Frequency Stability Enhancement in a Fully Solar Power Grid : A Case Study on the Saudi Model

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***Abstract*— Recently, renewable energy sources (RES) such as solar photovoltaic (PV) have been recognized for their significant potential. Several studies have explored the issue of frequency stability with high RES penetration. A significant observation related to this issue is the decline in the weighted short circuit ratio (WSCR), which has the potential to adversely affect system stability. This research uniquely focuses on the gradual transition of the Saudi Electricity Company (SEC) system to a fully integrated solar PV grid, offering insight and methodology that can be adapted for other power systems. While a variety of mitigation methods are available, synchronous condensers (SC) were used in this study to stabilize grid frequency, and their implementation has been shown to improve the overall performance of the system. In response to the observed decline in WSCR, a comprehensive short circuit analysis was applied across all regions in the Saudi power grid model to evaluate the reduction in short circuit power and highlight areas requiring enhancement. Scenarios illustrating frequency response with a gradual increase in SCR were analyzed, with the objective of establishing a stable, fully solar PV power system that is resilient to sudden power grid disturbances.**

Keywords—Solar photovoltaic, Renewable energy integration, frequency stability, synchronous condensers, weighted short circuit ratio.

I. Introduction

With the growth in electricity demand and the environmental challenges caused by traditional generation, the transition toward renewable energy sources (RES) has been observed worldwide [1,2]. Saudi Arabia has great solar potential, receiving more than 2100 KWh/m^2 of solar radiation annually [3]. The serious commitment the country has made towards sustainable growth and energy diversity has lately started leading to a slight decrease in the reliance on fossil fuel-based electricity generation [4].

Even though RES offers several benefits, it also introduces challenges to the power system, such as maintaining frequency stability and providing adequate inertia response [5]. The Short Circuit Ratio (SCR) is defined as the proportion between the short circuit capacity and the rated capacity of the electronic equipment at the point of interconnection (POI) [6]. Considering inverter-based resources (IBR) interactions, the Electric Reliability Council of Texas (ERCOT) suggests that a system should maintain an adequate weighted short circuit ratio (WSCR) of at least 1.5 at the POI [7]. As solar PV is integrated into power grids, synchronous generators (SG) are replaced, leading to a reduction in the overall SCR of the system [7,8]. A system with low SCR can experience challenges related to stability and robustness [7].

Frequency stability is defined as the capability to keep a consistent frequency during operation and return to a steady state after a major disruption that causes a mismatch between electricity supply and demand [9]. Inertia, in the field of power systems, represents the kinetic energy provided by rotational force within the power grid [10]. IBR such as solar PV differ from traditional generators since they lack the rotational part [10]. A power system with high inertia is less likely to experience large changes in frequency after an unexpected loss of generation or load, while low inertia systems can be more sensitive to these changes, leading to a high rate of change of frequency (RoCoF) [11].

Synchronous condensers (SC) offer several benefits in enhancing frequency stability, especially with the rise of RES in power systems. The spinning mass of such a component assists inertia and thereby improves overall performance [12]. SC not only enhance grid stability by adding more short circuit MVA (SCMVA) at their installation points but also support frequency response with high-RES integration [13,14]. In [15], integrating SC into a system with high RES showed a notable reduction in the maximum RoCoF value, enhancing overall system performance. Furthermore, research in [16] and [17] has shown that RoCoF can be maintained within acceptable limits by integrating SC into RES grids. One key advantage of SC is their capability to both generate and absorb rotational energy, which is beneficial in stabilizing frequency variations, especially with disturbances [14].

While SC can address frequency stability challenges, there are other potential mitigation strategies that have been explored such as static var compensators, static synchronous compensators, and energy storage [8,11]. However, the effectiveness and feasibility of these solutions can vary based on the specific characteristics of the power grid and desired output. While this study has been focused on the Saudi Electricity Company (SEC) power grid, the methodology employed can be adapted and applied to other power grids worldwide.

