J. Electrical Systems 20-3 (2024): 2902-2919

[1] Abdelaziz Salah Saidi
[2] Lina Alhmoud
[3] Adel Ali Alqahtani
[4] Osama Ali Zemi
[5] Muhammad Umar Malike

Modeling, Integration, and Simulation of the 20 MW Photovoltaic Power Plant in the Saudi Arabia Distribution Network Considering LVRT Capability

Journal of Electrical Systems

Abstract: - The evolution of Saudi Arabia's electricity sector has accompanied distinct phases, culminating in a modern era marked by a solid commitment to renewable energy development, notably through the establishment of renewable energy power plants since 2010. Given the country's diverse topography, there's a keen interest in exploring renewable energy technologies, with a particular focus on solar energy. Saudi Arabia's strides in renewable energy could serve as a blueprint for other nations aiming to embrace clean energy transitions. This article explores the impact of high photovoltaic (PV) energy penetration on the transient stability and voltage regulation of Saudi Arabia's distribution power system. The study analyzes time response simulations to grid disturbances through modeling and simulation using PSSE and PSCAD-EMTDC software. Managing reactive power from solar power plants is crucial for seamless PV integration into power grids across varied operational scenarios. Various network faults, such as the disconnection of heavily loaded buses and three-phase short circuits at PV solar farms, are examined. The findings aim to pinpoint necessary protective measures and operational strategies for ensuring system stability and reliability, especially during transient events and grid fault recovery operations. Consequently, this study holds practical significance for utility planning and operation.

Keywords: Photovoltaic Power Penetration, Saudi Arabia Distribution Network, Transient Voltage Stability, Voltage Regulation, Saudi Grid Code.

I. INTRODUCTION

The electrical power grid has evolved globally. Centralized power generation facilities have been decommissioned and replaced by smaller distributed generators (DG). These new, smaller energy providers tend to disconnect during system disturbances and without the large generators acting as a backbone of the power grid. The two key drivers in the energy transition are (i) climate change, including global warming and large-scale shifts in weather patterns, and (ii) energy demand, including fast growth in population and energy consumption. Hence, government actions take place to reduce CO_2 emissions by shifting the energy mix and financial investments in green technologies [1]. Electrical utilities structure the company's strategies by investing in specific technologies and markets. Growth of wind and PV power generation and H_2 production, besides discontinuing conventional power plants and pushing the technologies enabling sustainable mobility. The consequences of the power system are:

- A frequent generation and load imbalance causes a variation in power generation and less control of power flow due to an increase in renewable energy sources (RES). A decrease in conventional power plants causes a reduction in the active power reserve. Thus, it is a challenge for the frequency stability of the network [1].
- Decrease in the reactive power reserve due to the less reactive power reserve available and a fast voltage response required to counteract voltage fluctuations. This is considered a challenge for voltage stability [2].
- Decrease in network inertia: less rotating mass in the grid, therefore more dynamic. The network becomes more sensitive to faults, which is a challenge for angular stability [3].
- The worsening of the power quality due to the increase in power electronic devices that generate harmonics and the increasing use of high-power switching devices that generate flickers. This is a challenge of power quality [4].

These challenges cause a decrease in the network strength, leading to instability and the drastic action of load

[1] Laboratoire des Systèmes Électriques, École Nationale d'Ingénieurs de Tunis, Université de Tunis El Manar, Tunis, Tunisie
[2] Department of Electrical Power Engineering. Yarmouk University, Irbid 21163, Jordan
[3] Saudi Electricity Company, Network Primary Distribution Department - South Operation Area, Saudi Arabia
[4] National Grid company, Project Management Office - Central Operation Area, Saudi Arabia
[5] Sr. Power systems Engineer of Power System Experts, Lahore, Pakistan

shedding. There are some counteractions to meet these challenges and enable energy transactions [5]:

(i) Using a synchronous condenser to provide the rotating mass for network inertia and reactive power [2].

(ii) Increasing the demand for peak shaving applications to provide fast power support during large transients [1].

(iii) Providing frequency containment reserve to maintain immediate active power support for the conventional plants [5].

(iv) Norms to connect to the grid by maintaining the minimum requirements for every piece of equipment connecting to the grid [5].

Hence, regulatory agencies have developed distribution codes. The vast penetration of RES and local generation has changed the system topologies with less centralized power plants. Hence, a series of rules and regulations that maintain the safe, reliable, cost-effective, and stable operation of components in the electrical network, including producers, end users, and grid operators. The codes may require some distributed sources to disconnect during disturbances in centralized power generation. Over that, they vary from region to region. On the other hand, the DG are not considered large generation supporters for system disturbances. These DG are required to stay connected for grid support.

The main trends in the distribution system are electrification, decentralization, and digitalization. Electrification of the end user can maintain the voltage level, avoid curtailment in their values, and support a decarbonized environment. Decentralization helps the deployment of distributed renewable energy. Thus, it turns the consumer into an active participant and fosters demand-side management. Digital technologies enhance management by connecting devices, collecting data, monitoring, and controlling. Distribution codes should be technically appropriate and evolved to fulfill distribution system needs [6]. It should enable expertise to control the grid's safety. These codes need to be tailored to the country's context, and they are considered a key to facilitating national power trade and ensuring competitiveness. In many situations, the imperfect distribution code is better than no code. Distribution codes may define how and when to connect or disconnect distribution resources. Also, these codes define the operational boundaries and establish methods to control active and reactive power to warrant grid monitoring. The automatic change of the active power setpoint concerning the frequency using the limited frequency sensitive mode method. On the other hand, the automatic change of the reactive power setpoint concerning the grid conditions using Low Voltage Ride-Through (LVRT) [7].

The current trends for distribution codes should evolve technical requirements for extending applications to smaller users to include controllability, communication interference, integration, and LVRT. Meanwhile, the requirements for the new users are storage and consumer-producer combinations and electric vehicle charging. The added requirement for the new technical capabilities is the inverters' high-voltage ride-through and grid-forming capabilities. RES enables power to be generated very close to where it is ultimately used. More research is needed to ensure the grid of tomorrow is safe, secure, reliable, and sustainable. To meet the demands of tomorrow. Hosting of technical, environmental policy, and security challenges enabling modernization grid through the design of an appropriate framework. The number of smart equipment connected to the grid grows daily. Thus, the communication between them and the grid operators with the right skills and tools, including cybersecurity. Creates a safe and controllable environment to ensure national security design for future grids. Thus, improving reliability and resilience to real-world grids is necessary [8].

Integrating distributed generation units into distribution systems has transformed the flow of real and reactive power, raising concerns about stability, especially regarding voltage and angle instability during faults [9]. Factors influencing stability in systems with DG units include control strategies [10], energy storage systems [11], load types [12], fault locations [2], and motor inertia constants [3]. The rise in the number of DG units connected to the grid is motivated by global initiatives targeting the reduction of greenhouse gas emissions and the preservation of fossil fuel resources, as well as economic developments and energy market deregulations [13]. DER units are categorized based on their capacity, with micro, small, medium, and large DERs serving different needs. The increase in renewable generation, particularly inverter-based DERs like wind turbines and photovoltaic (PV) systems, has introduced challenges such as inertia reduction, voltage rise, and reverse power flow [14]. However, DERs also offer potential benefits, including voltage support capabilities [15]. Key trends associated with DER integration include their predominance in medium- and low-voltage grids, their role as 'negative loads,' and the need to gradually assume ancillary services traditionally provided by conventional generators. DER units, often connected via electronic power inverters, behave differently from synchronous machine-based generators, with grid operation and stability implications [16].

This chapter is organized as follows: Section 2 presents the recent developments of distributed solar PV farms in the KSA. Section 3 explains the methodology. Then, the system description is introduced. Section 5 clarifies the distribution network code connected to KSA's variable renewable energy power plants. Then, the effects of high penetration of solar PV on the distribution system are discussed. Section 7 explains the simulation results and discussions. Finally, the conclusion is presented in Section 8.

II.RECENT DEVELOPMENTS OF DISTRIBUTED SOLAR PV FARMS IN THE KSA

The Kingdom of Saudi Arabia, one of the world's top oil producers, is going solar. The use of renewables reduces CO_2 emissions. Saudi Arabia generates a significant portion of its power by burning oil, a method that other nations have since most of Saudi Arabia's power plants and air conditioners utilized 70% of the kingdom's energy in 2013. The yearly increase in electricity consumption reduces the country's oil export volume and earnings. Many greenhouse emissions contribute to global warming and climate change; as to nuclear power plants, which generate trash and radioactive waste, clean energy emits no pollutants or emissions. A transition to clean energy and a shift away from fossil fuels, even the country with abundant oil and gas. Saudi Arabia will lower carbon emissions by more than 278 Mtpa (million tonnes per annum) by 2030. Renewables drive the shift towards net zero and set new standards in renewable energy. Additionally, Saudi Arabia leads the GCC region, as shown in Figure 1, closely trailed by the UAE; the UAE boasts 2.1 GW of installed photovoltaic (PV) capacity, with an additional 5.3 GW of active development or under construction set to be commissioned by 2025 [17].

