have constant variations by nature as electricity consumers react to the change of time, weather, and other day-to-day events. In the case of a special or an extreme event, load in a power system can be found at an unusual level. For example, in a system with a large integration of behind-the-meter solar, the load level at specific locations may experience a sharp drop as a result of power line outages following extreme weather conditions.

For the development of operation scenarios that reflect typical conditions, the synthetic bus load time series can be used directly to set the load level at each bus. To develop an event scenario, the original bus load time series can be used as a benchmark, where changes can be made depending on the details of situations.

B. Generation Level

Considering the fact that the sources of wind and solar power come from nature, renewable generation is susceptible to the change of temperature, time, and other various factors and therefore has volatile trend. In order to compensate for the unpredictable characteristics of renewable generation and always meet the varying load demand, conventional operating systems have specific seasonal generation level settings for dispatchable generators (i.e. coal, hydro, gas, and nuclear fuels). Dispatching the maximum capacities of the generators through seasons can help to store enough reserve fuels and prevent electricity shortages.

According to the Seasonal Assessment of Resource Adequacy (SARA) and the Capacity, Demand and Reserves (CDR) Report [20], most dispatchable generators from Texas always use their full capacities as shown in table I. Only hydro power has been dispatched diversely by seasons and its own maximum capacity factors are able to be obtained using equation 1.

TABLE I
MAXIMUM CAPACITY FACTORS OF GENERATORS BY FUEL TYPE [20]

Generator by Fuel Type	**Spring**	**Summer**	**Fall**	**Winter**
Coal	100	100	100	100
Hydro	83.5	83.2	70.8	82.3
Gas	100	100	100	100
Nuclear	100	100	100	100

$$CF_{max} = \frac{capacity\ contribution\ (top\ 20\ hours)}{operational\ capacity\ total} \tag{1}$$

Hence, taking into account those seasonally changing capacity factors, the dispatchable generation level of each bus for the ACTIVSg2000 operation scenarios has been determined. For the creation of the renewable generation level, the synthetic bus renewable time series is directly applied to the operation scenarios.

C. Scheduled Outages

At any point in the year, system elements (i.e. generators, transmission lines) may be scheduled for maintenance outages. These are necessary to allow regular maintenance on system components to be performed in a safe manner (i.e. while the components are de-energized). In practice, these scheduling requests are made by utilities and, following system studies, approved by the regional balancing authority (such as ERCOT in Texas) [21], [22]. The coordination of these outages is governed by NERC TOP-003-1 [22], a standard designed to ensure that system reliability is maintained even with scheduled generator and transmission outages.

The scheduled generation outages applied in these scenarios are based on the maintenance outages reported in ERCOT's SARA [20], which provides a total of the generation outages for the season of study. The generation maintenance outages in these scenarios are based on the 2019 reports and are summarized in Table II. The values provided, however, are representative of the scheduled maintenance outages over the course of an entire season. In order to quantify outages in a scenario's snapshot depiction, a simplifying assumption that the average duration of a scheduled maintenance outage is 4 days, meaning that the seasonal outage capacity can be reframed as a seasonal outage energy. Capacity outage in the scenario can be represented per the following equations, where $P_{out,low}$ and $P_{out,high}$ are the scheduled maintenance outage in the scenario, t_{avg} is the average outage duration in hours, $P_{m,seas}$ is the anticipated seasonal maintenance outage from SARA, t_{seas} is the number of hours in the season, and $P_{L,high}$ is the seasonal peak load and $P_{L,low}$ is the seasonal minimum load.

$$P_{out,low} = \frac{t_{avg} * P_{m,seas}}{t_{seas}} \frac{P_{L,high}}{P_{L,low}} \tag{2}$$

$$P_{out,high} = \frac{t_{avg} * P_{m,seas}}{t_{seas}} \frac{P_{L,low}}{P_{L,high}} \tag{3}$$

These totals are represented in Table IV. Specific generators are scheduled for maintenance outages during each season's

TABLE II
TYPICAL GENERATOR MAINTENANCE OUTAGES IN ERCOT [20]

Season	Maintenance Outages (MW)
Winter 2018-2019	3,964
Spring 2019	6,024
Summer 2019	381
Fall 2019	10,158

TABLE III
MAINTENANCE FREQUENCY OF GENERATORS BY FUEL TYPE [24]–[29]

Generator by Fuel Type	Period between Maintenance (months)
Coal	12
Hydro	7-12
Natural Gas	7-24
Nuclear	18-24
Solar	6-12
Wind	13

scenarios according to the relative frequency of outages by fuel type informed by the data in Table III and industry practice, i.e. nuclear outages are also informed by data published by the U.S. Energy Information Administration [23].

