Modeling and Validating System Dynamics in Saudi Synthetic Electric Grid

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***Abstract*—This paper introduces a modeling approach for creating a synthetic Saudi power grid, designed to simulate the transient dynamics of a real power grid. This synthetic grid model, created from open-source data, is available for open sharing and can be utilized for educational, and research purposes. The cases are built to match a detailed model of Saudi power system elements, Saudi code requirements, and statistical characteristics found in actual power grids. First, we describe how we built, tested, tuned, and validated this synthetic Saudi grid model by using statistics from currently available data. The CURENT Large-scale Testbed (LTB) and its ANDES package enabled power flow calculations, simulations of transient stability, and analysis of small-signal stability in transmission systems. Second, we describe our use of the ANDES package for dynamic simulation and testing, and our use of the LTB's AGVis package for grid visualization. This Saudi synthetic grid model has 223 buses that have been tested, tuned and validated to ensure that they are realistic and are practical for various studies. Also, it greatly enhances the diversity of existing collections of synthetic grids in the current literature.**

***Index Terms*—Synthetic grid, grid code requirements, generator dynamics, model and validation, Large-scale Testbed**

I. Introduction

The practice of simulating power systems with specialized tools has become a firmly established field, with numerous commercial options readily accessible. Although many of these tools exhibit high computational efficiency and are relatively user-friendly, they use a closed architecture, making it exceedingly challenging or even impossible to inspect or modify most component models [1]. The CURENT LTB platform streamlines the procedure of prototyping and simulating expansive power systems [2]. With a modular architecture, the LTB encompasses a collection of individual open-source packages, namely ANDES, AGVis, and DiME. The LTB provides comprehensive functionalities in simulation, communication, and geographical visualization. Among several LTB packages, ANDES, an open-source dynamic power system platform, employs a hybrid symbolic-numeric approach for rapid prototyping [3], [4]. Besides the simulation engine, a data messaging tool is essential for various other power grid modules, such as geographical visualization and the energy management system [5].

Meanwhile, large-scale power systems cases are substantial to the study of dynamic system response and provide contingency analysis. However, due to administrative concerns, the public has limited access to these models. This prevents researchers from carrying out studies related to power system stability. Therefore, using a synthetic electric grid case allows researchers to thoroughly investigate, tune and validate power system models for various dynamic studies like frequency response and provide accurate analyses of the stability of the studied power system [6], [7].

Similar to previous works in synthetic system models, this study creates synthetic grids of entire Saudi power systems. As such, the objective of this paper is to build a synthetic Saudi grid model that could be used in power system studies, using actual data gathered from the available public database provided by Electricity & Cogeneration Regulatory Authority (ECRA) and Saudi Electricity Company (SEC) [8].

The research work in [9] developed a single scenario featuring a reasonable combination of machine, governor, and exciter and a practical combination of fuel type, with the main objective of producing large synthetic grid dynamic situations which involve several scenarios. The study outlined in [10] suggests enhancements to static and transient voltage levels, the maintenance of transmission capacity within specified limits, and the mitigation of low-frequency disturbances, all in accordance with established standards. Grid code regulations hold paramount significance since they are essential to guaranteeing the safe, reliable, and effective operation of the electrical system, as mentioned in [11]. The core objective of grid codes is to avert any adverse impacts on the system's operation, dependability, and power quality by the concept that has been represented or simulated. This paper introduces a comprehensive synthetic grid model encompassing buses, generators, loads, transformers, and transmission lines, each operating at various voltage levels.

This paper is divided as follows. In Section II, we describe the Saudi grid systems and discuss the process of creating a synthetic Saudi grid. Simulation results and validations of the synthetic Saudi model in different scenarios are presented in Section III. Section IV and Section V present directions for future work and our conclusion, respectively.