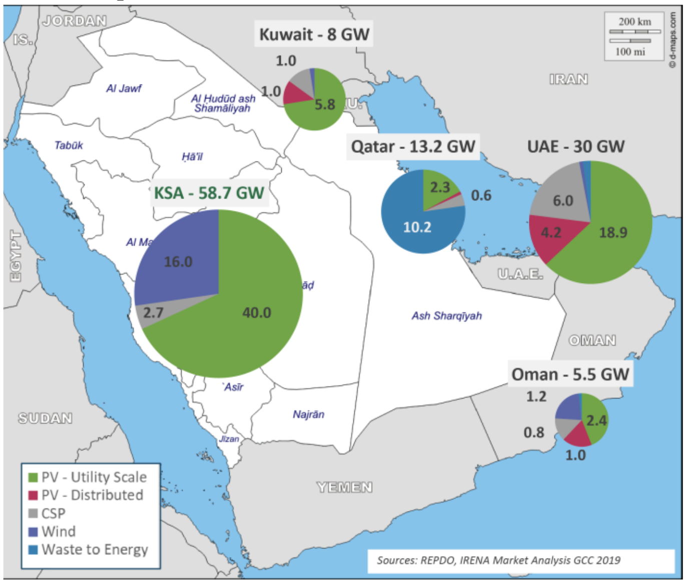

Figure 1. GCC 2030 Targets.

Saudia Arabia launched the clean energy strategy program with the ambitious goal of making the kingdom have the lowest carbon footprint on the planet by 2032. Saudi Arabia has set a new product goal of producing and installing 3.1 GW of clean energy sources, which is expected to increase demand [17]. The kingdom accelerates the development and localization of renewable energy technologies, with 50% of all electricity needs provided by solar power plants and 50% by other energy sources. The Red Sea projects are 100% powered by renewable energy. The abundance of sunshine and wind contributes to the kingdom's energy mix diversification during the day and perfect wind at night. The wind blows up in the Neon area of northwest Saudi Arabia, which helps reduce the number of batteries. The Saudia government established a public investment fund (PIF) to hit the goals of Vision 2030 towards helping Saudi green initiatives through doable projects. Saudi Arabia's Vision 2030 strategy aims to add 20 GW of renewables to the energy supply by 2030. This initiative opens the market to an unprecedented increase in private-sector and foreign investment. The government is vital in facilitating partnerships as investors seek new suppliers and emerging technologies to discover the business case for the future of Saudia Arabia's renewable sectors [18].

Projections suggest that the worldwide installed capacity of solar photovoltaics (PVs) will maintain its upward trajectory in the foreseeable future. By 2030, estimates indicate it could reach around 1630 GW, with the potential to surge up to 4500 GW by 2050 [19, 20], illustrated in Figure 1. Saudia Arabia invites bids for seven solar energy projects (Qurayyat, Shuaiba, Madinah, Rabigh, Sudayr, Rafha, and Jeddah) with a combined capacity of 3670

MW. It invited 60 prequalified companies to submit bids for seven solar energy projects. The Sakaka solar project (300 MW) and the Domat Al Jandal wind project (405 MW) can produce enough energy to power over 100,000 homes, offsetting one million tons of CO_2 emissions annually and displacing over 1.2 million barrels of oil equivalent annually. Over that, the development of these two projects generates a capital investment of $800 million, contributing approximately $240 million to the national GDP and creating over 2000 new jobs [21].

In 2018, Saudi Arabia's Renewable Energy Project Development Office (REPDO) invited bids for the construction of a 300 MW solar PV plant in "Sakaka" and a 400 MW wind power plant in "Dumat Al-Jandal" [22]. Following that, in 2019, a set of eleven solar PV projects and one wind energy project, which were in the pre-development stage, were presented and put out for tender. These initiatives represent a combined capacity of 3.075 GW, as illustrated in Figure 2.

The energy, industry, and mineral resources ministry expects to attract 3.4 billion SAR of private sector investment. The government has ambitions to run a sustainable renewable energy sector to cover domestic energy needs. The Saudi project provides a vast new market for solar panel manufacturers; by 2025, enhancing Saudi Arabia's energy efficiency program (SEEP) 2030 will meet 50% of domestic energy needs with renewables. The idea is that Saudi Arabia can power its domestic energy needs through solar power, which leaves oil for export, creating significant employment opportunities and promoting economic diversification. The location of Saudi Arabia makes it simpler to transfer power to Europe and the Middle East. Furthermore, they are accelerating the kingdom's energy transition towards becoming the world's leading hydrogen producer and exporter, with the ambition of transitioning to 2030 and beyond, expanding its role among the world leaders in renewable energy [23].

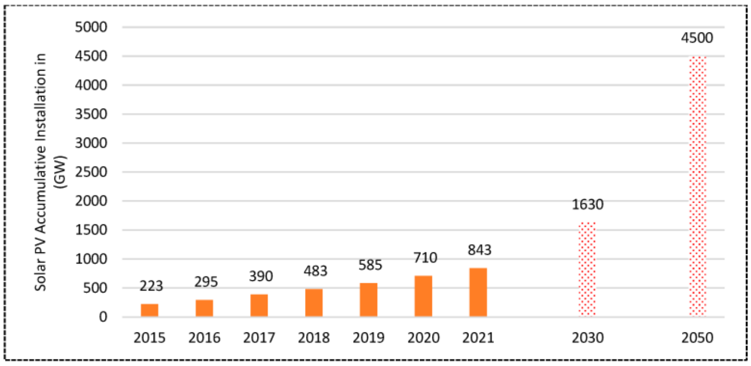

Figure 2. Solar PV accumulative installation projection till 2030 and 2050.

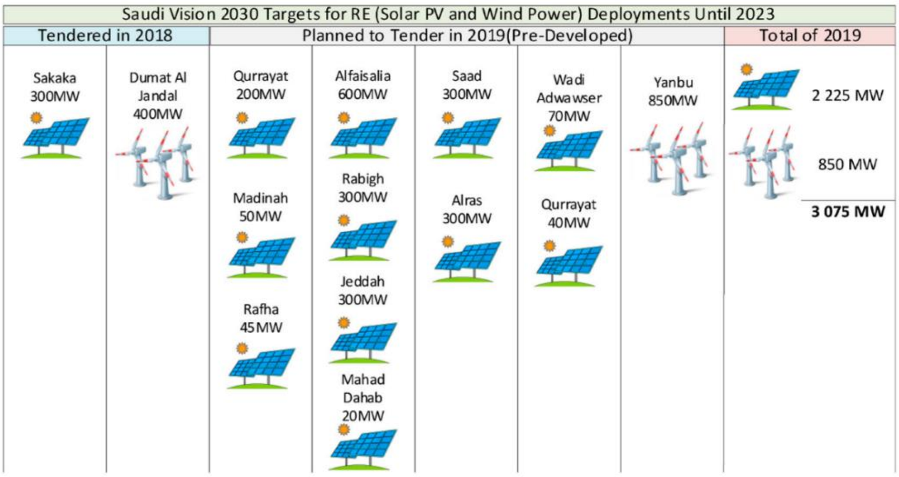

Figure 3. Saudi Vision 2030 targets RE (solar PV and wind power) deployment.

III. METHODOLOGY

The methodology for this conducted work is divided into two main sections: network data description and the strategies used. The network data include bus information, solar irradiations, line information, transformer ratings, etc. The static analysis and dynamic analysis of power flow analysis are strategies evaluation. PSCAD/EMTDC version 2023 [25] investigated the transient stability time domain simulations under different scenarios. Figure 4 clarifies the framework of the proposed study for the system mentioned in the following section.

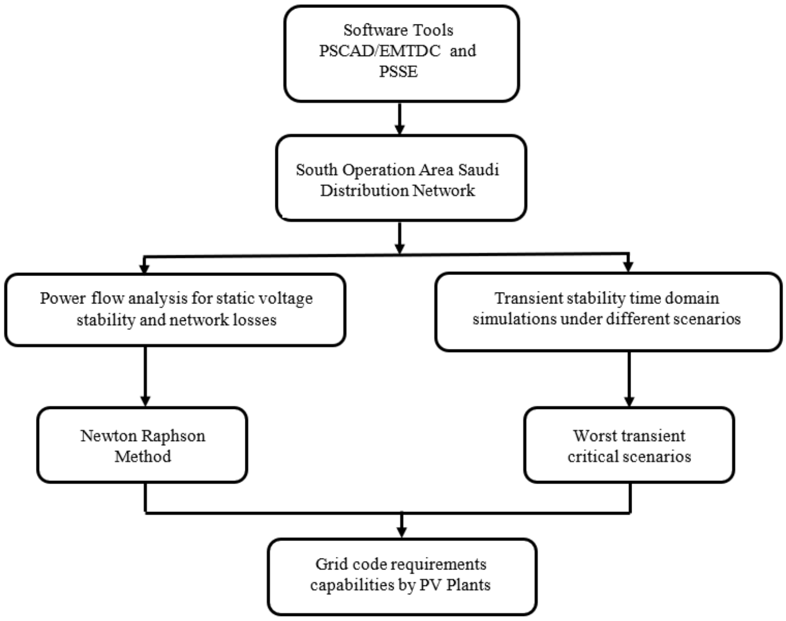

Figure 4. The framework of the study.