Transmission outages are scheduled to allow for maintenance or construction that require specific branches to be de-energized. The transmission outages are applied to the scenarios such that connectivity of the system is maintained considering N-1 security. In order to do this, the system is considered as a graph. Candidate transmission lines for outages are screened using the bus admittance matrix as a proxy for a connectivity matrix. If removing the candidate line in combination with previous accepted scheduled transmission outages creates a bridge in the system, the candidate is rejected and thus must remain in the case to ensure connectivity under N-1 conditions. Outages of lower capacity lines are prioritized by having a relatively high probability of selection when randomly identifying candidate lines. This process is repeated until the desired number of outages was reached for each scenario. The quantity of transmission capacity outaged in each case is summarized in Table IV.

D. *Unit Commitment and Dispatch*

The commitment and dispatch of generators schedule the specific amount of power that each unit should generate in scenarios. Unit commitment determines the on/off states of units that are not in scheduled outages from the previous section. This paper formulates unit commitment as a priority list optimization problem [30]. At each hour, with the cost function of generators sorted, the subset of generators that can supply the system load with the lowest operation cost while satisfying the generator min on/off and ramping constraints is set to be online [30]. Economic dispatch calculates the specific generation amount of each unit knowing the on/off states from the unit commitment [19].

IV. POWER FLOW SOLUTIONS

Convergence to a power flow solution is an indicator that the developed scenario has a feasible solution. Having an initial power flow solution is a good starting point to initialize other studies such as contingency analysis, optimal power flow, unit commitment, and transient stability simulations, et cetera. If the created scenario represents an event that spans over time, the power flow solution of the first time point is also used as the initial guess for power flow solution of the following time step.

Since the system operating condition of a customized scenario might be very different compared to the base case, its power flow solution can be far from the base case's solution. Sometimes special techniques are needed to aid the power flow algorithm to converge to an acceptable solution.

A. *Incremental Steps*

The selection of initial guess is a critical key for the power flow convergence [31]. In the case of a customized synthetic scenario, the initial guess usually includes the voltage magnitude and angle that are obtained from the base case AC power flow solution. However, the power flow may take more iterations to converge or sometimes divergence can happen due to a big discrepancy of the operating conditions between the base case and scenario.

To address this issue, incremental steps can be established to gradually move the solution from the base case to the designed scenario case, where the solution from the previous step is used as the initial guess of the current step. For example, the spring minimum load scenario for the ACTIVSg2000 synthetic system experienced a non-convergence issue when using the base case solution directly as the initial guess. When 100 intermediate steps are added to gradually bring down the system load of 67 GW from the base case to 23 GW from the scenario case, Newton-Raphson power flow algorithm is successfully able to converge to a solution.

B. *Low Voltage Solutions*

As power flow problems are inherently non-linear, multiple solutions usually exist. While power systems are normally operated at the solution with highest voltage, sometimes the power flow algorithm might converge to a low voltage solution, resulting in being an inaccurate reflection of the real system values [32].

For each bus in the system, the self sensitivity of the voltage magnitude and reactive power injection can be used to confirm if a low voltage solution has been reached [33]. If dV/dQ is negative at one bus, it indicates the occurrence of a low voltage solution, where locally increasing reactive power would not provide voltage support. Starting with a higher-valued initial guess on those buses, and temporarily disabling controls are common techniques to help the returning of a high voltage solution [34]. If low bus voltage violation occurs but the sensitivity of voltage with respect to reactive power injection stays positive, the result is still at a high voltage solution, where reactive power devices can be implemented to help with the voltage profile.

C. *Reactive Power Devices*

Reactive power devices such as shunt capacitors, reactors, and load tap-changing (LTC) transformers are commonly used

TABLE IV
ACTIVSg2000 OPERATION SCENARIOS DESCRIPTION

Case Name	**Case Description**	**Load (MW)**	**Wind Generation (MW)**	**Solar Generation (MW)**	**Generation Outage Capacity (MW)**	**Transmission Outage Capacity (MVA)**
SPR1	Maximum expected load in Spring	53329.7	5443.4	175.4	114.0	31590.4
SPR2	Minimum expected load in Spring	23072.3	7788.7	0.0	610.7	37998.0
SUM1	Maximum expected load in Summer	66275.7	1482.6	198.3	6.4	15942.6
SUM2	Minimum expected load in Summer	25350.1	3849.1	0.0	44.2	19324.1
FAL1	Maximum expected load in Fall	55848.5	2376.3	110.7	188.0	51627.5
FAL2	Minimum expected load in Fall	23379.4	8625.7	0.0	1215.0	45258.9
WIN1	Maximum expected load in Winter	53964.3	11514.2	3.9	75.0	23518.0
WIN2	Minimum expected load in Winter	23295.2	10152.9	0.0	407.7	21387.0

for bus voltage regulation that improves the voltage profiles of a solution [35]. The reactive power planning for the base case of synthetic transmission system recognizes that the placement and settings of reactive power devices are designed to optimize the operating condition of the base case, and leaves a margin to allow extra shunt devices to be added as needed for special-case situations and future development [10].

To accommodate the varieties of scenario development for the ACTIVSg2000 synthetic system, 24 additional shunts are added to the system to address the voltage violations.