The main objectives are to focus on the effects of increasing solar penetration levels on WSCR, highlight the significant role of SC in improving frequency stability, and achieve a decarbonized, fully solar PV power system that is resilient to sudden disturbances such as unit trips and load increases. These objectives will be explored using SEC power grid as a case study model, with simulations conducted via the Power System Simulation for Engineering (PSS/E).

This research is structured as follows: Section II provides the background and Section III shows the effect of high solar penetration on SCMVA. Section IV presents the results obtained from the short circuit analysis. The simulation process is discussed in Section V. Section VI shows the results and enhancements. Finally, Section VII concludes the study.

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II. BACKGROUND

The impact of IBR on power systems can be evaluated through several methods. Among them, SCR and WSCR are evaluation methods used as power system strength indicators [11,18]. From the perspective of frequency stability, a power system must maintain a constant frequency under normal operating conditions and even after experiencing significant faults [10,11]. The inertia provided by spinning SG can compensate for any power lost after a contingency. However, with the increased use of IBR that lacks rotational parts, it becomes necessary to compensate for the decrease in inertia. SC can increase inertia and effectively compensate for the reduction occurs due to SG replacement [10,11]. Since SC are structurally similar to SG but without a turbine, retired SG can be refurbished and adapted to serve as SC, facilitating IBR integration [15].

A. Short Circuit Ratio (SCR) and Weighted SCR (WSCR)

The integration of solar PV and its interconnection through power electronics result in a drop in the SCMVA. This decrease impacts the power system strength, as indicated by the SCR or WSCR. The formula used to calculate SCR is presented in Eq. 1 [7]:

$$SCR = \frac{S_{SCMVA}}{P_{RMW}} \quad (1)$$

Where S_{SCMVA} represents the MVA capacity before connecting the IBR, and P_{RMW} denotes the rated power in megawatts (MW) from solar PV at the POI. For a more accurate result and to account for the full interactions among IBR, ERCOT has utilized the WSCR method to evaluate the strength of a power system [11,19,20]. WSCR is the ratio between short circuit capacity and rated P_{RMW} assuming that all IBR are connected to the same POI and defined in Eq. 2:

$$WSCR = \frac{Weighted\ S_{SCMVA}}{(\sum_i^N P_{RMWi})^2} = \frac{\sum_i^N S_{SCMVAi} * P_{RMWi}}{(\sum_i^N P_{RMWi})^2} \quad (2)$$

Where N is the number of solar PV plants and i is the plant index [7].

B. Power system inertia

Inertia in the power system can be defined as the total energy from rotating machines [10]. Eq. 3 presents the formula used to calculate the rotational energy [14]:

$$E_{rot} = \sum_{i=1}^{n}(S_i H_i) \quad (3)$$

Where S_i represents the MVA capacity, and H_i denotes the inertia constant. Eq. 3 can be modified to illustrate the equivalent inertia as follow [14]:

$$H_{sys} = \frac{E_{rot}}{S_{sys}} = \frac{\sum_{i=1}^{n}(S_i H_i)}{S_{sys}} \quad (4)$$

Where S_{sys} represents the rating MVA and H_{sys} denotes the inertia constant of the system.

C. Rate of change of frequency (RoCoF)

RoCoF occurs due to the instantaneous changes in power between generation and demand. Eq. 5 expresses RoCoF in terms of changes in active power and inertia [21]:

$$RoCoF = \frac{F_o}{2H_{sys}} \frac{\Delta P}{S_{sys}} \quad (5)$$

Where F_o represents the nominal frequency in Hz, and ΔP denotes the change in active power in MW.

D. Synchronous condensers

SC can contribute additional MVA to the system, thereby improving both inertia and the overall SCR. Eq. 1 can be modified to account for the power contribution from SC as follow:

$$SCR = \frac{S_{SCMVA} + S_{SCs}}{P_{RMW}} \quad (6)$$

Here S_{SCs} represents the SC power contribution in MVA.