IV. SYSTEM DESCRIPTION

Figure 5 shows the map for the system under study location. The single-line diagram of the proposed 20 MW solar power plant distribution grid has been shown in Figure 6-a. The network includes 22 MV bus bars. A 20 MW PV power plant model has been constructed and linked to the power grid at bus 1 to supply the distribution network inside it as shown in Figure 6-b. This plant comprises 10 sets of PV arrays, each rated at 2 MWp. These arrays are connected to the grid using a three-phase inverter and a step-up transformer. The modular inverter, consisting of multiple parallel units, has a rating of 2 MW. Each transformer has a power capacity of 2 MVA, with a rated frequency of 60 Hz and a voltage ratio of 0.4/22 kV. Simulations utilizing PSCAD software are conducted to acquire the active and reactive power outputs supplied to the grid and the voltage at each point for the ten integrated generators [26-27]. Table 1 displays the V_{dc} and current controller values [28], while Table 2 presents the PV array parameters [29], including a fill factor of 0.73, representing solar PV panel efficiency.

Table 1. Parameters of the controller

Parameter	**Value**
Nominal power P_{nom}	2 MW
Nominal frequency	50 Hz
Initial DC voltage	700 V
Nominal DC voltage U_{dc}	700 V
Rated power P_{nom}	20 MW
V_{dc} regulator gains K_p and K_i	7 and 800
Current regulator gains K_p and K_i	0.3 and 20
Choke impedance	1 mΩ, 250 μH
Transformer leakage impedance $R_x f_o$, L_{xf} / P_{nom}	0.002, 0.06

Table 2. PV array parameters

Parameter	**Value**
Open circuit voltage V_{oc}	64 V
Short-circuit current I_{sc}	5.87 A
MPPT voltage V_{mp}	54.7 V
MPPT current I_{mp}	5.49 A
Number of parallel modules N_p	445
Number of series modules N_s	15

Figure 5. Location of the system under study (adopted from Google Maps, 2023).

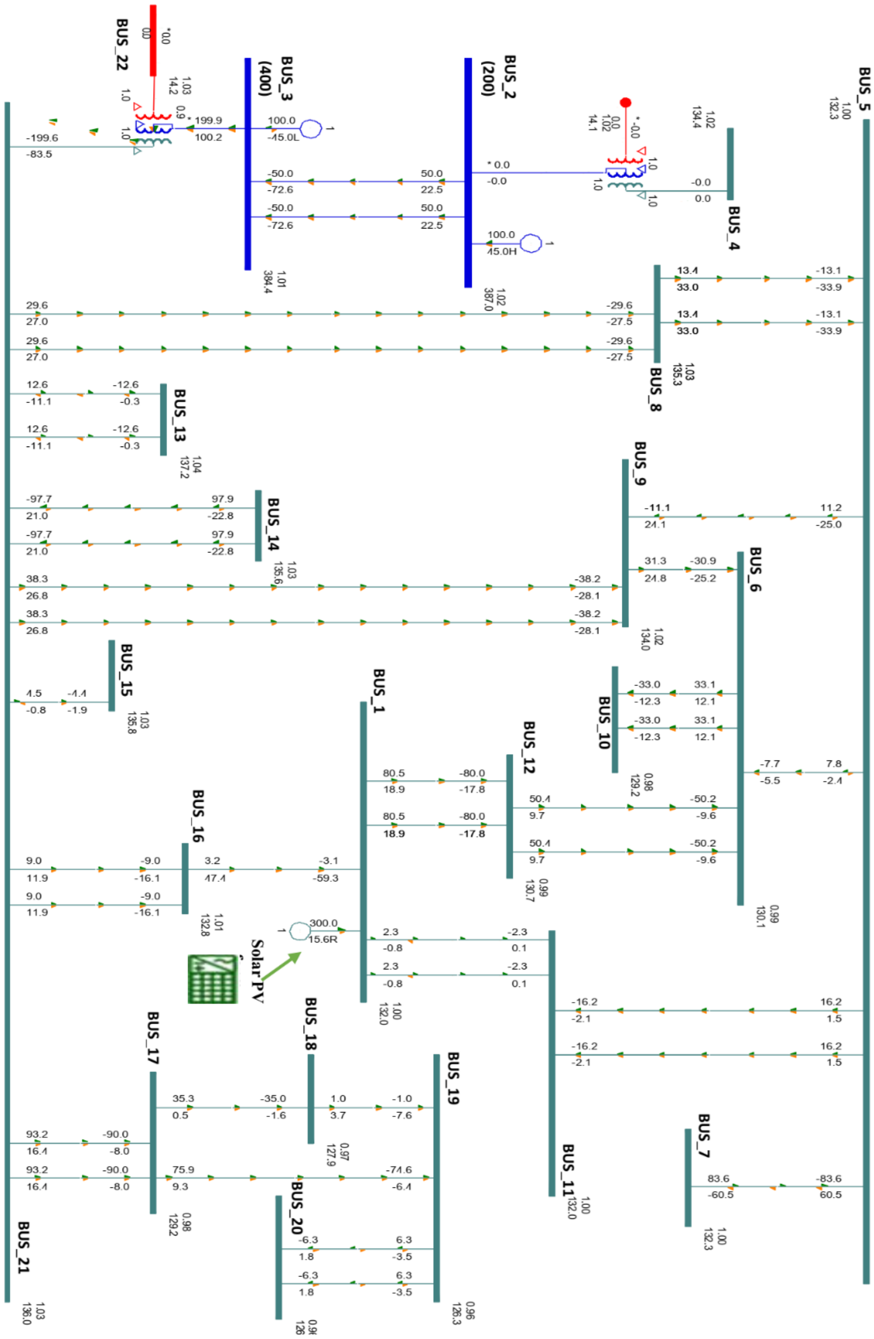

Figure 6-a. Saudi Arabia distribution network under study with 20 MW solar PV integration.

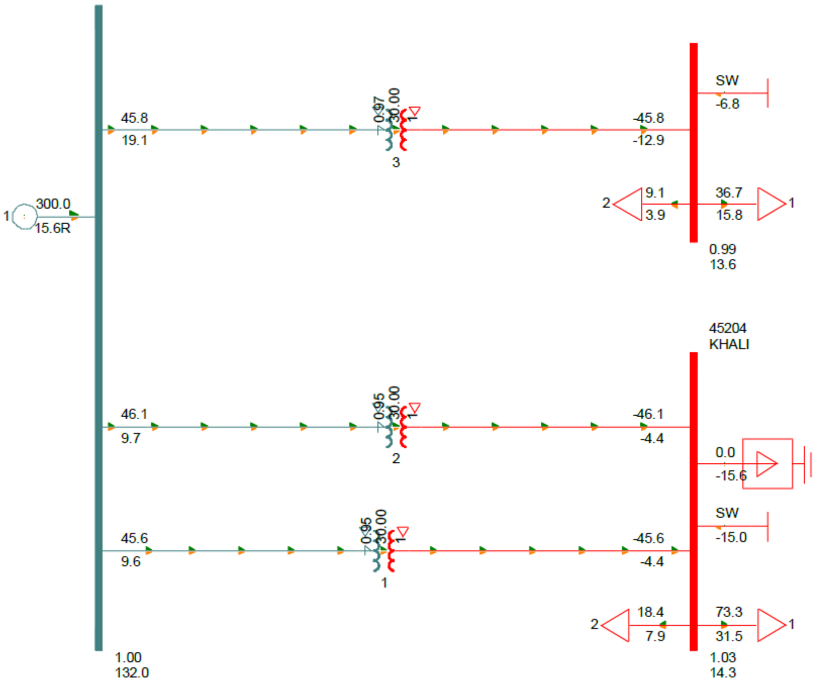

Figure 6-b. Saudi Arabia distribution network under study with 20 MW solar PV integration.

V. Distribution network code connected variable renewable energy power plants in KSA.

Nowadays, the grid is incredibly costly, while energy is getting cheaper. However, network companies can use RES to reduce costs. Hence, the penetration of RES in transmission networks is growing. The main challenges of high penetration of RES are the low inertia, lack of visibility of operation to power system operators, lack of central control, and environmentally dependent power output. Hence, the Grid Code serves as a technical blueprint outlining the essential criteria a facility connected to a public electric grid must adhere to ensure the electric system's safe, secure, and economically efficient functioning [30]. Typically, this code articulates the required behavior of connected RES during system disturbances, emphasizing the need for hourly evaluations. Here, a vital requirement for stringent regulations emerges from grid operators, encompassing both transmission system operators (TSO) and distribution system operators (DSO). These regulations, encapsulated in grid codes, delineate the criteria for the electric system's steady and transient states. Static and dynamic power flow influence the grid code's fault ride-through (FRT) specifications and voltage control. Integrating variable RES introduces uncertainties and technical complexities into grid operations. Key facets of this integration involve steady-state analysis, short-circuit analysis, dynamic and transient stability, adherence to grid integration standards, and meeting the specified requirements for compliance with the grid [31]. As a result, the grid serves the market. The market is transforming, and the grid needs to change, too. The grid can be described as (i) reverse demand: the grid was designed for electricity to flow from the generator to the consumer. Thus, the traffic becomes two-way. (ii) unpredictability: the voltage levels can fluctuate widely due to distributed energy resources impacting the expected voltage profile. Network companies need help with unpredictability and reversing demand. (iii) local network challenges: creating situations where network capacity can be exceeded [32].