V. THE ACTIVSG2000 OPERATION SCENARIOS

The descriptions of the ACTIVSg2000 operation scenarios can be found in table IV. The voltage contours are depicted in Figure 5 as described in [36]. Note that the low voltage pockets vary seasonally. Figure 6 provides a snapshot representation of the line loading in the eight scenarios by creating pseudo-geographic mosaic displays (PGMDs) [37]. The PGMD snapshots contain 3206 individual "tiles," each representing the status of one line in the system. The color of each tile represents the line loading in the scenario, ranging from blue representing 0% line loading to red representing 100% line loading relative to the line limits. The tiles are placed to approximate the geographic location while optimizing for the available display space (e.g., the tiles located in the upper left of each snapshot correspond to the most northwestern lines in the system).

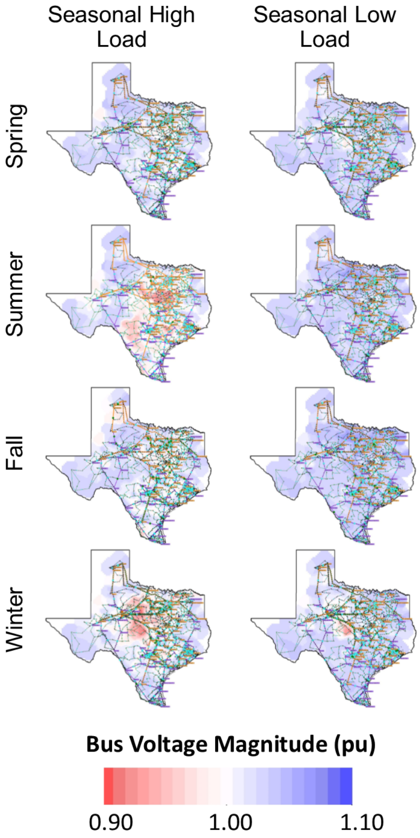

Fig. 5. Voltage Contour of Scenarios

VI. CONCLUSION AND FUTURE APPLICATIONS

Synthetic transmission systems have equipped the power system research community with public test cases that have the similar size and complexity as the actual grid, and are free to be used and shared without any confidentiality concerns. As the synthetic power system base case only represents a one-time snapshot, there is a need to create more scenarios reflecting a wide spectrum of system operating conditions.

This paper proposes a methodology to develop scenarios using the existing synthetic transmission models and time series. The detailed decisions on how a scenario should be created are dependent on the type of scenarios to be developed, and its purpose. In general, the scenario development process includes the determination of load and generation level, the scheduled outages, and the unit commitment and dispatch. Those steps are discussed in detail using the example of creating eight operation scenarios for the ACTIVSg2000, a 2000-bus synthetic system on the footprint of Texas.

Since each scenario represents a unique operating condition that can be very different from the base case's state, sometimes special techniques are needed to aid the convergence of a power flow solution. This paper provides the approaches of using incremental steps and reactive power devices to obtain power flow results and avoid low voltage solutions for the customized scenarios. The description and comparison of the eight operation scenarios are also presented. Those scenarios can be downloaded at [16].

The creation of scenarios for the synthetic transmission base case can provide better knowledge of the system's operating limit and expected response of certain contingencies. This can provide valuable insights for power system operation and

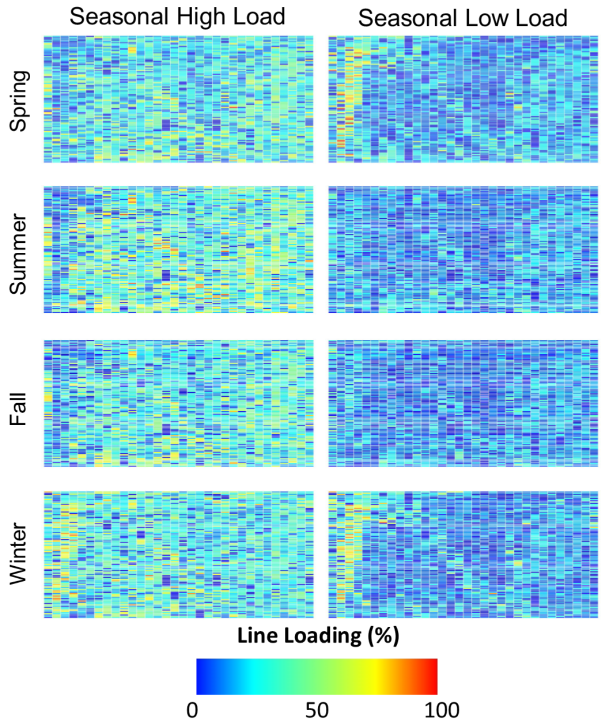

Fig. 6. Pseudo-Geographic Mosaic Display of Scenario Line Loading

planning studies. The ability of customizing scenarios also enables researchers to investigate the "what-if" conditions of the grid, which will improve the power system's reliability and resilience.

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