Visualizing Volt-Var Distributions in Large-Scale Electric Grid Models

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***Abstract*—This paper analyzes the North American and synthetic power grid models by examining their voltage and reactive power output distributions. Histograms are used to visualize this difference. The North American grids, managed by various utilities and independent operators, exhibit considerable variability in voltages and generator settings. In contrast, synthetic grids display uniform voltage levels and centralized control, indicating a simplified design approach. Statistical measures are presented to quantify these differences with the objective of making synthetic grids realistic.**

***Index Terms*—synthetic grids, large-scale electric grid models, voltage, reactive power, histogram**

I. Introduction

Monitoring voltages and reactive power in a power grid is crucial for maintaining stability and reliability. It ensures that voltage levels are kept within safe boundaries, preventing system failures. This monitoring also protects electrical equipment by preventing damage from excessive or insufficient voltage, thus extending its operational lifespan and enhancing efficiency. Reactive power helps regulate voltage levels. Reactive current, in particular, can mitigate the steady-state voltage variability impacts of several grid-connected devices such as Distributed Energy Resources (DERs) and Inverter Based Resources(IBRs), highlighting its significance in modern power systems.

Insufficient reactive power has been repeatedly cited as a reason for voltage collapse across a grid, creating blackouts in power grids around the globe [1], [2]. In the United States, the blackouts of July 2, 1996, and August 10, 1996, occurred due to voltage collapse. The blackout of August 14, 2003, was due to the failure to manage reactive power resources, which led to a voltage collapse [3]. Adhering to regulatory voltage standards is essential as it helps grid operators coordinate with utilities, which is critical for preventing issues like blackouts and ensuring grid stability.

The Federal Energy Regulatory Commission (FERC) and the North American Electric Reliability Corporation (NERC) oversee and enforce reliability standards for the U.S. electrical power grid. Key NERC standards address voltage and reactive power management, crucial for grid stability and efficiency. VAR-001 (Voltage and Reactive Control) and VAR-002 (Generator Operation for Maintaining Network Voltage Schedules) mandate coordinated voltage and reactive power management. These standards ensure voltage levels stay within safe limits and sufficient reactive power is available. Other standards, like VAR-003 (Standard Voltage Schedules) and VAR-004 (Generator Reactive Power Capability), set requirements for maintaining voltage schedules and generator reactive power capabilities. Collectively, these standards enhance grid reliability and prevent service disruptions.

While FERC and NERC provide the overarching framework for stability limits, regional bodies such as Regional Transmission Operators (RTOs) and Independent System Operators (ISOs) ensure adherence to these standards in practical settings by defining stability limits or system operating limits (SOLs) in their transmission planning guides. In line with the NERC standard TPL-001-04, in both MISO and CAISO, the transmission planning coordinators determine the voltage stability limits for the planning models which are studied by the ISOs [4], [5]. New England ISO defines the voltage stability limits for normal operation for each of its utilities [6]. On the other hand, PJM defines its voltage stability limits by voltage level [7]. The steady-state voltage limits for SPP can be within +/-5% of the nominal voltage [8]. These regional differences result in a natural variability in power system parameters across the grid.

This paper observes voltage and generator reactive power trends within the North American power grids, specifically the Eastern, Western, and Texas interconnects. While operational trends are distinct in actual grids, research grid models often do not exhibit the same patterns as actual grids. By identifying unique quirks in each, we aim to identify metrics that can be used to improve the realism of existing large-scale electric grid models of these regions. Insights gained from this analysis are useful in designing sophisticated fictitious (or ”synthetic”) power grids that closely emulate real-world conditions. These synthetic grids are invaluable platforms for innovation, testing, and learning in power system operation and planning research.

II. Methodology

Voltage and reactive power histograms provide additional insights into a power grid's behavior. This research uses his-

 Accepted for presentation at NAPS 2024, El Paso, October 2024.

tograms to visualize per-unit bus voltages, generator reactive power outputs, and set point voltages across the grids. For research purposes, actual grid data is analyzed, and results are provided without disclosing any Critical Energy Infrastructure Information (CEII). For large-scale electric grid models, this work uses large-scale synthetic grids (described in [9]), which are fictional yet designed to mimic actual power grids. This paper highlights the differences between these synthetic models and the actual power grids in voltage and reactive power distribution.