II. Saudi Grid System Description

The Saudi power system is growing and becoming more complex to manage, experiencing grid challenges and a need for economic efficiency and stability that is common to utilities globally [12]. In 2022, electricity generation from Saudi power plants amounted to 359,637 gigawatt-hours (GWh). The current power generation infrastructure includes a range of

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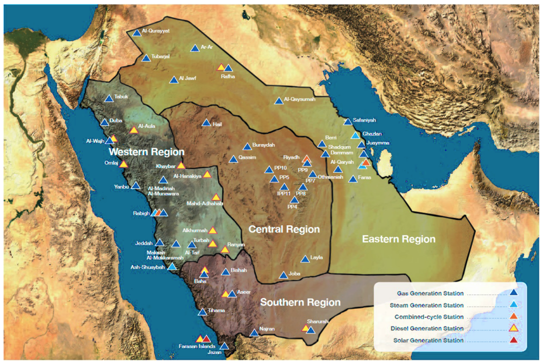

Fig. 1. Grid Standard Fuel Types in Saudi Arabia.

units, spanning from small 15 megawatt (MW) installations to large and modern 720 MW units, with a total actual grid installed capacity of 83,539 MW. The grid maximum load reached 65,301 MW in 2022, and the customer base exceeded 10.9 million, with over 398 thousand new customers acquired over the course of the year, as indicated in [13]. The available electric capacity amounted to 83,036 MW in 2021 with an increase of 4.23%, compared to 2020. The peak load also increased by 3.04% reaching 64,161 MW in 2021. By 2030, the energy generating capacity of the Saudi power system is projected to increase to 120 GW. This expansion is intended to meet the substantial anticipated rise in power consumption [14].

A. Saudi Arabian Power Grid Operating Areas, Voltage Level and Fuel Types

The electrical system in the Saudi Arabian is divided into many operational regions, with management entities overseeing each. Furthermore, Saudi grid standard voltage levels range from 380 kV to 13.8 kV. It has a developed electricity transmission grid that includes various types of transmission lines with different voltage levels [15]. As Figure 1 1 shows, Saudi Arabia relies on oil and natural gas to generate electricity due to the country's abundant reserves of these resources, utilizing a grid of 477 electric power-generating units situated across 46 power plants scattered throughout various regions. As of update in September 2021, the primary fuel types used for electricity generation in Saudi Arabia are all composed of gas turbine units (GT), steam turbine units (ST), combined cycle units (CC), and diesel generation units which are mostly used in remote areas [16].

B. Saudi Arabian Grid Code Requirements

The principal objective of a grid code requirement is to prevent any detrimental impacts on the operation, reliability, and power quality of the system [17]. Regarding the performance of transmission systems, the Saudi Arabian Grid Code (SAGC) demonstrates a high level of congruence with IEEE 1547 [18]. Adhering to the grid code and putting it into practice is what ensures the stability, security, and efficient operation of the electrical grid system [11]. The electrical parameters should be maintained within acceptable limits to improve the efficiency of the transmission system, as recommended by the SAGC recommendations. These parameters are listed below.

1) Frequency Variations: The standard frequency of the transmission system is 60 Hz, and it must be kept within the range of 59.9 to 60.1 Hz under regular operating conditions. The design of the generating system and auxiliary control equipment should align with the limits specified in Table I.

TABLE I
FREQUENCY OPERATION REQUIREMENTS

Below Nominal Frequency [Hz]	Above Nominal Frequency [Hz]	Operation Requirements
58.8 – 60.0	60.0 - 60.5	Continuous
57.5 – 58.7	60.6 - 61.5	For a period of 30 min
57.0 – 57.4	61.6 - 62.5	For a period of 30 sec

TABLE II
VOLTAGE REQUIREMENTS AS PER SAUDI ARABIAN GRID CODE

Nominal Voltage Range (KV)	Normal Range	30-Minute Range
110 kV	±5%	±10%
115 kV	±5%	±10%
132 kV	±5%	±10%
230 kV	±5%	±10%
380 kV	±5%	±10%

2) Voltage Variations: The specified nominal voltage transmission range values, as presented in Table II, should be upheld. In rare situations, the maximum overvoltage limits must not be surpassed for a duration exceeding 30 minutes.