III. THE EFFECT OF HIGH SOLAR PENETRATION ON SHORT CIRCUIT MVA

This section evaluates the effect of varying solar PV penetration levels on frequency stability using SCMVA and WSCR as key indicators. The analysis, conducted using the PSS/E, begins with the base case of the SEC model, in which all generation units are SG. Fig. 1 presents the SCMVA available when the SEC power grid operates solely with SG. In contrast, Fig. 2 illustrates the SCMVA when the SEC grid integrates up to 100% solar PV. A significant decline in SCMVA becomes apparent with increase of solar PV integration, which affects the WSCR. According to ERCOT recommendations, a system should maintain a minimum WSCR of 1.5 to ensure an adequate system strength that can resist failures and disturbances such as unit trips and load increases. Fig. 3 shows the MW capacity of the installed PV units (P_{RMW}) at which the SCR is set to 3 within the SEC power grid after 100% solar PV penetration. Any increase in P_{RMW} beyond this point will cause the SCR fall below 3.

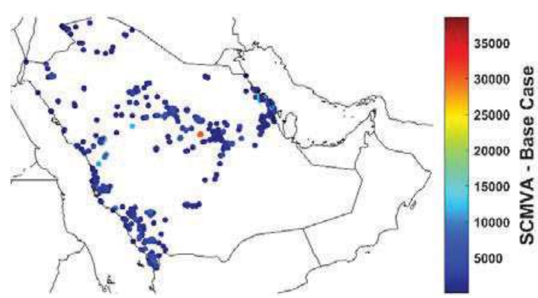

Fig. 1. Available SCMVA before the integration of solar PV.

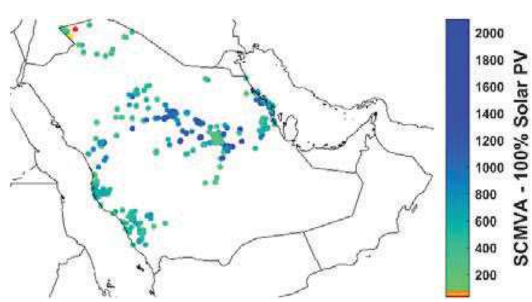

Fig. 2. Available SCMVA after integration to 100% level of solar PV.

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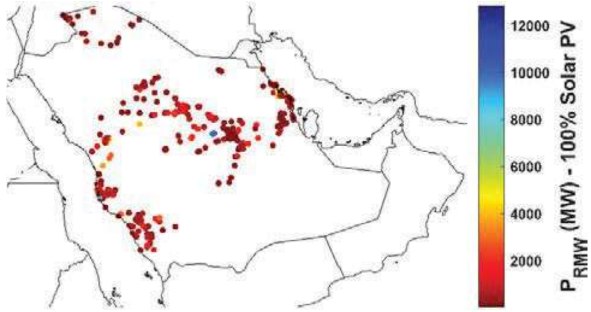

Fig. 3. Saudi grid map highlighting P_{RMW} capacity when the penetration level reaches 100% and the SCR is set to 3.

The impact is clearly captured in Figure 4, which illustrates the average decreasing trend of WSCR as solar PV integration incrementally rises.

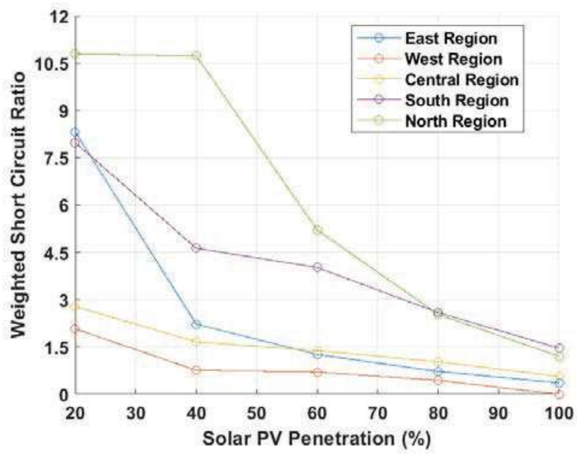

Fig. 4. Average WSCR decline vs. different solar PV penetration levels.