Before getting into the methodology, it is important to understand the creation of the electric grid models. The creation of the synthetic grids and their validation against metrics derived from the North American grids are explained in detail in [10]–[13]. In [14], the authors explain reactive power planning for all the synthetic grids, i.e., setting generator setpoint voltages and determining the location and limits of shunt devices to maintain reactive power and obtain a feasible AC power flow solution under different operational scenarios, ultimately ensuring an N-1 secure power grid. The crucial step of voltage schedule adjustment is important, where target voltages are assigned based on nominal kV range, acknowledging that this is an ideal selection and not observed in the actual power grids.

Due to their many time-varying parameters, such as load and generation, grids have a wide continuum of operating states, making comparing values one-to-one difficult. To maintain uniformity, we ensure that the ratio of generator MVA outputs to their maximum rated MVA is close. This is achieved by scaling the case's load, shown in Table I, to match the actual grids in their loading. The three North American grids used in this work are designed for the summer peak loading.

TABLE I: Generation to Capacity Ratio: System Loading

Parameter	**Synthetic**			**Actual**		
	7k	**10k**	**70k**	**ERCOT**	**WECC**	**EI**
$\frac{\text{Gen output MVA}}{\text{Max MVA}}$	0.71	0.57	0.66	0.75	0.59	0.65

First, a few filters are considered for a case (real or fictional) to prune the power grid information before analysis. The filters narrow the dataset to identify non-operational power generation facilities and generation facilities that do not contribute to voltage regulation. These include generators marked as ”open” in the case, ensuring they are no longer operating. Only transmission-level voltages are considered when analyzing the bus voltage distribution, excluding all generator voltages. The exclusion of solar-powered facilities focuses on selecting units relying on other fuel types capable of providing voltage regulation. Some reactive power requirements state that facilities greater than 20MVA must be able to provide reactive power support [15]. Our analysis considers facilities with a maximum reactive power output greater than 50 Mvar. This set of filters effectively extracts active, larger, non-solar generators capable of reactive power compensation.

Next, constructing a histogram is straightforward. The range of the data is divided into equal bins; the data points in each bin are counted, and these counts are graphically represented with bars. This visualization helps analyze the data distribution and identify any outliers. The calculations and visualizations in this paper have been done using PowerWorld Simulator Version 23.

III. Observations and Analysis

As a result of the proposed methodology, several insightful histogram plots have been obtained. These plots show results for three synthetic and three North American power grid models. The histogram plots in Fig.1 show information for the Texas (ERCOT), the western (WECC), and the eastern (EI) interconnect power grid models on the footprint of North America, whereas the histogram plots in Fig.2 shows information for the synthetic 7k grid model (which is modeled on the footprint of Texas), 10k grid model (which is modeled on the footprint of western United States) and the 70k electric grid model (which is modeled on the footprint of eastern United States).

The three parameters compared are the bus voltages in per unit (pu), the generator setpoint voltages in per unit (pu), and the reactive power output percent as a percentage of the maximum reactive power capacity of generators(%). Four statistical measures are selected to perform quantifiable comparisons. These are mean(μ), standard deviation(σ), skewness(γ_1), and kurtosis(γ_2). Mean is to observe the typical values in the different grids under study; for example, what is the typical generator setpoint voltage for a given power network? Standard deviation (derived from variance) is to observe the dispersion of the values from the mean, for example, by how much the bus voltages deviate from the mean. Kurtosis and skewness help us understand how different the data distribution is from a normal distribution [16].

