Mitigating Voltage Instability in the Saudi Grid for a Decarbonized, Fully Solar Power System

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***Abstract*—Lately, solar photovoltaic (PV) has received significant interest due to its economic and environmental benefits. As the integration of renewable energy sources (RES) increases into existing power grids, challenges such as the decrease in short circuit ratio (SCR) are introduced. This paper investigates a case study of the Saudi power grid, examining the voltage stability as the grid transitions from traditional power generation to 100% penetration of solar PV gradually. Moreover, the paper explores the relationship between the increase in solar penetration and the potential effects on the short circuit MVA (SCMVA), which could significantly impact the overall SCR of the system. To meet the North American Electric Reliability Corporation (NERC) recommendation of maintaining SCR at a particular level, synchronous condensers (SC)s were integrated into the grid. The effectiveness of utilizing SCs to maintain the system voltage at optimal levels in a fully solar grid is also considered. In addition, this paper covers the weak grid analysis via utilizing the Newton-Raphson load flow method, along with PV and QV curve analyses. The purpose behind that is to determine weak bus locations in need of voltage improvements, and to meet the amount of reactive power to be injected. Finally, the amount of power being delivered by SCs will be added progressively in three scenarios to show the enhancements on SCR more precisely.**

Keywords—Solar photovoltaic, renewable energy integration, synchronous condensers, voltage stability, short circuit ratio.

I. INTRODUCTION

With the increase of energy demands and the ongoing impact of global warming, most developed countries have started shifting towards renewable energy sources (RES) [1,2]. Given its geographical location, Saudi Arabia receives a significant amount of solar radiation making it an excellent candidate for solar power integration [3]. The country has already embarked on this journey, initiating several solar and wind energy projects, with more under construction [4]. While transitioning to RES offers valuable benefits such as mitigating carbon emissions and reducing environmental hazards, it also presents challenges to grid stability, particularly issues related to power system strength [5-7].

The Short Circuit Ratio (SCR) is a significant index that measures the degree of system strength or fault levels within a power grid [5,6]. Its amount depends on the ratio between the short circuit MVA (SCMVA) and rated generation capacity existing at the point of interconnection (POI) [5,8-10]. Inverter-based resources (IBR)s such as solar PV are different than traditional generators since they are decoupled from the grid [6,7]. As a result, solar PV integration and the retiring of synchronous generators (SG)s will result in reducing the overall SCR of the system [5,6]. A grid exhibiting low SCR could negatively affect the reference angles of converters and the control of relays, which may lead to undesired trips and unplanned isolation of certain areas [11,12].

Synchronous condenser (SC) is basically a synchronous machine without a prime mover that plays an essential role as voltage supporter within the power grid [13,14]. By producing or absorbing reactive power, SCs ensure a balanced power supply and enhance system efficiency [14]. The authors in [15] studied the SC allocation for improving SCR finding that with the assistance of SC with solar penetration, the system was able to ride-through faults and has an improved voltage recovery after disturbances. A key benefit of SCs lies in their ability to improve grid stability, particularly in grids with high renewable energy penetration such as solar PV by increasing the average SCMVA levels [16]. Additionally, the study presented in [17], used SC as a reactive compensator and an ancillary service provider. The strategic use of SCs can help boost SCR in a grid transitioning towards RES, offering a solution to power system resilience [10], and improving voltage at weak bus locations following contingency [18]. It is important to note that a robust system, as per the North American Electric Reliability Corporation (NERC), should maintain an adequate amount of SCR of at least 3 to ensure sufficient strength within the system [5].

The primary objective of this study is to focus on the consequences of increasing solar penetration levels on the SCR and to highlight the significant role of SCs in improving voltage stability. This objective will be achieved by determining the optimal locations for SCs within the Saudi Electricity Company (SEC) grid. The simulation will be conducted via the Power System Simulation for Engineering (PSS/E), a tool capable of performing a weak grid analysis using the Newton-Raphson (NR) method and P-V and Q-V analyses, short circuit calculations, and dynamic analysis.

This paper is organized as follows: Section II presents the background for the study. Section III explores the impact of high solar penetration on the SCR, using the SEC system as a case study. Section IV present the analysis of weak grids and methods for enhancing voltage stability. In Section V, the simulation method is discussed. Section VI is dedicated to discussing the results and improvements observed after integrating the SC into the system. Finally, Section VII provides the conclusion of this paper.