It is important to highlight that the system becomes unstable when PV penetration exceeds 83%, causing further simulations to be impossible without additional support. Fig. 5 shows the frequency response with solar PV penetration of 0%, 20%, 40%, 60%, and 80%. The curves indicate that as the penetration of PV rises, the frequency experiences a deeper nadir following a unit trip contingency.

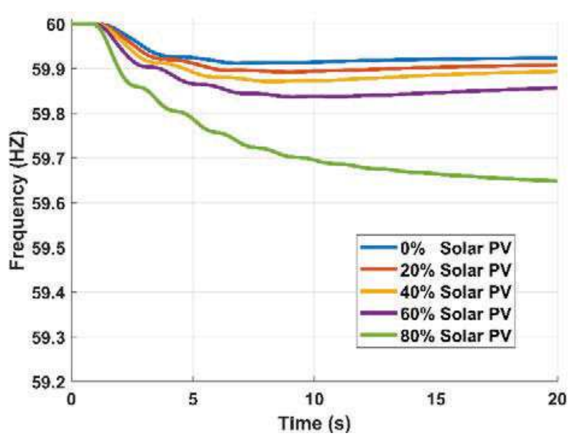

Fig. 5. Frequency response with different PV penetration levels.

IV. Short Circuit Analysis

This study focuses on the short circuit analysis to identify weak bus locations. A 3-phase short circuit fault study was applied on all branches within the SEC model to determine the SCMVA, first when operating with conventional generators and later when transitioned to 100% solar PV. Buses that experienced decrease in SCMVA after integration were prioritized for support with SC. Table I lists some locations with the reduction amount of SCMVA.

TABLE I.
BUS LOCATIONS WITH SCMVA REDUCTION AFTER SOLAR PV INTEGRATION

Bus No.	Short Circuit MVA reduction	Bus No.	Short Circuit MVA reduction
East_1	-187.16	Central_1	-40.88
East_2	-131.6	Central_2	-79.84
East_3	-48.25	West_1	-164.6

V. Simulation Procedure

A. Saudi Electricity Company (SEC) System

The SEC is the primary electricity provider in Saudi Arabia, covering five main regions. During the summer of 2021, it experienced its highest demand of 64,161 MW. This study is based on a grid that relies entirely on solar PV and accounts for the essential MW needed to charge batteries that will be used during periods without sunlight. Furthermore, the study accounts for an anticipated load growth to 89,161 MW due to emerging developments, such as the adoption of electric vehicles. The solar profile of Saudi Arabia and the assumed 24-hour load profile are shown in Figure 6 [22-23].

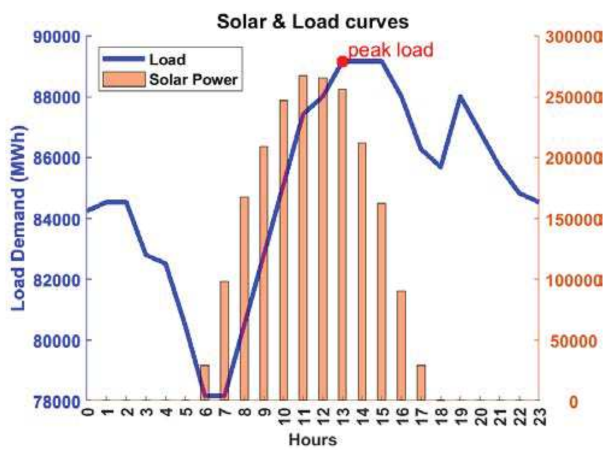

Fig. 6. The solar and assumed future load profiles.

B. Contribution of the Synchronous Condensers

Since both WSCR and SCR are indicators of power system strength, the integration of SC will be approached in two scenarios using SCR as the primary metric for simplicity. For each scenario, the SC will be sized to deliver a certain amount of power, ensuring an incremental increase in SCR. This approach is expected to yield more accurate results and potential improvements.