High kurtosis, known as leptokurtic distribution, suggests heavier/longer tails and a higher peak. Low kurtosis, or platykurtic distribution, implies a distribution with lighter tails and fewer extreme values but with a flatter peak. A distribution with kurtosis close to a normal distribution (kurtosis=3) is referred to as mesokurtic, indicating a balanced distribution with moderate tails and no significant outliers. Understanding these characteristics helps diagnose the operational behavior and stability of power systems. Skewness in power system data provides insight into the asymmetry of the data distribution. The following two subsections provide a detailed analysis of the synthetic and actual power grid models.

A. North American power grids models

The voltage distribution in the ERCOT grid(Fig.1a) is leptokurtic and features a slightly broader tail below 1.01 pu, highlighting occasional lower voltages. The WECC grid(Fig.1d) presents a platykurtic bus voltage distribution with a wider spread around 1.01 pu, higher variance, and slight right skewness, suggesting more dynamic voltage variations. The bus voltage distribution in the EI grid(Fig.1g) is leptokurtic,

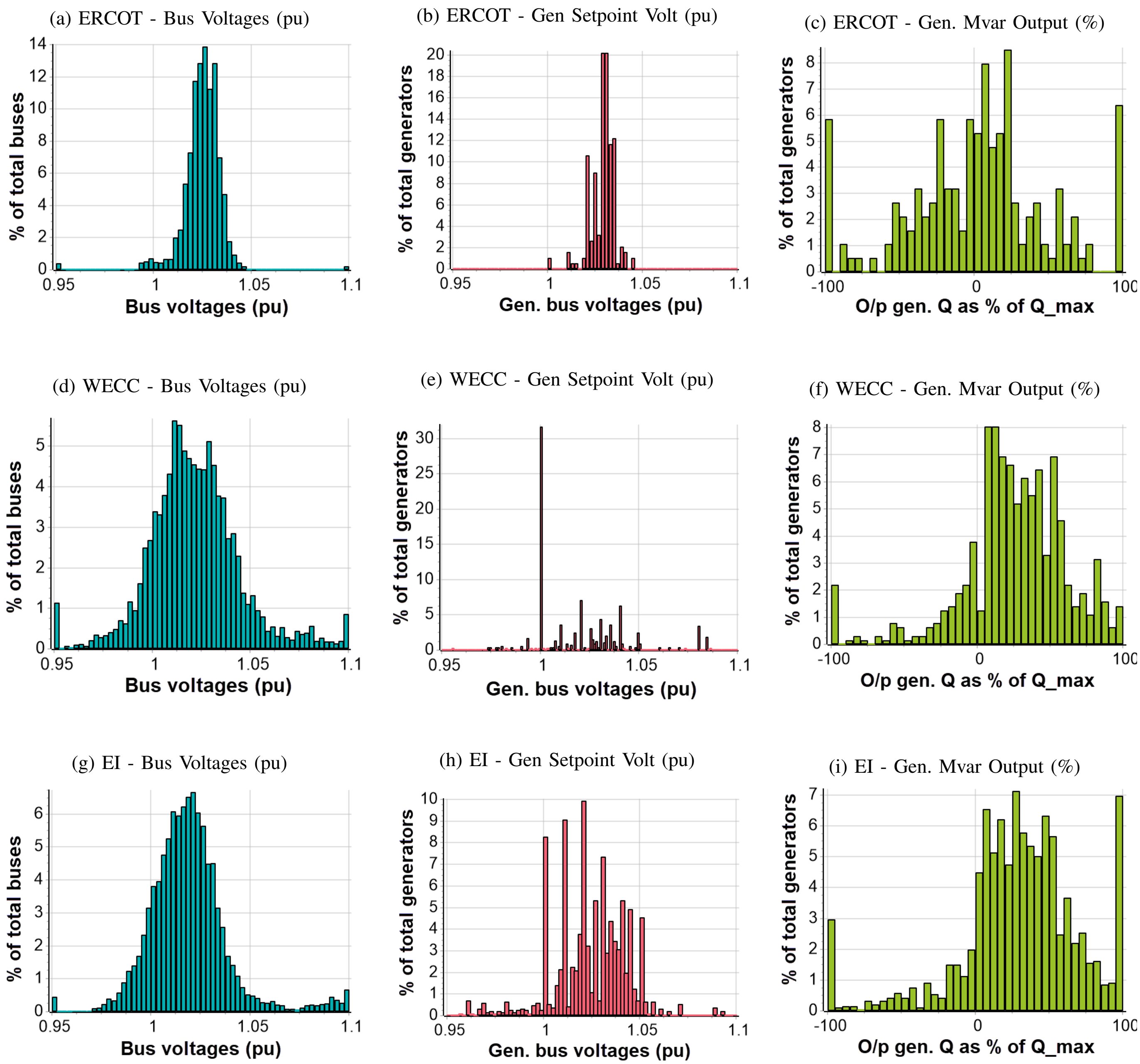

Fig. 1: Bus voltages, generator setpoints, and percent generator reactive power output for ERCOT, WECC, and EI power grids.

centered around 1.02 pu and presents a smoother curve, indicating lower variance and a higher right skewness than in WECC.

The generator setpoint voltages in all three North American power grids are centered around 1.02pu and are platykurtic but differ in other measures. These indicate greater operational flexibility at individual generators. The WECC(Fig.1e) and the EI grid(Fig.1h) display a broader spread of voltage setpoints than ERCOT (Fig.1b). They show higher variance with noticeable skewness and multiple peaks.

For reactive power distribution, the ERCOT grid(Fig.1c) has a mean reactive power output close to 30%, with higher standard deviation, highlighting greater variability and more frequent deviations from the mean. The platykurtic distribution and subtle skewness towards higher reactive power generation indicate a less uniform and more dynamically responsive reactive power system. The reactive power distribution in the WECC grid(Fig.1f) shows a platykurtic distribution centered around 23% with moderate variance, standard deviation, and slight left skewness. The EI grid(Fig.1i) also exhibits a platykurtic distribution centered tightly around 27%, with lower variance and subtle left skewness. This suggests fewer outliers and a more stable operational condition.

B. Synthetic power grid models