II. BACKGROUND

Voltage stability is defined as the system being able to sustain consistent voltage levels at all bus locations following a disturbance [19]. Power system strength refers to the capacity of the grid to preserve stable conditions, recover from substantial disturbances, equipment failures, and faults [6,11]. A robust system can facilitate the integration of IBR, enhance power quality, and uphold voltage within predefined limits [6,11]. SCR significantly influences system stability, serving as a primary indicator of system strength [5]. While synchronous generators (SGs) have traditionally supported SCR, as the contribution from IBR grows, SGs might not always be readily available [6,11]. Grid-following inverters that are used to set the voltage angle reference, may not operate as desired in the event of significant contingency [20]. With ongoing research into improving system strength, the focus of this paper is on using SCs for grid shifting to IBR.

A. *Short circuit ratio*

The SCR at a given point is the ratio of the available fault level to the nominal active power output of the IBR as it is defined in the following equation [5,7]:

$$SCR = \frac{S_{SCMVA}}{P_{RMW}} \tag{1}$$

Here the S_{SCMVA} is the MVA capacity at the bus, and P_{RMW} is the rated megawatt from solar PV. As a result, P_{RMW} obviously will equal the total demand required to meet the daily solar PV needs of hot summer day of the model system being investigated. To find the SCMVA, a three-phase short circuit analysis in accordance with the IEC 60909 standard [8] can be performed through PSS/E.

B. *Synchronous condensers*

SCs are generally modeled as a synchronous motor, except that its shaft is not connected to any load and freely rotates without restriction [13,14]. The field of a SC is managed by a voltage regulator, which either generates or absorbs reactive power as necessary to adjust the voltage of the grid or improve the power factor [21]. After adding the power contributed from SCs, Eq. 1 will become:

$$SCR = \frac{S_{SCMVA}+S_{SC}}{P_{RMW}} \tag{2}$$

Where S_{SC} is the power contribution from SCs in MVA.

III. IMPACT OF HIGH SOLAR PV PENETRATION ON SCR AT SEC

This section evaluates the impact of high solar PV penetration levels on the SCR within the SEC power grid, through PSS/E. The primary objective is to determine how increasing solar PV penetration impacts voltage stability, as characterized by SCR. This effect was studied by performing 3-phase short circuit fault in accordance with the IEC 60909 standard [8]. In the SEC model, synchronous machines are progressively replaced with solar PV units at incremental penetration levels of 20%, 40%, 60%, 80%, and 100%, which evenly performed across the five main areas of the SEC power grid. Fig. 1, Fig. 2, and Fig. 3 illustrate the corresponding changes in SCMVA with different percentages of SGs replacement with solar PV units.

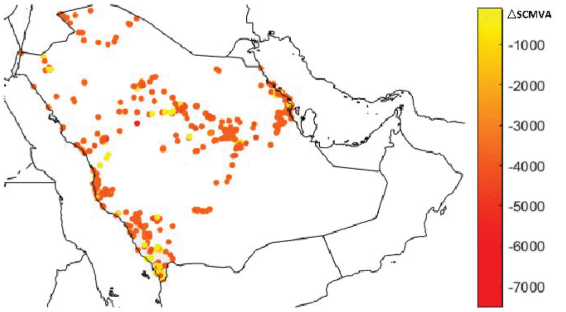

Fig. 1. Saudi grid map shows the change in SCMVA after integration to 20% level of solar PV.

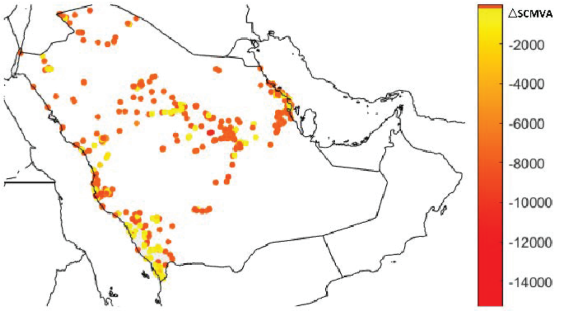

Fig. 2. Saudi grid map shows the change in SCMVA after integration to 20% level of solar PV.

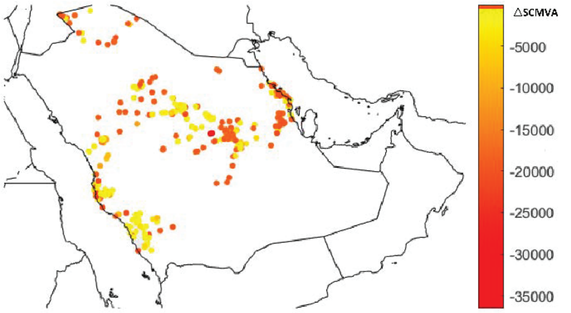

Fig. 3. Saudi grid map shows the change in SCMVA after integration to 100% level of solar PV.