C. Model Selection and Assignment

According to the statistics all generation machines in the Saudi power system are thermal units [19], therefore the process of constructing a synthetic grid places its emphasis on modeling generators that constitute the predominant portion of the overall installed generation capacity. Additionally, lower order dynamic models and a lower level of complexity are chosen.

1) Synchronous Generators: **Governor**: Since governors are strongly dependent on fuel types, steam turbines and gas turbines have been chosen for the steam-governor model (TGOV1) and gas-governor model (GAST). **Machine**: In [19], it is established that the GENROU machine model applies primarily to gas-fueled units. Consequently, the GENROU model is the dominant machine model across the synthetic grid, assigned to all gas-fired generators. **Exciter**: In the Siemens PTI PSS®E library, there are 38 exciter models adopted for natural gas power plants. However, a simplified excitation system (i.e., the SEXS model) will be applied to the excitation systems within each machine in the Saudi model.

2) Load: The actual load information is collected from the General Authority for Statistics (GASTAT). Both public and private electricity demand is highly correlated with population

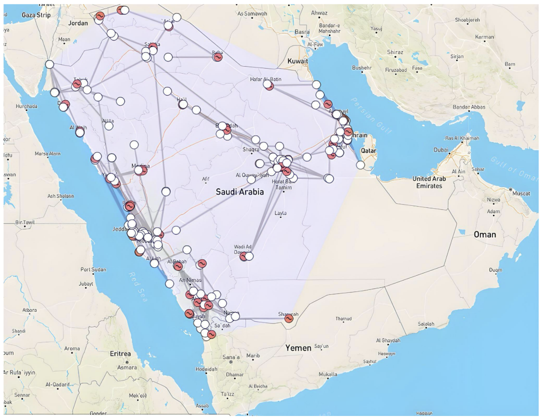

Fig. 2. The synthetic grid representing the Saudi power system by AGVis.

[11], as determined by using geographic coordinates in a statistical analysis of consumed electrical energy by residential sector by region. However, there is no information about load dynamics. As a result, a simplified load model is used to provide an approximate representation of the influence of the load on system dynamics. The active and reactive power loads are transformed into a load constant current of 100% and a load constant admittance of 100%.

D. Transmission Line

The substations are connected using synthetic transmission line configurations at different specified voltage levels, as noted in reference [20]. Most of the Saudi transmission line system is in the form of overhead lines. As a result, synthetic lines are configured with parameters that resemble those of overhead lines, as mentioned in reference [21]. The configuration of the transmission lines is developed using Google Maps. For the purpose of AC power flow analysis, the essential electrical parameters for transmission lines encompass series impedance, shunt admittance, and mega-volt-ampere (MVA) limits. The line length (L) is determined by the straight-line distance between the geographic coordinates of the designated substations. Figure 2 shows the synthetic grid representing the Saudi power system. This synthetic grid is generated using AGVis, and the datasets of grid elements are presented in various formats.

III. Simulation Results and Validation of the Synthetic Model

A. Power Flow Results

Steady state data, including active power and load demand, is made available via the use of statistics and open data. In instances where data is missing such as the reactive power of each bus, estimation techniques are employed, assuming a power factor of 0.95. The synthetic Saudi power grid consists of 224 buses with voltage levels ranging from 380 kV to 13.8 kV. Using ANDES, the power flow simulation is conducted using the Newton Raphson method with four iterations for the base operating conditions, making sure that the voltage magnitudes are within 0.95 - 1.05 p.u. as the standards imposed by the SAGC. Table III presents the composition of the synthetic Saudi power system model.