A. Voltage range of operation

Table 3. The standard service voltage on LV.

Nominal voltage	Lowest voltage	Highest voltage
220 / 127 V	209 /120 V	231/134 V
380 / 220 V	360 / 209 V	400 / 231 V
400 / 230 V	380 /218.5 V	420 / 241.5 V
13.8 kV	13.1 kV	14.5 kV
33 kV	31.4 kV	34.7 kV
69 kV	65.5 kV	72.5 kV

Note from Table 3 that:

- For all these values, e.g., 220/127 V, the lower value refers to the phase to the neutral voltage, and the higher value refers to the phase-to-phase voltage.
- These values are based on steady-state and normal system conditions. The nominal voltage ±5% to allow for normal load variation.
- The old system 220/127 V will be replaced with the new system 400/230 V on ongoing installations. The replacement will be completed within 25 years per the Council of Ministers NO. 324 dated 20/9/1430.
- The generating units may be tripped to protect the plant.

B. Harmonics

According to the distribution code, Table 4 shows the total harmonic distortion (%), and Tables 5-7 show individual harmonic planning level limits [32].

Table 4. The THD (%) of voltage at fundamental frequency [32]

Nominal Voltage	**Total Harmonic Distortion (%)**
230 – 400 V	5.0
127- 220 V	5.0
11 kV & 13.8 kV	4.0
33 kV- 69 kV	3.0

Table 5. The maximum continuous individual HD planning levels are expressed in (%) of voltage at the fundamental frequency at voltage up to 1 kV [32].

Odd harmonics (Non-multiple of 3)		Odd harmonics (Multiple of 3)		Even harmonics	
Order \`h\`	Harmonic voltage (%)	Order \`h\`	Harmonic voltage (%)	Order \`h\`	Harmonic Voltage (%)
5	7.4	3	5.0	2	1.5
7	5.5	9	1.5	4	0.9
11	3.5	15	0.4	6	0.7
13	3.0	21	0.3	8	0.6
17	2.3	>21	0.2	10	0.5
19	2.0				
23	1.7				
25	1.5				
>25	(38.5/h-0.27)				

Table 6. The maximum continuous individual HD planning levels are expressed in (%) of voltage at the fundamental frequency at 1 kV ≤ V ≤ 35 kV [32].

Odd harmonics (Non-multiple of 3)		Odd harmonics (Multiple of 3)		Even harmonics	
Order \`h\`	Harmonic voltage (%)	Order \`h\`	Harmonic voltage (%)	Order \`h\`	Harmonic Voltage (%)
5	7.4	3	5.0	2	1.5
7	5.5	9	1.5	4	0.9
11	3.5	15	0.4	6	0.7
13	3.0	21	0.3	8	0.6
17	2.3	>21	0.2	10	0.5
19	1.5			12	0.4
23	1.2			14	0.4
25	1.1			16	0.3
>25	(32.3/h)-0.2			>16	(2.5/h)+0.22

Table 7. The maximum continuous individual HD planning levels are expressed in (%) of voltage at the fundamental frequency at 35 kV ≤ V ≤ 69kV [32].

Odd harmonics (Non-multiple of 3)		Odd harmonics (Multiple of 3)		Even harmonics	
Order \`h\`	Harmonic voltage (%)	Order \`h\`	Harmonic voltage (%)	Order \`h\`	Harmonic Voltage (%)
5	4.1	3	2.0	2	1.1
7	2.9	9	1.0	4	0.6
11	1.9	15	0.3	6	0.5
13	1.6	21	0.2	8	0.4
17	1.2	>21	0.2	10	0.4
19	1.1			12	0.3
23	0.9			14	0.3
25	0.8			16	0.3
>25	20.4/h			>16	1.9/h+0.16

C. Phase unbalance

Under steady state and normal operation conditions, and at HV, the three-phase voltage should be balanced, and the negative voltage sequence should be within 1% of the positive voltage phase sequence [32].

D. Power factor (pf)

a) The pf ≥ 0.85 lagging at the point of common coupling.
b) A connection agreement between the user and the distribution service provider (DSP) when the pf is leading.
c) Users should approve their demand pf range is within (0.9 lagging ≤ pf ≤ 0.95 lagging), whereas for users with generation and demand pf, their pf and reactive power should be within the range allowed in the connection agreement with DSP.

E. Users with demand and generating units [32]

- Users with demand units should comply with distribution code requirements relating to their load equipment. In addition, users with generation units should adhere to the distribution code requirements based on generation registered capacity.
- Vehicle charging is managed as a demand and within a limit in the connection agreement.
- Vehicle charging is managed as a controllable demand and within a limit in the connection agreement by the DSP. Here, it is treated as energy storage.
- Energy storage is counted as a demand when energy is imported from the supply, and it is counted as a generating unit when power is exported to the load. The DSP should monitor whether the distribution code's transient voltage is within limits [32].

F. Power producers

In the distribution code, the DSP defined its users as demand customers, power producers, licensed retailers, and licensed traders. The generation units are classified into synchronous generation units and asynchronous generating units. These generating units should comply with the Saudi Arabia Grid Code (SAGC) [32].

G. Frequency [32]

- The generating units ≥ 2 MW must continue supply power with a 58.8 Hz ≤ f ≤ 60.5 Hz as in the connection agreement.
- The generating units ≥ 2 MW must maintain supply power with no reduction in output with a 59.5 Hz ≤ f ≤ 60.5 Hz as in the connection agreement.
- The generating units ≥ 2 MW can supply power with a reduction power output not more than pro-rata with a 57 Hz ≤ f ≤ 59.5 Hz as in the connection agreement.
- In renewable energy resources, the power output should be stated in the power curve in the connection agreement. Still, the generating unit should be disconnected if the frequency is below 57.0 Hz.
- The frequency change rate is allowed up to 1 Hz/s without disconnection from the network.

- The reconnection of synchronous generating units should be within the system frequency 58.8 Hz ≤ f ≤ 60.05 Hz, and the 95 % ≤ V (PCC) ≤ 105 % of nominal voltage for a 60 s.
- At synchronization, the transient voltage should not exceed 4%.

H. Active power control [32]

- The generating units ≥ 200 kVA should be capable of operation in the frequency-sensitive mode.
- The active power output of the generating units ≤ 2 MW should vary proportionally to the voltage range of operation (point 2.1). In addition, ± 10% of nominal voltage for up to 30 minutes, and the frequency should be maintained within 57.0 Hz ≤ f ≤ 60.5 Hz (see Figure 7).
- The active power output of the generating units ≥ 2 MW should not be affected by the voltage range of operation (point 2.1). In addition, ± 10% of nominal voltage for up to 30 minutes, and the frequency should be maintained within 59.5 Hz ≤ f ≤ 60.5 Hz.

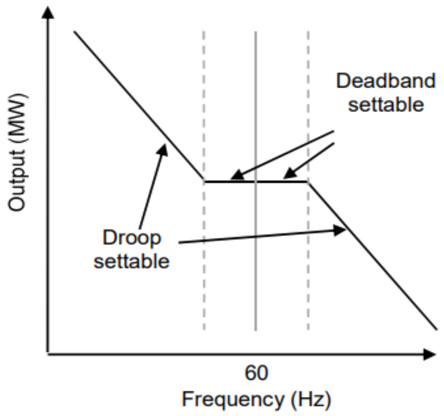

Figure 7. Governor function for synchronous and asynchronous generating units.

I. Reactive power performance and control

- Generator units ≤ 2 MW can control pf to prespecified value with an agreement with DSP.
- The reactive power of the generating units that are operated at their full load should lie within + .95 p.u (absorbing) ≤ Q ≤ - 0.95 p.u (delivering) at the PCC.
- A voltage regulator in the generating units can automatically adjust the reactive power output to maintain constant terminal voltage to operate within the stability limit and equipment rating set in the DSP agreement [32].

J. Low Voltage Ride Through

- FRT does not apply to the generating units ≤ 200 kW.
- FRT capability for generating units 200 kW ≤ P ≤ 2 MW should be withstanding faults (see Figure 7) at 0.7 p.u ≤ V PCC ≤ 0.8 p.u.