The voltage distribution in the synthetic 7k grid, as shown in Fig.2a, is centered around 1.03 pu with a heavier left skewness, limited variability, and a sharp peak. The 10k grid(Fig.2d) also exhibits a sharp peak around 1.03 pu, low variance, but with slight right skewness. In the 70k grid(Fig.2g), the voltage distribution is centered around 1.06 pu with high variance and standard deviation from two distinct peaks at 1.05 pu and 1.1 pu. This platykurtic distribution has a slight right skewness due to higher magnitude of voltage outliers. Compared to the grids of Fig. 1, the synthetic grids show smoother bus voltage distributions with sharper peaks.

Examining the generator setpoint voltages, the 7k grid(Fig.2b) shows a leptokurtic distribution with a mean of 1.04 pu. Such low deviation is unrealistic for such a large system. Similarly, the 10k grid(Fig.2e) has a mean of around 1.03 pu with low variance and right skewness, suggesting tightly controlled and centrally clustered voltage setpoints conducive to stable operational conditions but unrealistic for a large system. The 70k grid(Fig.2h), centered around 1.04 pu with slightly higher variance and a mesokurtic (γ_2 close to 3) distribution, indicates more uniformity and potential flexibility in voltage regulation. Compared to the grid models of Fig. 1, the synthetic grids show lower variance, indicating a tighter control of the generator setpoint voltages.

In terms of reactive power distribution, the 7k grid(Fig.2c) has a mean reactive power output close to -11%, with moderate variance and standard deviation, low kurtosis, and slight left skewness. The 10k grid(Fig.2f) shows a mean of -35%, high variance, low kurtosis, and standard deviation, with a pronounced peak at the extreme right. This indicates a right skewness and the presence of outliers, reflecting a wide data spread. Similarly, the 70k grid(Fig.2i) has reactive power output near -23% with high variance and multiple peaks, indicating substantial variability in generator outputs and a platykurtic nature with noticeable right skewness, with 35% of generators at their minimum capacity. Both the synthetic 10k and 70k grid models have 45% and 35% generators at their negative maximum reactive power output, respectively. Having many generators operating at their maximum capacity is problematic as they have no room to increase output in response to sudden increases in demand or unexpected outages of other generators. This limits the system's ability to handle fluctuations and maintain transient stability. In reality, many generators provide ancillary services and operate far from their maximum limits to account for the reserve margin.