TABLE III
Composition of Synthetic System Model

Region	Area Code	Number of Buses	Number of Power Plants
Central	300	52	15
Eastern	200	40	14
Western	100	66	19
Northern	500	38	9
Southern	400	28	11

In the synthetic Saudi power grid, the aggregate generation capacity of units belonging to the same type is combined and represented by one unit. QURAYA bus (202) is chosen as the SWING BUS because it has the largest generation capacity. The aggregate active and reactive power generation amounts to 64,637 MW and 19,087 MVar, respectively, whilst the active and reactive power demands stand at 64,033 MW and 14,569 MVar, respectively. Tables IV and V provide a comprehensive overview of the results power flow outcomes and operational regions power flow.

TABLE IV
The Comprehensive Power Flow Result

Parameter	Value
Voltage limits [p.u.]	0.953 to 1.045
Total active power generation [MW]	64,637.7
Total reactive power generation [MVar]	19,087.8
Total active power load [MW]	64,033.3
Total reactive power load [MVar]	14,569.1

B. Flat Run Simulation

This disturbance-free ”flat run” simulation is carried out to verify that dynamic models generate minimal or no transients. NERC suggests that simulations should ideally run for a minimum of 20 seconds to effectively detect any possible small signal or control-related instabilities that might emerge within this timeframe, as mentioned in reference [22]. In the framework of the synthetic Saudi power system model, a simulation without disturbances is conducted, with a duration of 40 seconds. The machine speed deviation of the machines in the model were measured and the results are shown in figure 3. The observed deviations show small magnitudes, falling within the range of around $10^{(}-4)$. This result shows that this model exhibits dynamic stability in the absence of any disturbances.

C. Dynamic Performance Analysis

Accurate event analysis in the synthetic power system grid is of paramount importance for ensuring situational validation, conformity to code requirements and verification of the responsiveness of the grid behavior.

TABLE V
COMPREHENSIVE OVERVIEW OF THE OPERATIONAL REGIONS POWER FLOW

Area	Area Code	Generation [MW]
CENTRAL	300	17,761.6
EASTERN	200	22,027.2
WESTERN	100	17,805.0
NORTHERN	500	3,430.4
SOUTHERN	400	3,613.5
Area	**Area Code**	**Generation [MVar]**
CENTRAL	300	5,936.7
EASTERN	200	6,343.7
WESTERN	100	4,812.2
NORTHERN	500	947.7
SOUTHERN	400	1,047.6
Area	**Area Code**	**Load [MW]**
CENTRAL	300	18,471.8
EASTERN	200	20,673.8
WESTERN	100	17,531.7
NORTHERN	500	3,323.7
SOUTHERN	400	4,032.3
Area	**Area Code**	**Load [MVar]**
CENTRAL	300	4,399.6
EASTERN	200	4,769.8
WESTERN	100	3,822.4
NORTHERN	500	767.4
SOUTHERN	400	809.9

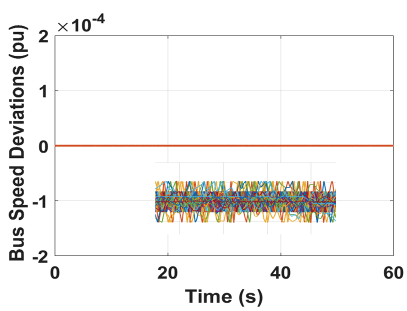

Fig. 3. The machine speed deviation of all machines.

1) Generator Trip Event: In the Central region in the city of Riyadh, a generator at bus 352 in PPT10 power plant station tripped. The generating capacity of the unit is 1,965 MW. Figure 4a shows the system frequency response 10 seconds after this gas turbine unit is tripped at the five operating regions representing the whole of Saudi Arabia: Central (RIYADH bus), Eastern (JUBAIL bus) Western (JEDDAH bus), Southern (ABHA bus), and Northern (NEOM bus). Since the RIYADH bus (354) is very close to the tripped machine bus, its frequency took slightly more time to damp out than the other two frequency responses. By comparison. The NEOM bus in the Northern region is very far from the tripped machine bus,