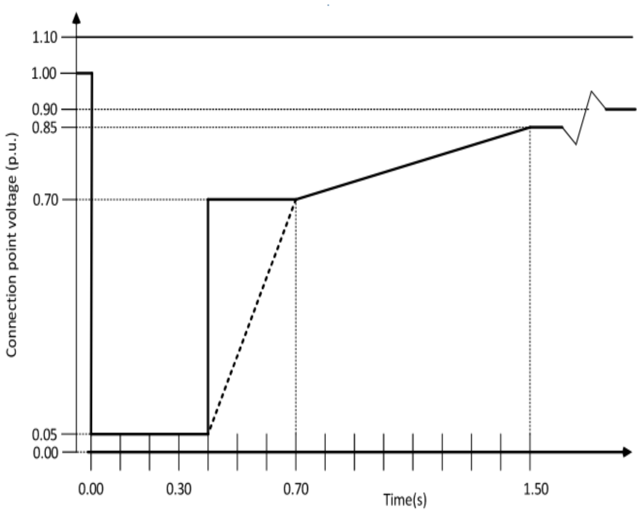

Figure 8. Fault ride-through requirements for synchronous and asynchronous generating units.

K. Short circuit contribution

The limit of short circuit fault current fault is set down in [32]

- Schedule 1: performance of all synchronous generating units.
- Schedule 2: performance of all asynchronous generating units.

VI. Effects of high penetration of solar PV on the distribution system

Solar PV should be operated at safe penetration levels. Thus, increasing solar PV penetration has pros and cons for power systems. These effects are not significant for the lower penetration levels. The penetration limit restriction is based on reliable integration and the technical ability of the grid [33]. At present, there is no ideal regulation for determining penetration limits. The limit depends on electrical load, consumer behavior, and climate change. It varies from region to region and can be determined using simulation software. The effect of high solar PV farms' penetration on power system:

1. Replacing large-scale generation units can limit reactive power availability because most PV systems only provide active power. Hence, poor pf.
2. Reducing inertia within the system can cause rotor angle stability problems and lead to potential transient stability issues.
3. Variations of bus voltage. The power system tends to have more significant oscillations during post-fault.
4. Increase harmonics.
5. Increasing voltage dips during the transient.
6. Voltage fluctuation increased. Hence, modern PV inverters have LVRT capability to improve transient stability.
7. Concerning protection issues affecting short circuit levels, reverse power flow, and islanding.

- In high penetration and during a fault, the PV system continued to inject current into the feeder until islanding conditions were detected and the breaker was open. Otherwise, further damage to the power system causes damage to conductors and transformers.
- The protection schemes are designed according to the unidirectional power flow in the radial distribution system. RES connection can cause alternating in the coordination of the relays due to a reverse in power.
- The PV continues to supply local loads during and after faults. Thus, the protection relays should be able to island. Otherwise, the inverters may remain online and severely threaten equipment and services.

The penetration of intrinsic intermittent at ultra-high solar PV systems can be overcome economically with optimized technology portfolios, including optimized wind /PV blend storage. Thus, large-scale interconnection is cheap but not indispensable. Integrating subregions is slightly more expensive but provides resilience benefits and is easier to implement.

In transient stability, the fault type and location reduce the voltage on all buses, and the generator terminal is sensed by AVR, which helps to restore the voltage. Here, a high-speed excitation system, reduction in transfer reactance, or a high-speed reclosing breaker can remedy the situation using AVR during fault.

VII. Simulation results and discussions

This section considers two scenarios for a Saudi electricity distribution network. A real case study is built to check the behavior of the 22-buses reduced network, both with and without a PV farm. The distribution grid is implemented and simulated based on dynamic analysis. The performance is checked to compare before and after the newly interconnected 20 MW solar PV farm. It is installed at the most loaded distribution bus of the network at the 33 kV level. The two scenarios on the reduced networks are carried out as follows:

1. The disconnection of the most significant load– without and with a newly connected solar PV farm.
2. Fault at interconnector – without and with a newly connected solar PV farm.

Here, the results of these two scenarios are presented:

A. Disconnection of the most significant load– without and with the connected solar PV farm

A proper selection of bus 6, which is the most loaded bus and operates at 13.8 kV, as the faulted bus due to its consistently weak static voltage. At t=1 sec, the load bus is disconnected for a duration of 200 ms. Active and reactive power flow of the distribution substation 33 kV under the fault condition is monitored, and results have been reported. In Figure 9, a slight dip is observed in the active power flow of 33 kV substations, but as the fault is clear, it is observed an increase in the active power level, and after some ms, the active power consumption is stabilized without oscillations. Figure 10 shows the reactive power flow recovery at a 33 kV network. On the one hand, a spike is depicted in some buses and a dip in others due to the nature and type of the loads connected to the distribution grid. After clearing the fault, the transient in the reactive power load was damped out, and the system returned to its typical operation.

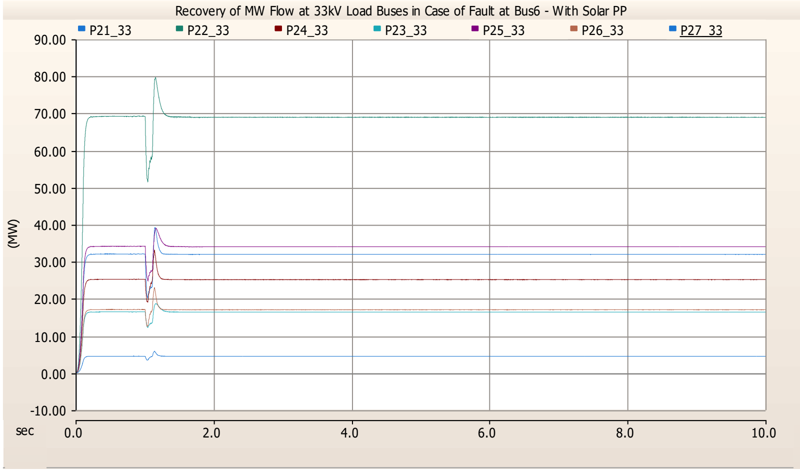

Figure 9. Active power recovery at 33 kV load buses with solar PV farm (MW).

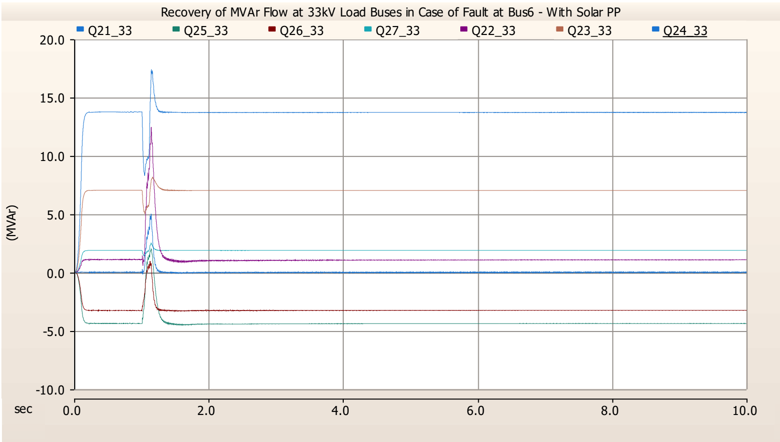

Figure 10. Reactive power recovery at 33 kV load buses with solar PV farm (MVAr).

Figure 11 shows the recovery of load bus voltages. Under fault conditions, and at 1 sec, the voltage dip occurs, which went up to 0.7 p.u for 0.2 sec. As the fault is cleared, voltages are stabilized within ±10% of the permissible range without oscillations.

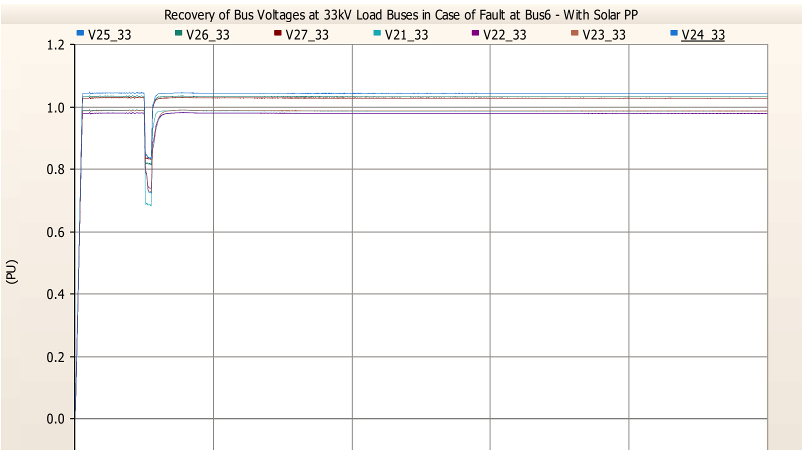

Figure 11. Recovery of 33 kV load bus voltage with solar PV farm (p.u).