SC were configured with a rating of 200 MVA. The SCMVA contribution of SC vary at each POI, based on the specific requirements that arise from the integration of IBR at each location. Fig. 7 illustrates the SCMVA at selected POI before and after the installation of SC. These adjustments enhance SCMVA and inertia, which increase grid resilience against disturbances such as unit trips and load increases. In areas with a significant deficiency, multiple SC were installed

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to ensure a sufficient increase in SCMVA and inertia. The Q-V curve analysis technique has facilitated this process by indicating the amount of reactive power required at different location. Fig. 8 illustrates that the real power output of the SC varies, reflecting the dependency on their respective installation locations.

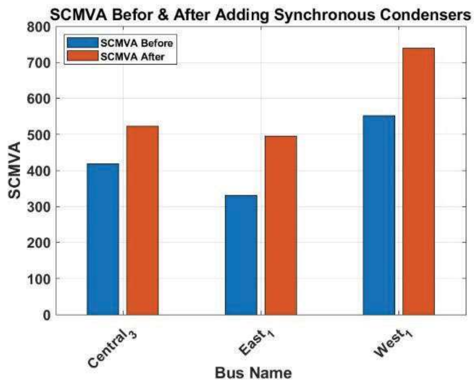


Fig. 7. SCMVA improvements after adding SC.

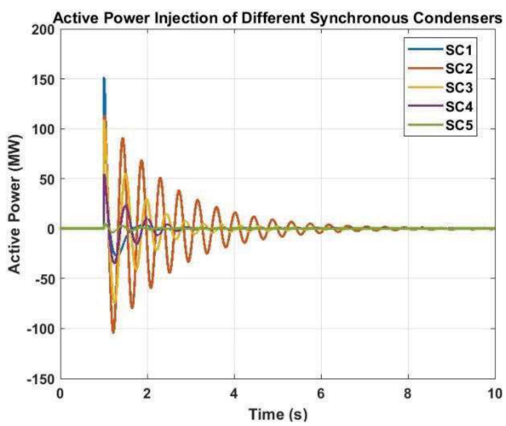


Fig. 8 the real power output of SC.

VI. Result

A. Scenario 1: sizing SC to increase the SCR by 2

As outlined in Eq. 1, to increase the SCR by 2, the total SCMVA must be increased by an amount equivalent to twice the rated power of the system (P_{RMW}), which is 89,161 MW. However, the frequency response of the system presented in Fig. 9 indicates challenges in returning the system to steady state condition after a unit trip.

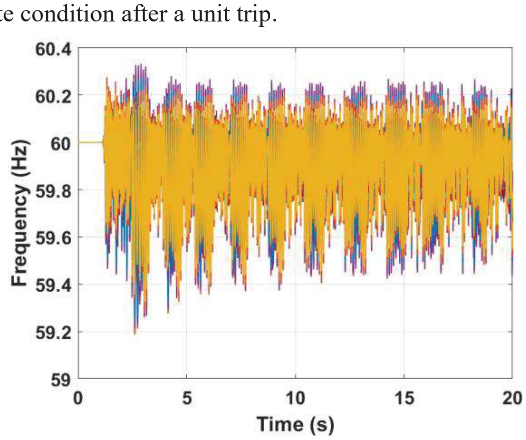


Fig. 9. The system frequency response for scenario A.

The power system experienced an imbalance between generation and load after the trip, leading to frequency deviations. One primary factor that prevented the system from effectively dampening these deviations and restoring balance was the insufficient inertia provided by SC.

B. Scenario 2: sizing SC to increase SCR by 3

In this case, the total SCMVA supplied by the SC is three times the rated power of the system, which results in the SCR value being increased by three. Fig. 10 and Fig. 11 show how the system responds to a 755 MW PV unit trip: Fig. 9 focuses on the overall system frequency response, while Fig. 10 provides detailed insights into the behavior of a bus located in the west region of the SEC model.

