# Photovoltaic Integration with the Saudi Electricity Grid

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Due to uncertain photovoltaic (PV) power generation, analyzing the voltage stability of transmission networks with a large PV plant is challenging. The stability of PV output power is a critical factor in establishing PV penetration levels in active transmission networks when assessing loading capabilities.

Keywords: solar photovoltaic generator ; STATCOM ; power quality ; transient stability

## 1. Renewable Energy State of Art in Saudi Arabia

With the increased interest in renewable energy sources (RESs) to enhance their contribution and participation in the utility grid, the renewable energy industry has made rapid changes and technological progression to tackle the different challenges that face the deployment of such an industry. The recent trend in energy consumption indicates the need for alternative energy sources to balance the energy generated and load demand. Thus, solar photovoltaic generation plants (SPVGPs) have experienced a phenomenal increase over the past few decades. In addition, more interest has been oriented toward photovoltaic (PV) technology as a promising and encouraging solution to overcome fossil fuel emissions, produce green energy, and mitigate fast climate changes [1][2].

Saudi Arabia is one of the most fortunate countries with plenty of solar energy. The amount of solar energy in kilowatt-hour/kilowatt peak (kWh/kWp) that Saudi Arabia receives as solar irradiation in various parts of the country is indicated in the map published by the World Bank group. The potential of solar PV in Saudi Arabia is depicted in **Figure 1** [3]. As per the details posted in the Saudi Arabia national renewable energy program (NREP), the government has identified more than 35 locations to deploy renewable energy projects. Renewable energy generation primarily includes solar photovoltaic, wind, and concentrated solar power (CSP) [4][5][6][7]. The program was planned considering the long-term targets to be met by 2030. **Figure 2** shows the location of renewable energy projects that shall be completed by 2030 as per the NREP report. Moreover, the government decided to tender 12 pre-developed projects with a total capacity of approximately 3.1 GW. Around 2.2 GW would be generated using solar PV. The locations selected for solar plants are Qurrayat, Madinah, Rafha, Al Faisalia, Rabigh, Jeddah, Mahad Dahab, Saad, Alras, and Wadi Adwawser. The remaining 0.9 GW will be generated using wind in Yanbu [7][8]. One of the essential strategies of the government of Saudi Arabia is to include private-sector investment and public-private partnerships. The inclusion of the private and public-private sectors will help the government manage the nation's power needs more effectively. The 300 MW Sakaka Solar PV project, tendered by Saudi Arabia's renewable energy development office (REPDO), is one of the most significant projects in Saudi Arabia. The completion of the Sakaka Solar PV project has made a substantial contribution to the energy diversification and development plans of Saudi Arabia. With the opening of the Sakaka plant, Saudi Arabia has announced that agreements have been signed for seven new solar power projects. The seven new solar projects will be in Madinah, Sudayr, Qurayyat, Shuaiba, Jeddah, Rabigh, and Rafha. The total capacity of these projects, including the Sakaka solar project and the Domat Al jandal wind project, is expected to be 3670 MW as per the details available from the Saudi Ministry of Energy [9][10]. In tandem with the opening of Sakaka, the Public Investment Fund of Saudi Arabia unveiled its plans for Sudair Solar PV, a distinct renewable energy project that would eventually grow to be the largest solar plant in Saudi Arabia. The Sudair Solar PV project, with an estimated investment value of SAR 3.4 billion and a capacity of 1500 MW, will be able to power 185,000 houses and offset over 2.9 million tons of emissions annually.