Figures 12, 13, and 14 show the recovery of active and reactive power consumption and voltage at 13.8 kV load busses under the disconnection of the most loaded bus. The fault is applied at t=1 sec for 200 ms. There is a significant drop in the active power loads, particularly at the most loaded bus. The active power network has a strong transient process with fast recovery of terminal active power during and after the fault clearance. Figure 13 shows the recovery of reactive power load at 13.8 kV level. It is observed that 41 MVAr for the reactive power consumption at the loaded bus is just during the transient of the short circuit fault, which has been damped out, and the system returned to its typical operation. There is a slight increase in the reactive power level after clearing the fault in other buses. Figure 14 shows the recovery of load bus voltages, where the characteristic of the dip differs from bus to bus according to its type, class, and load type. Due to the disconnection of the most loaded bus, a dramatic voltage value of 0 p.u was recorded at the most loaded bus and the solar PV bus. These variations caused an overall voltage drop in the overall voltage grid, dropping between 0.1 p.u. and 0.82 p.u., as shown in Figure 14. As the fault is cleared, voltages are stabilized within ±10% permissible range and above 1.0 p.u with no oscillations. Based on the distribution code, when the terminal voltage drops to 0V, the solar PV system must remain connected to the grid for 200 ms. Concurrently, the PV system should inject the necessary reactive current to recover the grid voltage. This simulation scenario validates the efficacy of the proposed control strategy by the Saudi regulation code.

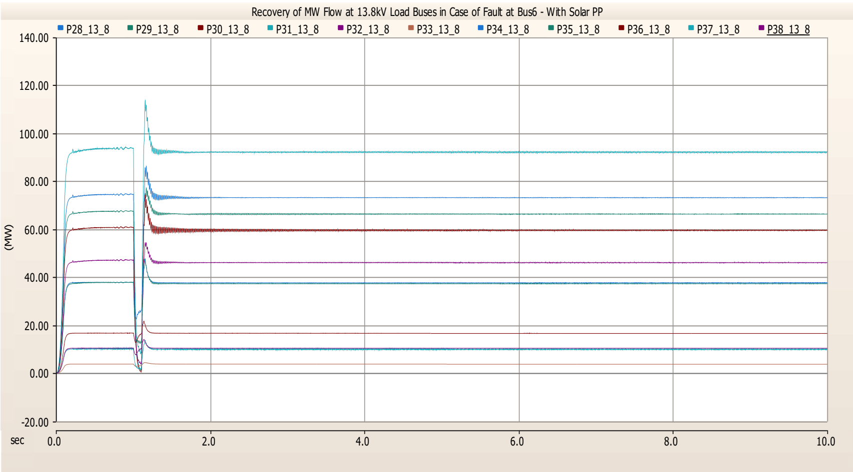

Figure 12. Active power recovery at 13.8 kV load buses with solar PV farm (MW).

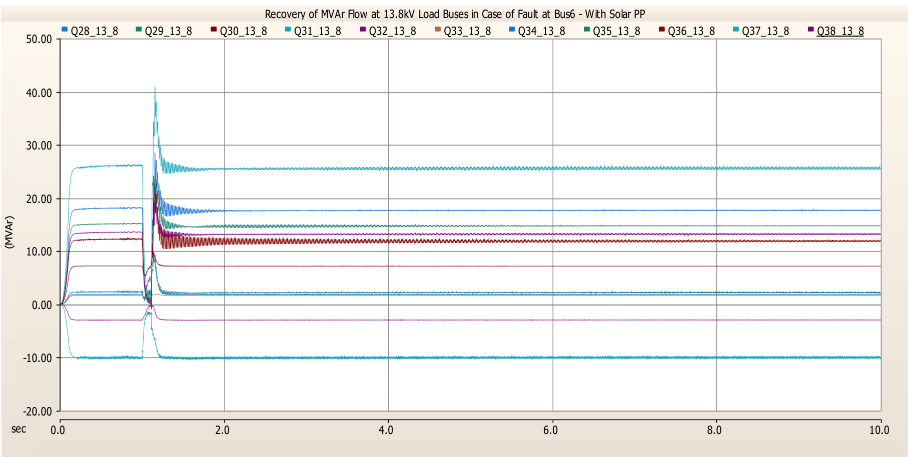

Figure 13. Reactive power recovery at 13.8 kV load buses with solar PV farm (MVAr).

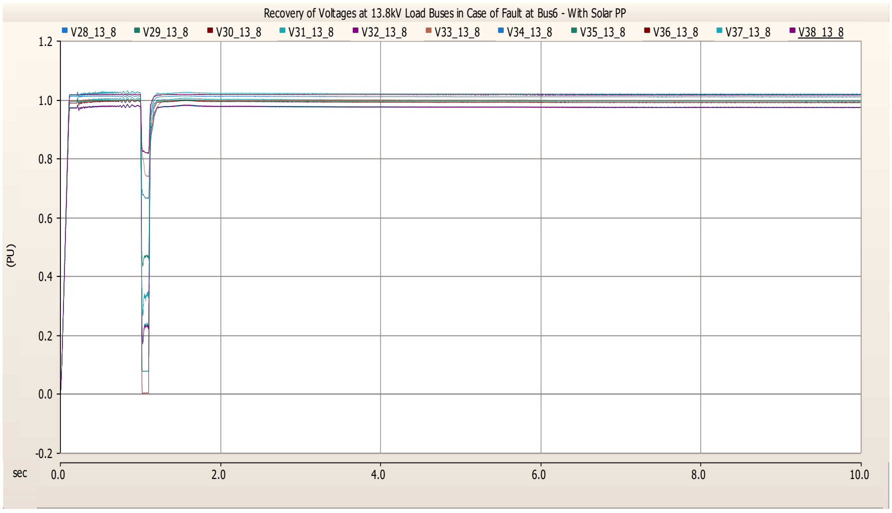

Figure 14. Recovery of 13.8 kV load bus voltage with solar PV farm (p.u).

B. Fault at interconnector – without and with a newly connected solar PV farm

In this scenario, simulations were carried out for a three-phase short-circuit at PCC connecting solar PV point at t=1sec to illustrate the solar PV farm operation. The equivalent PV generator produces 20 MW in normal operating conditions. At this operating condition, the PV generator delivers active power only when the reactive power equals zero (cosϕ = 1). In the simulation model, a three-phase short-circuit at the PV bus is simulated and removed after 200 ms. The simulation will analyze the behavior of the system under three lines to ground fault conditions, in which changes in voltage and power profiles, fault currents, and system stability have been tested. The results help demonstrate the protective devices and strategies needed to be maintained for the stability and reliability of the system. The active, reactive power, and voltage figures are plotted before and after the time of the fault, respectively, in two cases without and with solar PV farms.

In Figures 15 and 16, no active power is consumed throughout the fault period in both cases, but the recovery of the active power is depicted with a transient peak in the case with the PV farm due to the integration of the solar PV farm to the grid reaching 120 MW.

Subsequently, the transient was swiftly resolved within a brief duration. Figures 17 and 18 illustrate the reactive power load at the 13.8 kV side, revealing notable declines in the overall network's reactive power profile. A substantial drop of approximately 100% in reactive power was observed in scenarios where no solar power injection occurs. The pronounced peak in reactive power (41 MVar) from the inverter current poses a risk of damaging the inverter power semiconductor devices unless they are adequately sized to withstand grid faults. To prevent this undesirable outcome, adjustments must be made to the control of the VSI to ensure better performance during grid faults.

In terms of transient stability analysis under this condition, the voltage near the fault location decreased nearly to zero, particularly at the bus with the highest load. During the fault period (1-1.2 sec), when PV power injection was enabled, the solar PV farm consistently supplied the grid with enough reactive and active power, aiding in voltage recovery throughout the interval. As the voltage sag dissipates and due to the control strategy employed, all parameters revert to their pre-fault values, and voltage stabilization is achieved without oscillations as the PV bus transitions into a voltage regulation mode.

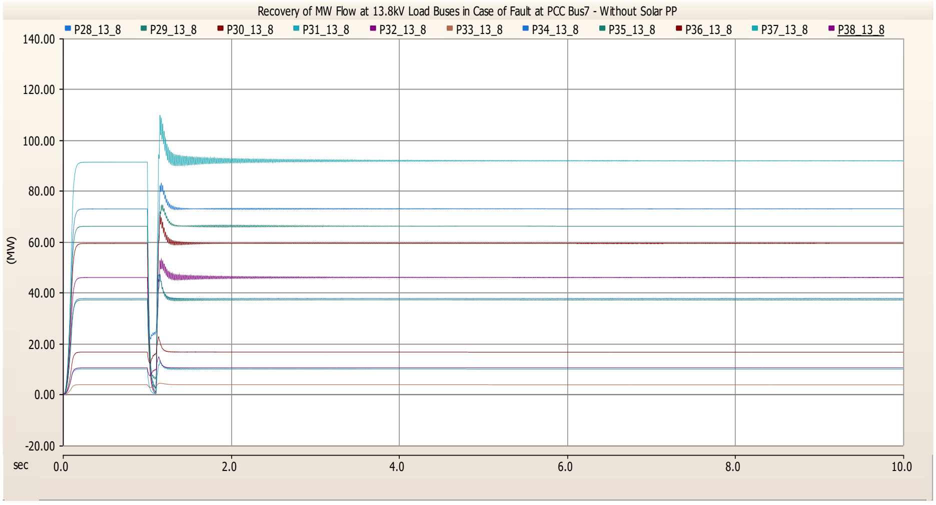

Figure 15. Active power recovery at 13.8 kV load buses without solar PV farm (MW).