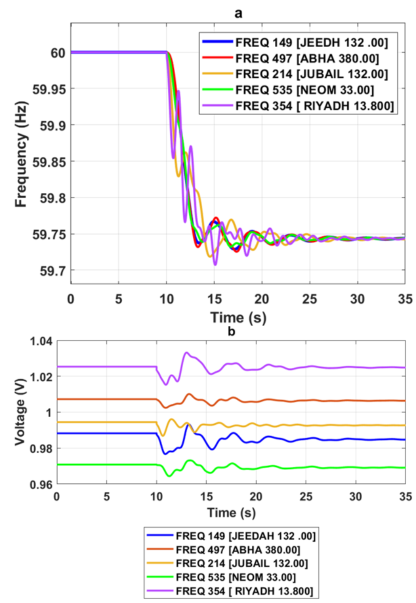

Fig. 4. System frequency and voltage response after generator trip at Bus 352 in the Central Region.

so its frequency wasn't affected much. In the same case, Figure 4b shows that the voltage magnitude at the RIYADH bus (354) fluctuated slightly between 1.0330 to 1.0153 per unit, with little effect across the other regions.

2) Load Shedding Events: Load shedding events involve the disconnection of loads at certain buses. After a duration of ten seconds, a load of 772 MW located at the MADINAH bus 106 inside the western operating region is intentionally reduced. Figure 5a illustrates the frequency responses of different buses. It can be observed that the frequency grew to reach 60.1146 Hz before it peaked and then dropped down after 30 seconds to 60.0958 Hz especially for the JEDDAH bus which is close to the event area. The voltage responses of the same buses after the load disconnection are shown in Figure 5b. The figure shows that the voltage at the JEDDAH bus fluctuated between 0.9808 and 0.9926 per unit, but the voltage responses of the other buses are not greatly affected.

3) Line Trip Event: The third scenario is to trip a transmission line between cities in different operating regions. After ten seconds, a transmission line between RIYADH bus 338 in the Central region and DAMMAM bus 293 in the Eastern region tripped. This transmission line carries 516 MW of power. Figures 6a and 6b showcase the simulation outcomes results for the frequency system and voltage magnitude responses, respectively. The reason is that this transmission line transmits a large quantity of MW. The frequency of RIYADH bus 354 and JUBAIL bus 214 reached oscillation between 59.985 and 60.033 Hz, while the other buses' responses outside the region were only affected slightly because they are out of region and there is no direct connection with those buses. The figure shows that the voltage at the JUBAIL bus dropped from 0.995 to 0.993 per unit, but the voltage responses of the other two buses are not greatly affected.

4) Model Validation Case: The standard approach for verifying a certain power flow scenario involves using the

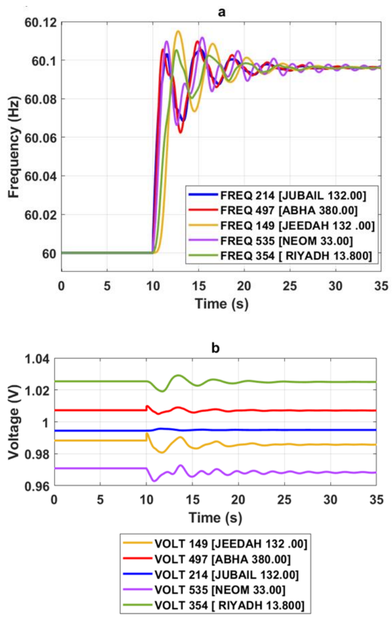

Fig. 5. System Frequency and Voltage Response After Load Disconnection at Bus 106 in the Western Region.