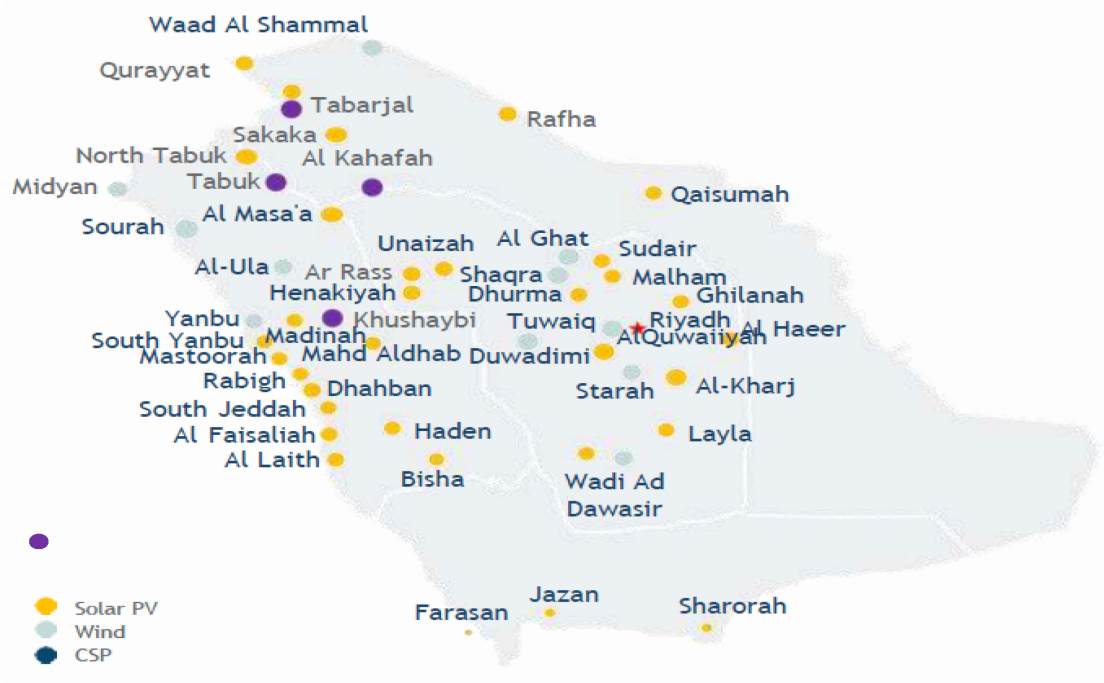


**Figure 1.** Location of renewable energy projects to be deployed across Saudi Arabia.

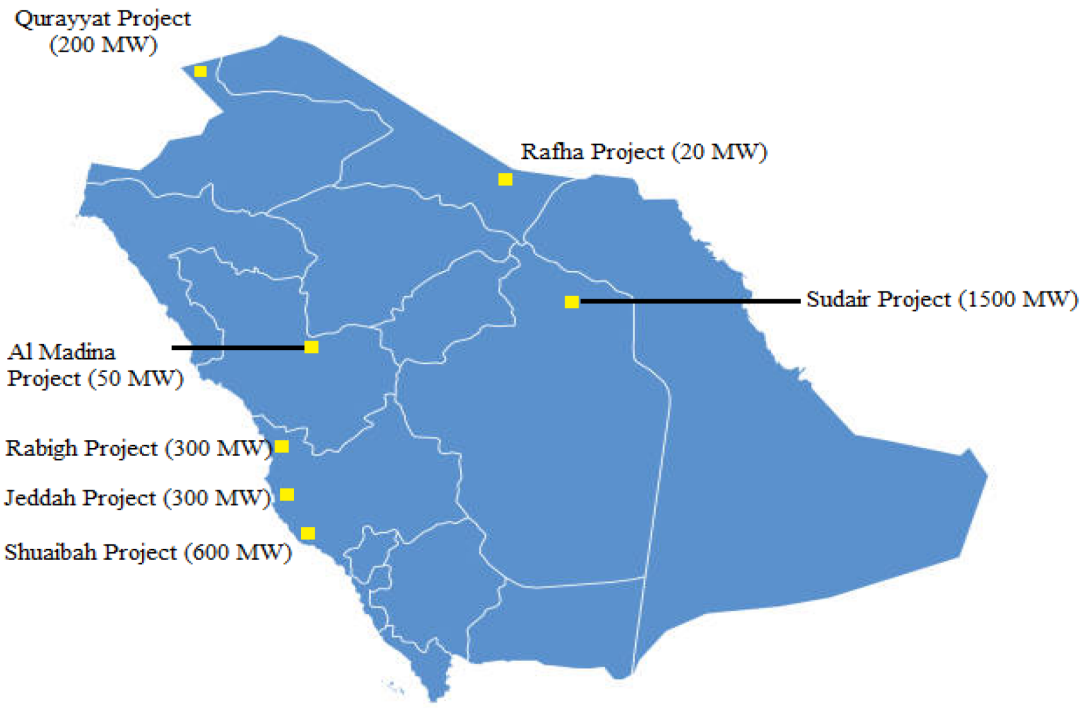


**Figure 2.** Location of seven new solar PV projects [7].

## 2. Impact of PV Integration on Power System Stability

The effect of a large PV integration with the Saudi electricity grid needs to be analyzed in detail. The intermittent nature of PV plant power generation increases the concerns about providing the national grids with secure and reliable power operation [11][12]. With more PV deployment worldwide, the effect of PV technology on grid frequency stability, oscillations, transient angle stability, and voltage stability have become popular research topics.