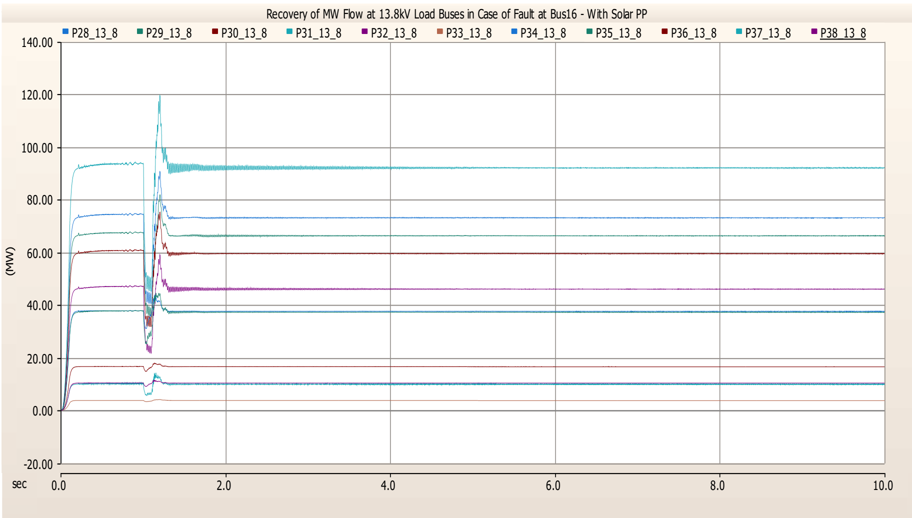

Figure 16. Active power recovery at 13.8 kV load buses with solar PV farm (MW).

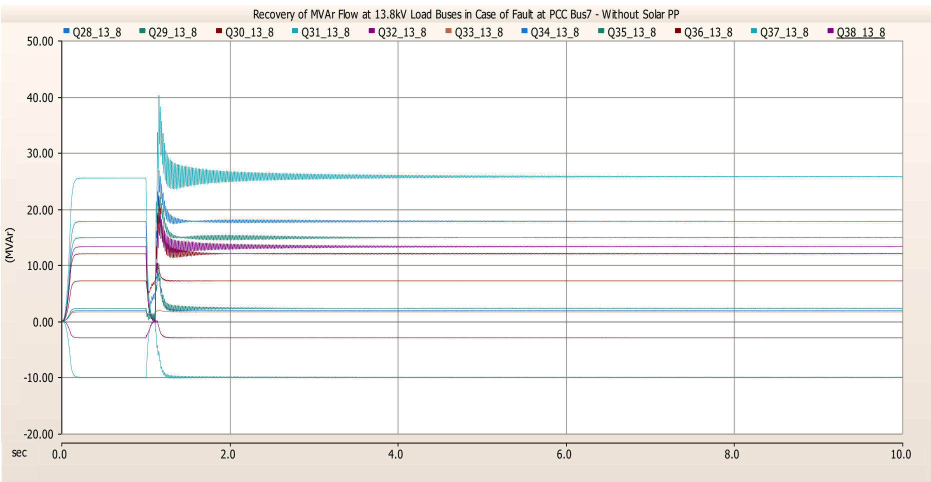

Figure 17. Reactive power recovery at 13.8 kV load buses without solar PV farm (MVAr).

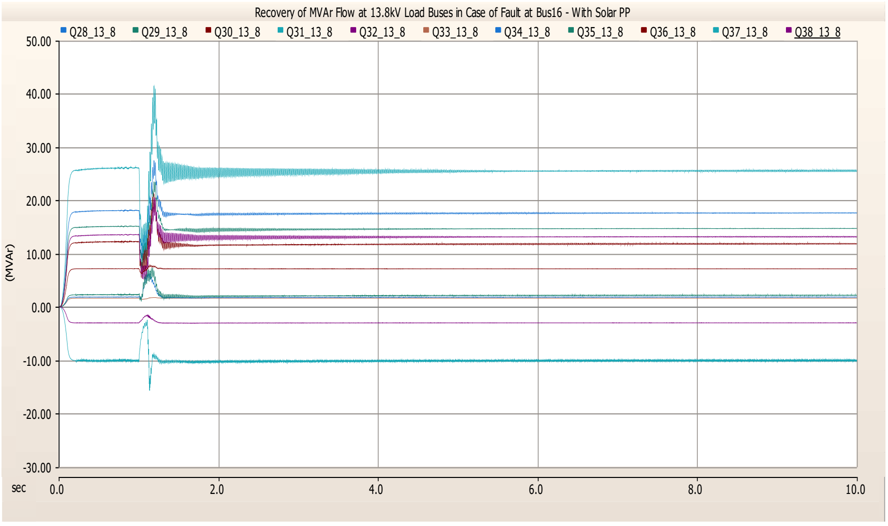

Figure 18. Reactive power recovery at 13.8 kV load buses with solar PV farm (MVAr).

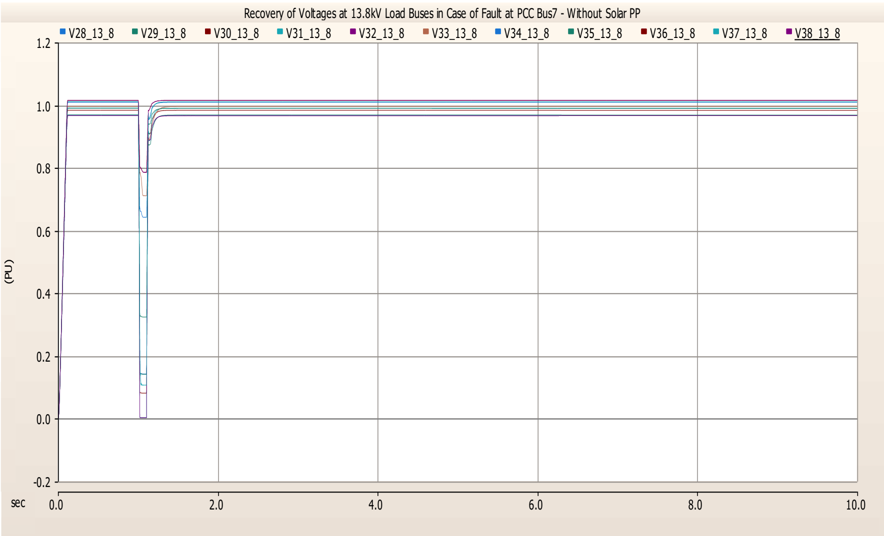

Figure 19. Recovery of 13.8 kV load buses voltage without solar PV farm (p.u).

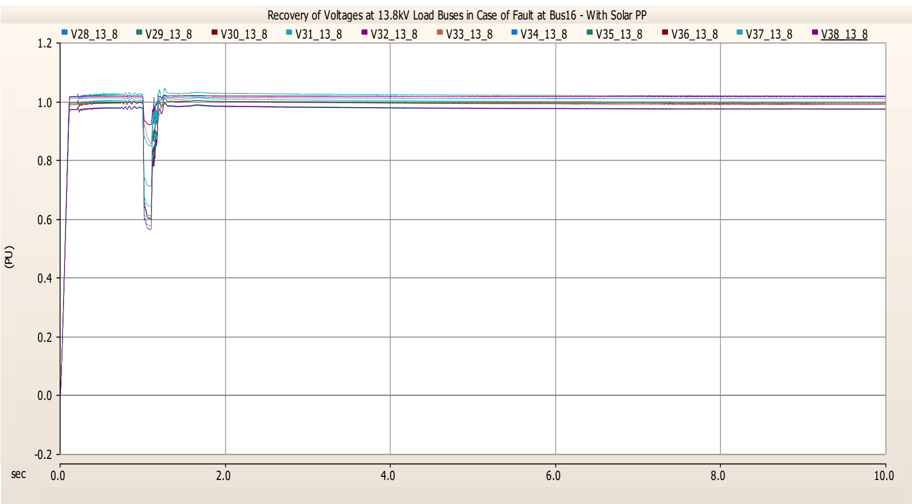

Figure 20. Recovery of 13.8 kV load bus voltage with solar PV farm (p.u).

VIII. Conclusion and Future Work

The large-scale penetration of PV systems into the grid is expected to increase in the foreseeable future. As the efficiency and lifespan of these systems advance, environmental advantages increase, and the energy break-even point decreases. Nevertheless, a significant portion of the current infrastructure was not designed initially to accommodate distributed generation, particularly with the level of intermittency characteristic of PV systems. Simulation studies, as demonstrated in this thesis using PSCAD, become essential to enable utilities to assess the potential impact of such interconnections on voltage, rotor angle, and frequency stability. These studies offer insights into the intricate dynamics of integrating renewable energy sources into the existing power grid infrastructure.

The results show that the reduced network's voltage profile is improved compared to when local generation is not introduced. Similarly, introducing a small local generation in the reduced network improves the active power profile, and the power at the source bus is reduced, reducing the main transformer's loading. Furthermore, infinite solar energy sources available in the kingdom will reduce the basket price of the energy. Introducing the local source in the system will improve the power quality of the system and will reduce the transmission line loading.