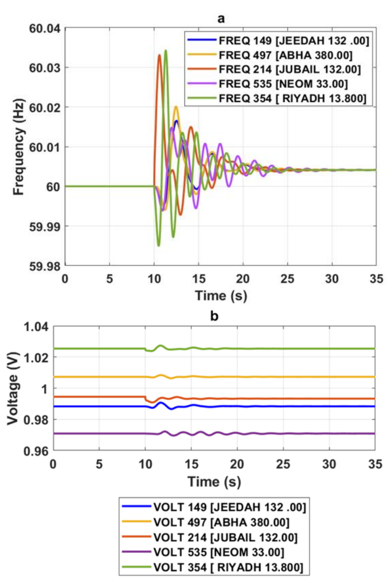

Fig. 6. Line trip between Bus 338 and Bus 293.

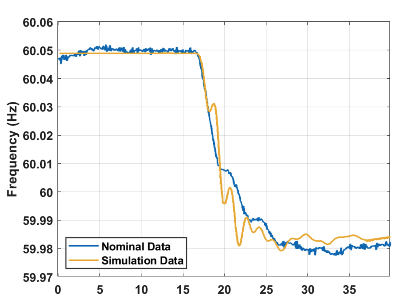

Fig. 7. Simulation and measurement comparison of cases.

scenario to replicate the prevailing system situations at a specific temporal instance (referred to as a snapshot) in the past [23]. This model was validated with a real frequency incident that occurred as shown in Figure 7, in which the blue line indicates the 333 MW generation trip event that happened at Central region, Unit 1, on 14:20:48 UTC, 2016-08-09. The initial frequency was 60.0456 Hz, while after the disturbance the frequency decreased to 59.982 Hz. The parameters of the model have been modified to accurately reflect the dynamic characteristics of the real Saudi power system. The yellow line in Figure 7 illustrates the dynamic behavior of the accepted model in relation to the synthetic Saudi power system.

IV. Conclusions and Future Works

This paper represents an initial step towards constructing synthetic grids for the Saudi electric grid that are geographically and statistically plausible. Despite being entirely fictional, the synthetic grid is based on real public domain data. The synthetic grid model is built and subjected to various disturbances at various parts of the system to verify the stability of this synthetic model. The results of simulations presented in this research provide empirical evidence validating the assertion that the system under investigation exhibits dynamic stability based on code requirements. Employing the CURENT LTB packages significantly simplifies power system prototyping and simulation on a large scale, guaranteeing that the synthetic grids accurately replicate the geographic constraints of real systems. Ultimately, the 224-bus synthetic Saudi electric grid case serves as a demonstration of the grid synthesis methodology's capabilities. It includes geographic coordinates, load and generation profiles, and the results of power flow solutions. Also, the synthetic Saudi grid presented in this paper greatly enhances the diversity of many synthetic grids in the current literature.

In future research, there is potential to extend this model to create test cases for various domains within power systems research and for educational purposes. In addition, future research may explore the integration of renewable energy sources, including Saudi Arabia's focus on wind power for its grid. It will assess reliability by computing indices for load interruptions after substituting conventional units, using actual data from both unit types, along with considerations for cybersecurity. Models will be developed to evaluate the resilience and reliability of the Saudi electric grid, especially in extreme events.

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References

[1] M. Larsson, "ObjectStab-an educational tool for power system stability studies," *IEEE Transactions on Power Systems*, vol. 19, no. 1, pp. 56–63, Feb. 2004, Conference Name: IEEE Transactions on Power Systems.

[2] F. Li, K. Tomsovic, and H. Cui, "A Large-Scale Testbed as a Virtual Power Grid: For Closed-Loop Controls in Research and Testing," *IEEE Power and Energy Magazine*, vol. 18, no. 2, pp. 60–68, Mar. 2020.

[3] H. Cui and F. Li, “ANDES: A Python-Based Cyber-Physical Power System Simulation Tool,” in *2018 North American Power Symposium (NAPS)*, Fargo, ND: IEEE, Sep. 2018, pp. 1–6.

[4] H. Cui, F. Li, and K. Tomsovic, “Hybrid Symbolic-Numeric Framework for Power System Modeling and Analysis,” en, *IEEE Transactions on Power Systems*, vol. 36, no. 2, pp. 1373–1384, Mar. 2021, Number: 2.