The information visualized in Figs. 1 and 2 is quantified in Tables II, III, and IV. The analysis done in the above three subsections has revealed significant differences in the operational behaviors in synthetic grids versus actual power grids.

Some interesting observations are made only by looking at high transmission level voltages (greater than 230kV) for

TABLE II: Per-Unit Bus Voltage Distribution

Parameter	Synthetic			Actual		
	7k	**10k**	**70k**	**ERCOT**	**WECC**	**EI**
μ	1.03	1.03	1.06	1.01	1.01	1.02
σ	0.0011	0.0011	0.0027	0.0069	0.0099	0.0068
γ_1	-0.41	0.07	0.91	-1.39	0.37	1.03
γ_2	0.88	-0.07	0.43	17.02	1.53	3.47

TABLE III: Per-Unit Generator Setpoint Voltage Distribution

Parameter	Synthetic			Actual		
	7k	**10k**	**70k**	**ERCOT**	**WECC**	**EI**
μ	1.04	1.03	1.04	1.02	1.02	1.02
σ	0.0023	0.0102	0.0115	0.0154	0.0243	0.0196
γ_1	-3.89	0.59	-0.96	-0.52	0.80	-0.37
γ_2	21.1	0.36	2.66	0.22	0.54	1.26

TABLE IV: % Generator Reactive Power Output Distribution

Parameter	Synthetic			Actual		
	7k	**10k**	**70k**	**ERCOT**	**WECC**	**EI**
μ	-11.35	-35.15	-22.4	29.71	22.93	27.01
σ	40.30	78.8	70.23	34.41	36.71	41.61
γ_1	-0.36	0.48	0.12	-0.33	-0.91	-0.86
γ_2	0.95	-1.53	-1.54	0.06	1.88	1.48

the three interconnects and the synthetic grids. Fig.3a, Fig.3b, and Fig.3c compare the bus voltages with the actual grids all showing higher variance than the synthetic grids. The differences between the synthetic and actual power grids are significant. In the ERCOT versus synthetic 7k network(Fig.3a), the synthetic 7k network shows distribution entirely above 1.03 pu whereas the ERCOT network has voltages more spread out also including occasionally lower than 1 pu. The Western Interconnect has the most interesting distribution, showing the highest variance and lowest kurtosis, with a flatter voltage spread from 0.95 pu to 1.1 pu in Fig.3b.

Additionally, comparisons within the real grids reveal distinct regulatory differences in voltage management between the Eastern and Western Interconnects. As seen in Fig.4, the EI (blue) distribution shows a fairly spread distribution with multiple peaks, suggesting some variability in the voltage control at these higher voltage levels. Peaks around 1.00 pu and above 1.05 pu indicate that while the system aims to maintain voltages around these levels, there's a significant spread, which might be due to operational, environmental, or load variability within the EI system. The WECC (orange) distribution shows a dramatic variation, with substantial activity below 1.00 pu and spiking at around 1.10 PU. This indicates a less tightly controlled voltage regulation, which might reflect broader operational challenges or a wider range of conditions that affect voltage stability in the WECC system.