The figures show that as solar PV penetration increases in all areas, the SCMVA noticeably decreases. Fig. 4 shows the voltage response at a selected bus as solar PV penetration change.

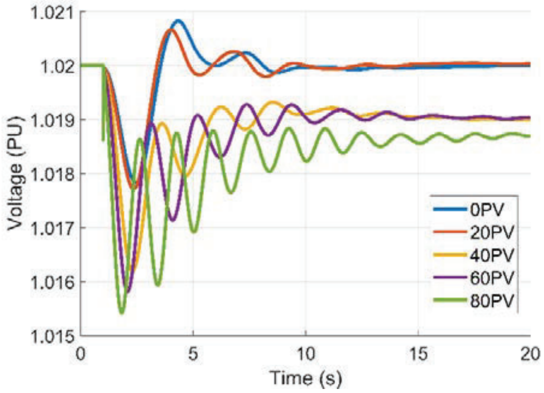

Fig. 4. Shows the voltage response for one of the buses in the system model after a generator trip event among different solar PV penetration levels.

It is important to highlight that the system becomes unstable when solar PV penetration exceed 83%, making further simulations difficult without extra system support. For the voltage response with solar penetration of 0%, 20%, 40%, 60%, and 80% the curves show that as the penetration of solar PV increases, the voltage experiences a more significant drop following a contingency. Table I provide the SCR values under different solar PV penetration scenarios. Even with the significant decrease in SCR value from 0% PV to 80% PV, the system has kept a ratio above 3.

TABLE I.
COMPARSION BETWEEN SCR WITH DIFFERENT SOLAR PV PENETRAION

No.	Case	Short Circuit Ratio (%)
1	Base Case	4.99
2	20% PV	4.72
3	40% PV	4.41
4	60% PV	4.03
5	80% PV	3.42
6	100 PV	0.9

The SCR demonstrates a declining trend as the solar PV penetration level increases. These findings suggest that the voltage stability at SEC power grid becomes less reliable with increasing solar PV penetration, and impossible to operate under contingency with solar PV penetration above 83%, highlighting the need for an appropriate compensation.

IV. WEAK GRID ANALYSIS AND VOLTAGE STABILITY ENHANCEMENT

To improve the reliability and resilience of the power grid, it is essential to carry out comprehensive grid analysis, including the exploration of sensitive regions. This study focused on identifying and addressing the weak regions through the load flow results obtained using the NR method, along with the P-V and Q-V curve methods that provide the amount of var required to reach the desired voltage in each bus after a contingency. A major benefit of NR is its precision, which makes it exceptionally suitable for power system analysis involving large-scale networks [22,23]. In the other hand, P-V and Q-V curve methods offered the potential to predict and prevent system collapses that can significantly disrupt the power stability [24]. Table II presents hypothetical bus numbers that showed weak voltage response after a contingency obtained from NR load flow. Fig. 5 depicts the Q-V curve from PSS/E, indicating the reactive power injection needed at various weak buses to sustain the desired voltage response after a contingency.

TABLE II.
BUS VOLTAGE MAGNITUDE BEFORE AND AFTER A CONTINGENCY WITH 80% PENETRATION OF SOLAR PV

No.	Bus Num.	Bus Volt. Before-Contigency (P.U)	Bus Volt. After-Contigency (P.U)
1	West_1	1.0	0.9272
2	West_2	1.0	0.9273
3	South_1	1.0	0.9180
4	South_2	1.0	0.8980
5	West_5	0.98	0.8656
6	West_6	0.98	0.8700

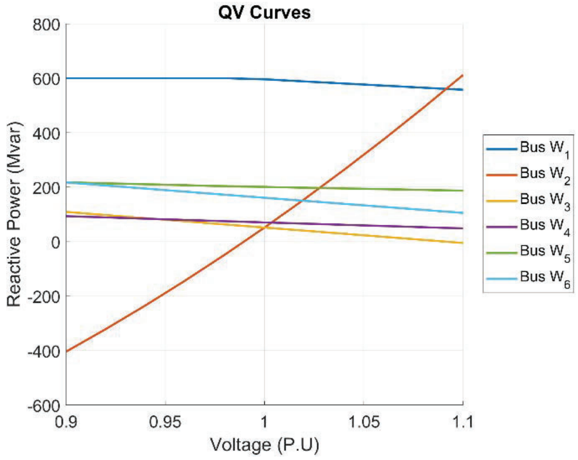

Fig. 5. shows the Q-V curve with 100% solar PV penetration for some buses in the western region at SEC power grid.