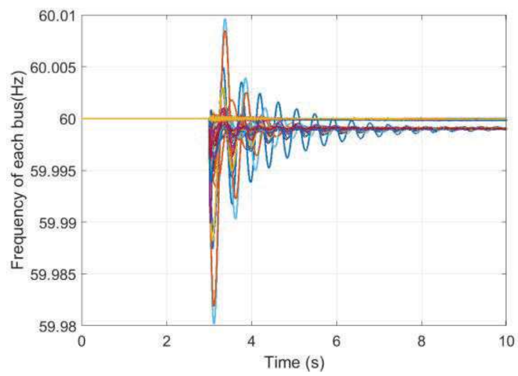


Fig. 10. The system frequency response (Scenario 2).

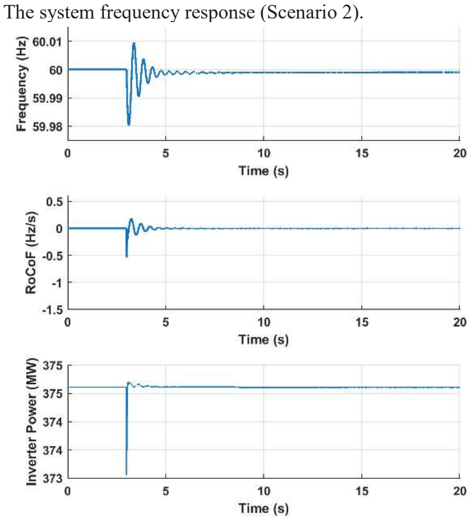
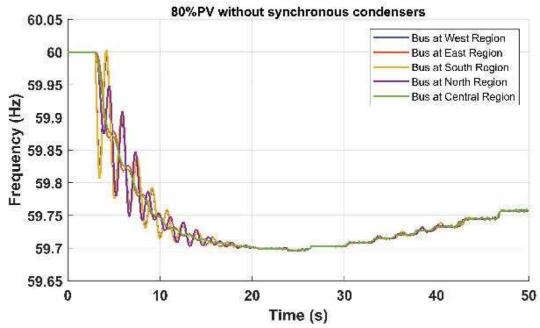


Fig. 11. System response for a bus located in the west region (Scenario 2).

C. Scenario 3: Evaluating solar PV integration with SC vs. without SC.

In this scenario, two cases are examined: the first involves 80% solar PV penetration without the support of SC, and the second involves 100% solar PV penetration with the support of SC that increase SCR by 3. Due to the power imbalance and simulation challenges, a case with 100% solar PV penetration without SC is not considered. While the comparison might not seem equitable because of differing levels of PV penetration in the two cases, there was a notable improvement in the frequency nadir in full penetration with SC over 80% penetration without SC, as shown in Fig. 12.



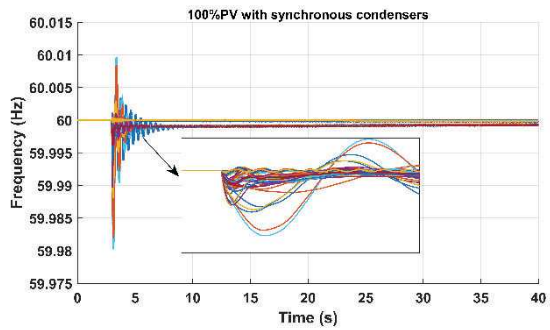


Fig. 12. Presents a comparison in frequency nadir between two cases.

VII. CONCLUSION

The impact of solar PV penetration on frequency stability at the SEC power grid was investigated. While the integration of solar PV significantly impacted on frequency stability, the incorporation of SC has facilitated this transition. In terms of RoCoF and recovery time against sudden power system disturbances, a clear improvement was recorded. While the SEC system was used as a case model, the solutions identified in this research may apply with other power systems globally, emphasizing the broader relevance of the findings. For future studies, it is necessary to conduct a comprehensive analysis of how low SCMVA may affect the protection system.

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