The variability in distributions seen in the North American grid models may be attributed to the diverse management practices of multiple utilities and Independent System Operators

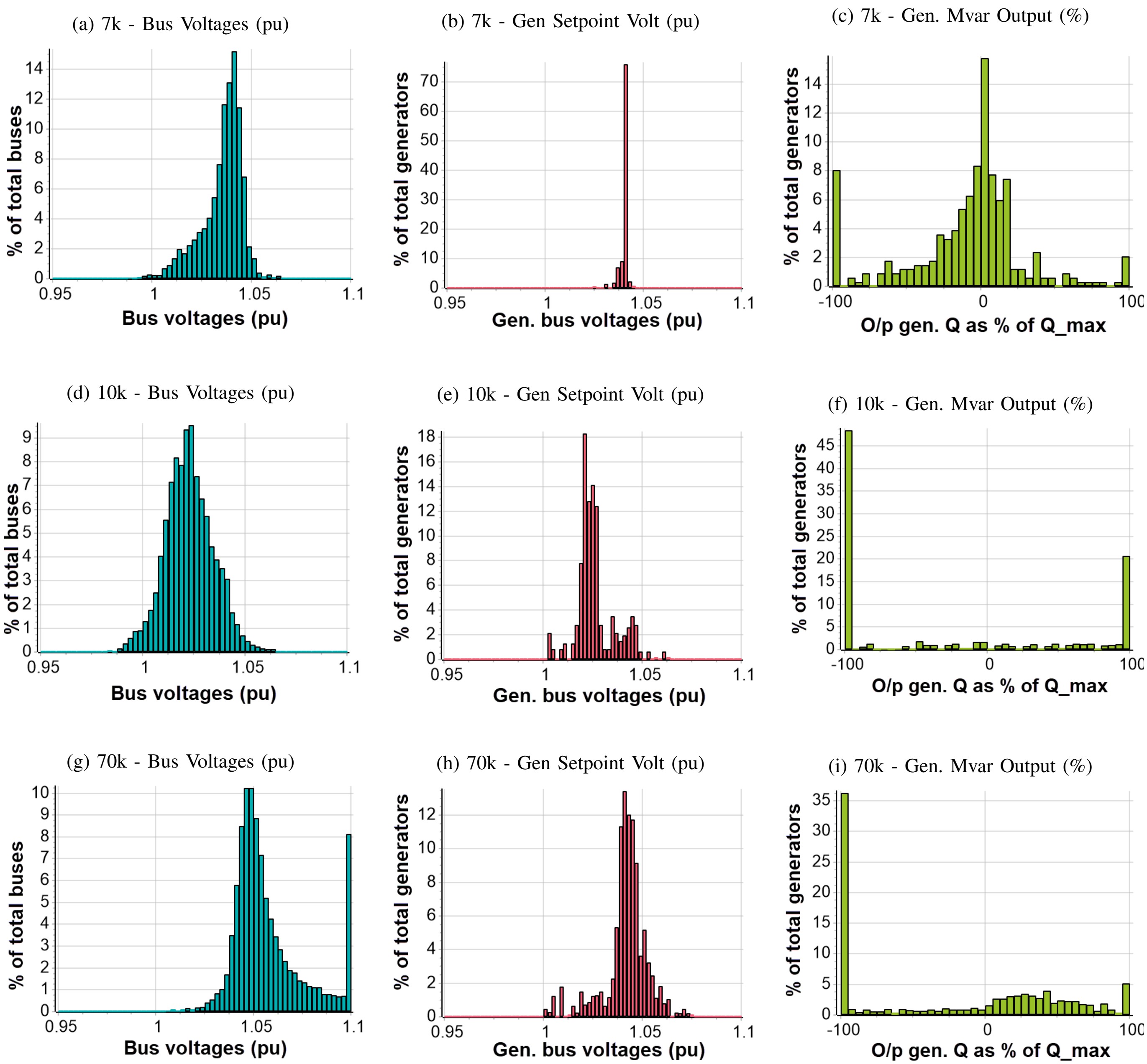

Fig. 2: Bus voltages, generator setpoints, and percent generator reactive power output for synthetic large-scale grid models.

(ISOs). This can be shown with a plot of the generator setpoint voltages for a few selected operational areas of anonymized utilities from EI and WECC, as seen in Fig. 5. The standard deviation for all four utilities is between 0.009 and 0.017. The generator set point voltages in these utilities show a lower standard deviation, indicating a tighter regional control. This decentralized approach provides flexibility, allowing the grid to adapt more effectively to local demand changes and operational challenges.