V. SIMULATION METHOD

A. Saudi Electricity Company (SEC) system

The SEC system consists of five main regions. During the summer of 2021, it experienced a peak load of 64,161 megawatts (MW), resulting in a total daily consumption of 1,436,686 MW. [25,26]. The simulation being considered is based on a grid entirely powered by solar PV, accounting for the MW needed to charge batteries for periods with no sunlight. Moreover, the assumed load growth due to emerging developments, such as the adoption of electric vehicles is considered. Consequently, the new peak load is estimated to reach 89,161 MW by 2030. Over a 24-hour period, the total demand is expected to be 2,033,686 MW. Fig. 6 shows Saudi Arabia solar profile and the assumed load profile in this study [26,27].

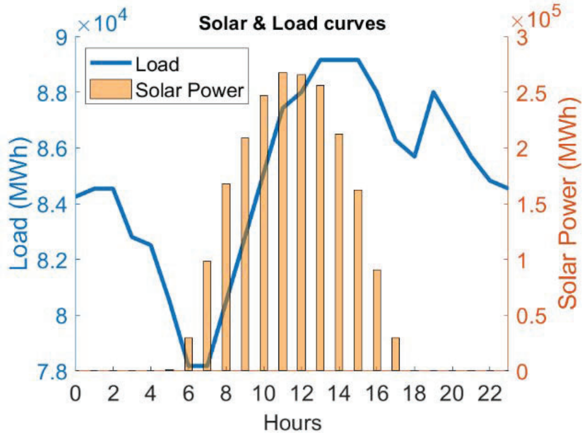

Fig. 6. Solar profile and assumed future load profile.

B. Incorporating the synchronous condensers

The SCs will be integrated in three different scenarios. In each scenario, the SCs are sized to supply a specific amount of reactive power, aiming to incrementally increase the SCR for better observation of the correction. The type of contingency applied to the three scenarios is the tripping of the largest solar PV unit with a capacity of 721 MW. However, line trip in scenario C will be considered too.

VI. RESULT

A. Case A: adding SCs to increase the SCR by 1

In this scenario, the total SCMVA contributed by the SCs equals the solar PV power requirements for a single day, as depicted in Fig 5. SCs are sized to increase SCR by 1. Unfortunately, in this case, the network did not converge, due to a power imbalance.

B. Case B: adding SCs to increase the SCR by 2

In this scenario, the total SCMVA contributed by the SCs equals twice the daily solar PV power requirement, as illustrated in Fig. 5. The SCs are sized to increase SCR by 2. The voltage response is depicted in Fig. 7, showing the waveforms that failed to return to steady-state and desired stabilization. Here, the weak grid analysis using Q-V and P-V curves has not been performed in this simulation yet.

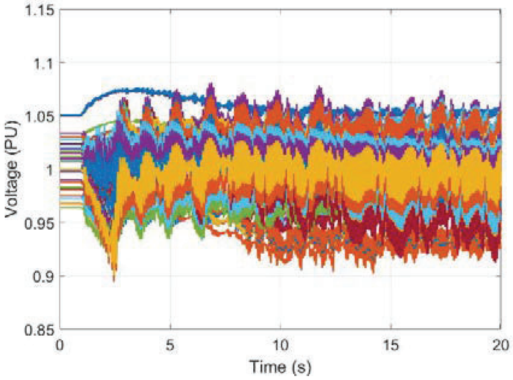

Fig. 7. shows voltage response when SCs increase the SCR by 2.

C. Case C: adding SCs to increase SCR by 3

In this case, the total SCMVA supplied by the SCs is equivalent to thrice the daily solar PV power need, as outlined in Fig. 5. This means the SCR associated with the SCs is increased by 3. Fig. 8 displays the voltage response following a solar PV unit trip, while Fig. 9 presents the voltage reaction after a 380KV line trip. It observes an improvement in both recovery time and smoothness. Here, the weak grid analysis has been performed to determine the weakest bus locations and amount of reactive power needed. Fig. 10 shows the injected reactive power of one installed SC used in this simulation.