High PV penetration causes relatively low system inertia, adversely affecting the steady-state and transient stability of the power system. The grid's ability to synchronize power will be hampered by the PV plants' massive power injection because of the increased angular disparity in AC bus voltages. In addition, the dynamic system behavior of the system with high PV penetration depends on the type and location of the disturbance. The literature shows that the stability of power systems with high PV penetration levels has been studied frequently [13][14][15][16][17][18][19]. In [13][14], the authors explored the impact of integrating large PV generation on the Tunisian power grid. Their results show that the grid performance highly depends on the LVRT capability, which can be improved using reactive power compensators. In [15], the authors explored the impact of the high penetration of PV systems on the Egyptian national grid. The simulation

results showed that the power grid can accept a PV penetration of up to 10% of the grid capacity. Moreover, the authors in [16] explored the influence of connecting wind and PV power plants on the Jordan national grid. It was suggested that the penetration capacity of renewable power sources should not be increased to more than 10% to avoid transmission line overloading. Furthermore, the authors in [17] examined the influence of adding 1 MW PV generation to the utility grid in Bahrain. This research attempted to use the exceptional weather conditions of Bahrain to balance the increased load demand. In [18], the authors studied the incorporation of large-scale hybrid PV and wind energy systems on the Nigerian power grid. The simulation results show the optimal PV and wind power penetration levels, satisfying the bus voltage criteria (1.0 ± 0.05 p.u.), based on the ratio of the maximum value of the active power margin and critical voltage-reactive value; this suggested power ratio is 35%. Further, a comprehensive study of the Ontario national grid investigating PV penetration levels is provided in [19].

Furthermore, a high PV penetration level can significantly affect voltage stability, making it an important reliability factor. Voltage stability refers to the ability of the power system to keep the bus voltages within permissible limits in post-disturbance clearance conditions. It was discovered that when PV penetration reached 50%, there was a more significant voltage dip following a disturbance in the system [20]. Furthermore, as the level of PV penetration rose, more voltage oscillations were observed. In addition, a significant disturbance with high PV penetration in the power system could cause voltage instability [21]. A voltage stability analysis was conducted using the grid simulation model of Ontario and system Eigenvalues. It was seen that the short-term voltage stability was highly affected by the disconnection of the PV power generation and voltage sag.

On the other hand, static voltage stability was presented [22][23][24][25][26][27][28][29]. The main factors affecting static voltage stability are the PV generation size, location, and control method. The effect of integrating PV generation on Bangladesh's power grid was presented in [29]. The results showed improved voltage stability near the load buses by integrating PV generation in a centralized style near the load buses or distributed near the load buses. Additionally, the authors of [30][31] studied the impact of the environmental conditions on the grid voltage and frequency stability by considering the irradiance and temperature profiles over the entire year. Reactive power control is crucial to enhance the voltage stability of highly penetrated PV power systems. Since significant power oscillations can be produced due to the intermittent and low inertial nature of PV systems, such fluctuations abruptly affect the power system stability and limit the penetration level of the PV generation.

Flexible alternating current transmission systems (FACTs) are often employed to overcome low-frequency oscillations and improve power transfer capability. Several methods for reactive power compensation were developed in [32][33][34][35][36]. By using the appropriate FACT devices, such as thyristor controller switched capacitors (TCSCs), static var compensators (SVCs), static synchronous series capacitors (SSSCs), and static synchronous compensators (STATCOMs), the reliability of grids could be increased with a reduction in the cost of power transfer. STATCOM and SVC are the standard modules commonly used for reactive power compensation. Both are useful for voltage stabilization, improving transient stability, maintaining transmission limits, and damping low-frequency oscillations. However, compared to SVC, STATCOM is much better at improving the transient stability and transmission limit [37]. When the damping of low-frequency oscillations is taken into account, STATCOM outperforms SVC because STATCOM represents an adjustable voltage or current source whose amplitude and phase can be controlled to change the reactive power delivered to the grid. Moreover, STATCOM indicates a better performance than SSSC [37]. In order to mitigate these problems, installing reactive power supply components is encouraged. Such mitigation is addressed by imposing VOLT/VAR control equipment as per the IEEE 1547 interconnection code for PV smart inverters connected to the grid [38]. PV intelligent inverters can provide reactive power support at all output levels of the solar PV plant. However, that comes with the cost of curtailing the real power output by the PV smart inverter unless the inverter is operating at 100% of the real power level and the voltage is outside of the dead band. On the other hand, PV smart inverters provide little reactive power support during abnormal voltage conditions. Thus, the dynamic voltage support (DVS) of PV smart inverters during abnormal conditions has not yet been introduced in the most recent IEEE 1547.1-2020 due to a lack of standard test procedures for such a function [38].

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