IV. Summary and Future Directions

The analysis reveals significant differences between synthetic and actual power grid models. Synthetic grids have uniform voltage distributions and generator setpoint voltages, unlike the variability of actual power systems. Additionally, synthetic grids often operate close to the reactive power limits of their generators, limiting their capacity for voltage regulation and their ability to provide dynamic support. Actual power grids exhibit broader distributions, higher standard deviation, and greater flexibility in voltage and reactive power

(a) ERCOT and the 7k model. (b) WECC and the 10k model. (c) EI and the 70k model.

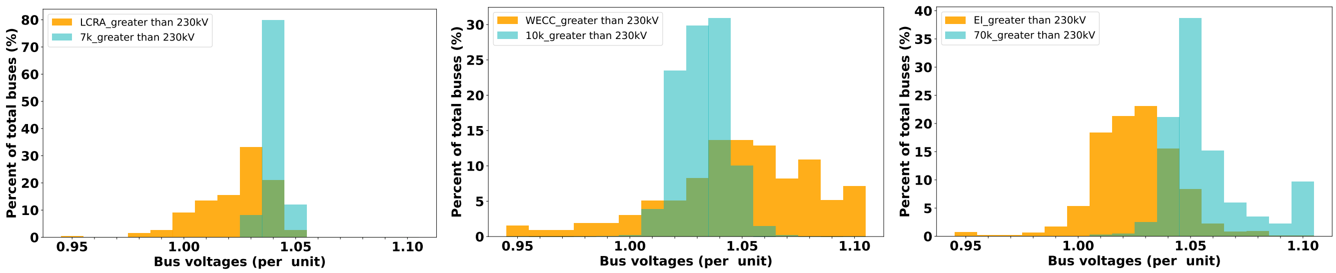

Fig. 3: Per Unit Bus Voltages for buses rated greater than 230kV.

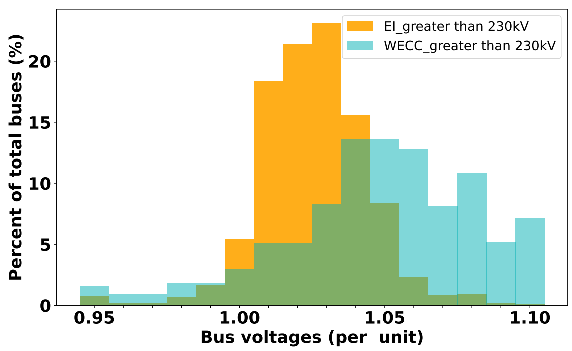

Fig. 4: Per Unit Bus Voltages for buses greater than 230kV.

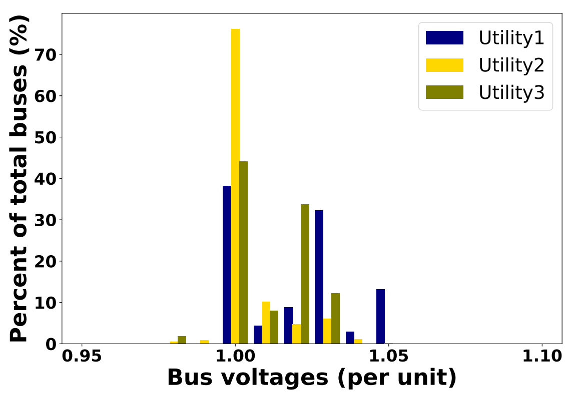

Fig. 5: Generator setpoint voltages(pu) for three individual utilities in WECC showing lower standard deviation and kurtosis, indicating tighter control within utilities.

regulation. These differences underscore the need for synthetic grid designs to incorporate realistic operational constraints and variability to better simulate actual grid dynamics. Future work aims to use these statistical metrics from actual grids to develop realistic large-scale electric grid models.

Acknowledgment

This work was partially supported by funding from the Power Systems Engineering Research Center(PSERC) and partially by Advanced Research Projects Agency-Energy(ARPA-E) for grid optimization projects.

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