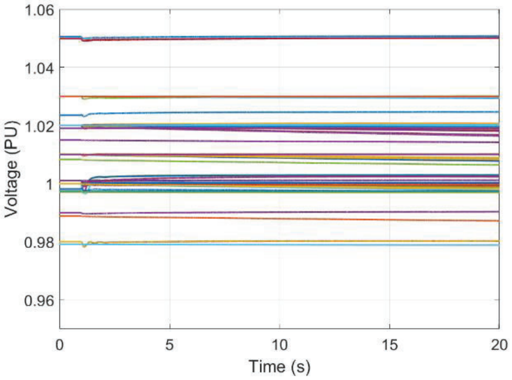

Fig. 8. presents the voltage response in case of PV unit trip when SCs increase the SCR by 3.

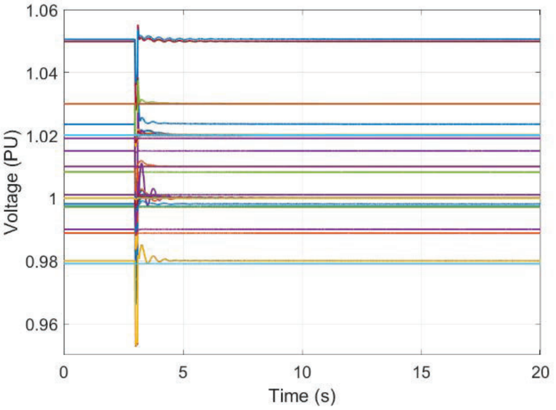

Fig. 9. shows the voltage response in case of 380-KV line trip when SCs increase the SCR by 3.

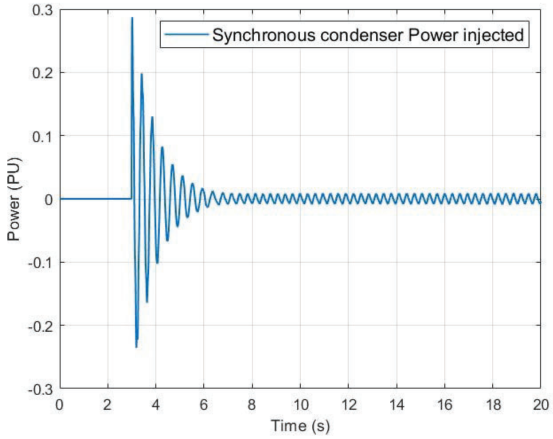

Fig. 10. Displays Power injected by a SC installed at the central region of the Saudi grid, during a contingency with 100% penetration of solar PV.

Moreover, Fig. 11 depicts the voltage response for the same bus that was illustrated in Fig. 3. With the installation of SCs at 100% solar PV penetration, it shows a significant improvement in voltage drop, as the curve only dropped to 1.0198 PU.

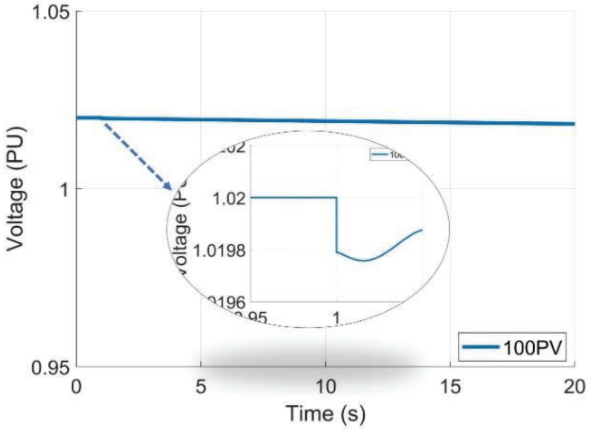

Fig. 11. shows the voltage response for the same bus shown in Fig. 3, but in this instance, with the contribution of SCs and 100% penetration of solar PV.

VII. CONCLUSION

In this study, the impact of solar PV penetration on the Saudi power grid has showed significant decline in SCR. However, the contribution of SCs into the fully solar-powered model of the Saudi grid has facilitated the procedure and notably increased the SCR to excellent levels that meet NERC recommendations. As a result, the resilience of the Saudi grid against sudden voltage changes was significantly improved. Weak grid analysis has provided a better understanding of voltage collapse issues, highlighting the capability of the Saudi power grid to integrate and transition towards a fully decarbonized solar PV system. For future work, it appears to be significantly important to utilize SCs to investigate the frequency response within the Saudi grid, when it operates fully on solar power. It carries the potential to tackle additional issues related to frequency stability and can contribute to improving the overall system strength with high penetration of solar PV.

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