Further research may be carried out to address the following issues:

- Develop comprehensive models for solar inverters and corresponding control systems to investigate and enhance stability during fault conditions. This includes thoroughly examining how inverters respond to faults and potential improvements in their control mechanisms.
- Load modeling: Consider additional variations in load models, particularly exploring modifications to the mechanical torque of induction motor loads. This might involve adjusting torque characteristics to create composite mechanical loads, impacting short-term voltage stability.
- Operating point: Incorporate more operating points into the test system, such as PV systems operating at non-unity power factors. Additionally, explore scenarios with higher levels of PV penetration to gauge their effects on the system's behavior.
- Contingency: Diversify the contingencies studied by varying fault parameters, including fault location [34], impedance, type, and duration. This variation aims to assess the impact on different components within the test system, including PV systems, induction motors, and synchronous generators. It provides a more comprehensive understanding of the system's resilience under various fault conditions.

These proposed enhancements aim to broaden the scope and depth of the study, allowing for a more nuanced analysis of the stability and performance of the power system, especially under diverse operating conditions and contingencies.

Dynamic response of the system: Due to the high sensitivity and industrial nature of this area, and due to the phenomenon of motor stalling, which poses a significant concern, the introduction of a dynamic reactive power compensation device is crucial to meet the dynamic response which cannot be fulfilled through the fixed capacitor. Unlike fixed capacitors, a dynamic reactive power compensation device offers more flexibility to address the significant drawback of heavy motor loads, especially in the context of increased penetration of renewable generation networks. The primary concern is that LVRT and motor stalling can lead to complications, and employing dynamic reactive power devices becomes imperative to mitigate these issues effectively. This approach ensures a more adaptive and responsive system to maintain operational stability in the face of dynamic industrial loads and the integration of renewable energy sources.

References

[1] L. Alhmoud and W. Marji, "Optimization of Three-Phase Feeder Load Balancing Using Smart Meters," in IEEE Canadian Journal of Electrical and Computer Engineering, vol. 45, no. 1, pp. 9-17, winter 2022, doi: 10.1109/ICJECE.2021.3113521.

[2] Mushi, A. T., Suwi, O., & Justo, J. J. (2024). Overview of renewable energy power system dynamics. In *Modelling and Control Dynamics in Microgrid Systems with Renewable Energy Resources* (pp. 3-18). Academic Press.

[3] Lavanya, L., & Swarup, K. S. (2024). Inertia monitoring in power systems: Critical features, challenges, and framework. *Renewable and Sustainable Energy Reviews*, *190*, 114076.

[4] Zahariah, J. (2024). Hybrid aquila arithmetic optimization based ANFIS for harmonic mitigation in grid connected solar fed distributed energy systems. *Electric Power Systems Research*, *226*, 109898.

[5] Shrestha, A., Rajbhandari, Y., & Gonzalez-Longatt, F. (2024). Day-ahead energy-mix proportion for the secure operation of renewable energy-dominated power system. *International Journal of Electrical Power & Energy Systems*, *155*, 109560.

[6] Markus Pöller, Nguyen Thanh Nam, Tran Anh Tuan, "Revision of Grid Code and Distribution Code for facilitating Variable Renewable Energy Integration – Final Report', Published by the Deutsche Gesellschaft für Internationale

Zusammenarbeit (GIZ) GmbH, Dec 2019.
[7] Ellithy, H. H., Hasanien, H. M., Alharbi, M., Sobhy, M. A., Taha, A. M., & Attia, M. A. (2024). Marine Predator Algorithm-Based Optimal PI Controllers for LVRT Capability Enhancement of Grid-Connected PV Systems. *Biomimetics*, *9*(2), 66.
[8] Yang, N. C., & Yang, H. Y. (2024). Determination strategies of low-voltage ride-through/zero-voltage ride-through curves in Taiwan grid codes. *Electric Power Systems Research*, *227*, 109984.
[9] Saidi A.S. Impact of large photovoltaic power penetration on the voltage regulation and dynamic performance of the Tunisian power system. Energy Exploration and Exploitation 2020; 38:1774–809. doi:10.1177/0144598720940864
[10] MALIK, M. U. Modeling, Integration and Simulation of the Photovoltaic Power Plant Considering LVRT Capability and Transient Voltage Stability.
[11] Boruah, D., & Chandel, S. S. (2024). Techno-economic feasibility analysis of a commercial grid-connected photovoltaic plant with battery energy storage-achieving a net zero energy system. *Journal of Energy Storage*, *77*, 109984.
[12] Tang, L., Han, Y., Zalhaf, A. S., Zhou, S., Yang, P., Wang, C., & Huang, T. (2024). Resilience enhancement of active distribution networks under extreme disaster scenarios: A comprehensive overview of fault location strategies. *Renewable and Sustainable Energy Reviews*, *189*, 113898.
[13] Cai, Q., Qing, J., Xu, Q., Shi, G., & Liang, Q. M. (2024). Techno-economic impact of electricity price mechanism and demand response on residential rooftop photovoltaic integration. *Renewable and Sustainable Energy Reviews*, *189*, 113964.
[14] Kaufhold, E., Meyer, J., & Schegner, P. Harmonic stability assessment of commercially available single-phase photovoltaic inverters in public low voltage networks. In *1. Helgoland Power and Energy Conference* (p. 35).
[15] Saidi AS, Alsharari F, Ahmed EM, Al-Gahtani SF, Irshad SM, Alalwani S. Investigating the Impact of Grid-Tied Photovoltaic System in the Aljouf Region, Saudi Arabia, Using Dynamic Reactive Power Control. *Energies*. 2023; 16(5):2368.
[16] He, L., & Yu, S. (2024). Systematic decoupling grid-forming control for utility-scale inverter-based distributed energy resources in weak distribution grids. IEEE Open Access Journal of Power and Energy.
[17] Market in Focus: Solar Photovoltaics (PV). SIDF. December 2022. www.sidf.gov.sa
[18] Country Analysis Executive Summary: Saudi Arabia. 2021.
[19] Van Opstal, W.; Smeets, A. Circular economy strategies as enablers for solar PV adoption in organizational market segments. Sustain. Prod. Consum. **2023**, 35, 40–54.
[20] International Renewable Energy Agency. Global Renewables Outlook. 2020. Available online: https://www.irena.org (accessed on 10 January 2023).
[21] Ghamdi Al, Saudi Arabia Energy Report. 2020.
[22] Shumkov, I. Saudi Auction for 400 MW of Wind Attracts 4 Bids. Renewables now. 2018. Available online: https://renewablesnow.com (accessed on 22 January 2023).
[23] Al-Sultan K.B. Chairman of KACARE: Saudi Arabia Aims to Adopt Electricity Production Using Renewable Energy by 50% in 2030. Saudi Press Agency; 2021.
[24] Ali, A.; Malik, S. Solar Photovoltaic End-of-Life Disposal Policy Assessment for the Kingdom of Saudi Arabia. In Proceedings of the 44th IAEE Conference on Pathe Way to a Clean, Stable and Sustainable Energy Future, Riyadh, Saudi Arabia, 4–9 February 2023; pp. 197–198.
[25] Manitoba Hydro International Ltd., "Simple solar farm model written for PSCAD X4 version 4.6.3," 2019. https: //www.pscad.com/knowledge-base/ download/simplesolarfarm2019.pdf, Last accessed on 22-12-2023.
[26] O. Anaya-Lara and E. Acha, "Modeling and analysis of custom power systems by PSCAD/EMTDC," IEEE Transactions on Power Delivery, vol. 17, pp. 266–272, 2002.
[27] B. Gorgan, S. Busoi, G. Tanasescu, and P. V. Notingher, "PV plant modeling for power system integration using PSCAD software," in 2015 9th International Symposium on Advanced Topics in Electrical Engineering, ATEE 2015, pp. 753–758, Institute of Electrical and Electronics Engineers Inc., 2015.
[28] Katiraei, F., Iravani, M.R., Lehn, P.W.: 'Micro-grid autonomous operation during and subsequent to islanding process', IEEE Trans. Power Deliv., 2005, 20, (1), pp. 248–257
[29] IEEE Recommended Practice for Industrial and Commercial Power System Analysis, IEEE Standard 399-1997, August 1998.
[30] Grid Code High and Extra High Voltage. EON Netz GmbH 2003.
[31] Loji K, Sharma S, Loji N, Sharma G, Bokoro PN. Operational Issues of Contemporary Distribution Systems: A Review on Recent and Emerging Concerns. *Energies*. 2023; 16(4):1732.
[32] The Saudi electricity company, "The Saudi Arabian Distribution Code", April 2021.
[33] Saidi, A.S.; Alsharari, F.; Ahmed, E.M.; Al-Gahtani, S.F.; Irshad, S.M.; Alalwani, S. Investigating the Impact of Grid-Tied Photovoltaic System in the Aljouf Region, Saudi Arabia, Using Dynamic Reactive Power Control. Energies 2023, 16, 2368
[34] A. Haj Hamida, K. Ben Kilani, M. Elleuch. Review of PES Failures and Lessons Learned from the Tunisian Blackout of August 2014. J. Electrical Systems 14-4 (2018): 64-84.