[5] N. Parsly, J. Wang, N. West, Q. Zhang, H. Cui, and F. Li, “DiME and AGVis: A Distributed Messaging Environment and Geographical Visualizer for Large-Scale Power System Simulation,” in *2023 North American Power Symposium (NAPS)*, Asheville, NC, USA: IEEE, Oct. 2023, pp. 1–5.

[6] A. B. Birchfield, “The Creation, Validation, and Application of Synthetic Power Grids,” en, Oct. 2018.

[7] A. B. Birchfield, T. Xu, K. M. Gegner, K. S. Shetye, and T. J. Overbye, “Grid Structural Characteristics as Validation Criteria for Synthetic Networks,” *IEEE Transactions on Power Systems*, vol. 32, no. 4, pp. 3258–3265, Jul. 2017, Conference Name: IEEE Transactions on Power Systems.

[8] Saudi Electricity Company, *Towards a Bright and Sustainable Future*, English, 2022.

[9] S. Alqahtani, A. Shaher, A. Garada, and L. Cipcigan, “Impact of the High Penetration of Renewable Energy Sources on the Frequency Stability of the Saudi Grid,” en, *Electronics*, vol. 12, no. 6, p. 1470, Mar. 2023.

[10] R. Kashyap, T. Meridji, M. Ahmed, *et al.*, “Selection of optimal transmission voltage level/technology for the Saudi Arabian transmission grid,” in *2017 Saudi Arabia Smart Grid (SASG)*, Dec. 2017, pp. 1–7.

[11] S. E. Company, *Saudi Arabian Grid Code*, en.

[12] W. Matar, “How would real-time electricity pricing affect the Saudi power sector in the long-run?” *The Electricity Journal*, vol. 34, no. 6, p. 106 977, Jul. 2021.

[13] Saudi Electricity Company, *10,000,000 Smart Meters*, English, 2020.

[14] *King Abdullah City for Atomic and Renewable Energy*.

[15] Saudi Electricity Company, *Thinking Globally... through The Accelerated Strategic Transformation Program (ASTP)*, English, 2014.

[16] Saudi Electricity Company, *Vision 2030*, English, 2021.

[17] A. S. Saidi, F. Alsharari, E. M. Ahmed, S. F. Al-Gahtani, S. M. Irshad, and S. Alalwani, “Investigating the Impact of Grid-Tied Photovoltaic System in the Aljouf Region, Saudi Arabia, Using Dynamic Reactive Power Control,” en, *Energies*, vol. 16, no. 5, p. 2368, Mar. 2023.

[18] A. S. Alsafran, “A Feasibility Study of Implementing IEEE 1547 and IEEE 2030 Standards for Microgrid in the Kingdom of Saudi Arabia,” en, *Energies*, vol. 16, no. 4, p. 1777, Jan. 2023, Number: 4 Publisher: Multidisciplinary Digital Publishing Institute.

[19] *General Authority for Statistics*.

[20] T. Xu, A. B. Birchfield, and T. J. Overbye, “Modeling, Tuning, and Validating System Dynamics in Synthetic Electric Grids,” *IEEE Transactions on Power Systems*, vol. 33, no. 6, pp. 6501–6509, Nov. 2018, Conference Name: IEEE Transactions on Power Systems.

[21] K. M. Gegner, A. B. Birchfield, T. Xu, K. S. Shetye, and T. J. Overbye, “A methodology for the creation of geographically realistic synthetic power flow models,” in *2016 IEEE Power and Energy Conference at Illinois (PECI)*, Feb. 2016, pp. 1–6.

[22] NERC, “Modeling Notification Model Usability and Accuracy Testing for MOD-026-1 and MOD-027-1,” Tech. Rep., Aug. 2019.

[23] NERC, “Procedures for Validation of Powerflow and Dynamics Cases,” Tech. Rep., 2011.