# Reactive Power and Voltage Control Issues Associated with Large Penetration of Distributed Energy Resources in Power Systems

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***Abstract*—As the penetration of distributed energy resources increases and large conventional generators are retired, voltage regulation of generators and reactive power control of the power system should be considered more carefully. In this paper, the impacts of adding renewable resources and changing generators' voltage regulating buses on static power flow convergence and voltage profiles are studied and reactive power status of critical areas as well as online and offline reactive power reserve capacities are visualized. The results show that if renewable resources are added without adding sufficient reactive power resources or if the voltage regulating bus of all generators move to the low voltage side of step-up transformers without tuning the voltage set points of generations, voltage violations and even voltage collapse may occur, which have a negative impact on the reliability of the power system. The paper also reviews possible solutions such as tuning the voltage set points of generators for reactive power management and adding voltage control devices such as switched shunts or static var compensators (SVCs) to the grid to compensate for this change.**

***Keywords*—reactive power management, voltage regulation, renewable energy resources, reactive power margins visualization, situational awareness***

## I. INTRODUCTION

As centralized renewable generation plants and distributed energy resources (DERs) are added to the grid and large conventional generators are retired, the reactive power control of such conventional generators is also being removed. Therefore, fundamental changes are being dictated to the power system. Voltage regulation is one of the most challenging issues that can limit the penetration of renewable distribution generators to the grid if sufficient reactive power resources are not added to the grid [1].

In the conventional grid, an essential part of voltage control was performed by large, centralized generators in the transmission system. However, due to several concerns such as emissions from power plants, large generation units are being retired and replaced by renewable energy resources such as wind farms and solar plants on the transmission system and rooftop solar panels on the distribution system. This can significantly change reactive power resources and voltage control in power systems, potentially leading to serious voltage issues which should be studied carefully and mitigative measures should be proceeded. Several studies in the literature review the voltage and reactive power issues due to the large penetration of renewable energy resources. Reference [2] reviews the stability challenges, such as frequency disturbances and voltage violation, due to the large penetration of photovoltaic (PV) to the grid. The impacts of high PV penetration into distribution systems on voltage profiles and possible solutions for voltage problem is also reviewed in [3]. References [1, 4, 5] review the control strategies to improve voltage profiles when the increased amount of renewable and DER are connected to the grid. In [6], the performance of classical control strategies which include voltage control by using reactive power, active power drooping and the modified damping control strategy is investigated. Reference [7] studies the technical challenges and relevant solutions of the electric power systems under large wind power penetration. Reference [8] shows that a real-time voltage control strategy, has to be implemented that takes advantage of control technologies, monitoring and communication, to mitigate grid stability problems. In addition, several methods are proposed to mitigate effects of highly intermittent renewable generation [9-13]. Reference [14] presents a methodology for mitigating voltage problems in low voltage networks with high integration of DERs, based on a smart grid type architecture. Reference [15] investigates the use of a smart transformer to dynamically control reactive power and demand to support voltage and frequency. Reference [16] presents a control strategy for the reactive power regulation of wind farms with double fed induction generators, for the voltage regulation of the electrical grid. Reference [17] shows that smart grid technologies such as demand side integration and energy storage mitigates voltage variation problems. In [18], active

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voltage control methods that can be implemented in real distribution networks are developed. In addition, an integrated var-voltage control strategy in the high-voltage side of generator step-up (GSU) transformers to improve short-term voltage stability of receiving-end power systems is presented in [19].

In this paper, the impacts of adding renewable resources and changing generators' voltage regulating buses on static power flow convergence, and voltage profiles are studied and reactive power status of critical areas as well as online and offline reactive power reserve capacities are visualized and importance of reactive power control devices such as switched shunts or static var compensators (SVCs) to the grid to compensate this change is highlighted.

## II. VOLTAGE AND REACTIVE POWER CONTROL

Reactive power plays an essential role in power system voltage stability. For the operation of power system, it is desired to maintain voltage levels within the acceptable range to deliver the required active power to the load in the system. The acceptable range depends on the Indeppendent System Operator (ISO) or Financial Transmission Rights (FTR) definitions and requirements and the largest acceptable range in the US is from 0.9 to 1.1 per unit (pu). In order to avoid voltage instability, the power system should have enough amount of reactive power reserves [20]. Therefore, it is critical for the power system to have an appropriate reactive power management and situational awareness to avoid possible voltage instability and even blackouts.

In general, voltage and reactive power are controlled from the power plants such as generators' regulators or from the transmission/distribution system. Generators and reactive power control devices such as shunts and static var compensators (SVCs) can be used to provide the required reactive power to the power system load and injection or absorption to the buses for voltage control purposes. Reactive power control devices such as switched shunts can be used to improve system voltages in normal operation or contingency scenarios. This section provides more information on the two types of voltage control:

### *A. Power plant voltage control*

The power system's voltage is controlled by selecting the regulating bus and regulating the set points of generators. Automatic voltage regulators (AVRs) are continuously regulating voltages of terminal buses or remote buses. [21] Conventional power plants are connected to high voltage (HV) or extra-high voltage (EHV) system through GSU transformers and can regulate voltage of the terminal bus or a remote bus in the transmission system. This protects generators in severe load change conditions. [22]

However, distributed and renewable energy resources are continuously being added to the grid and those are connected to lower voltage levels such as distribution system. Therefore, when there is a large penetration of distributed resources such as wind and PV panels, transmission side control would become more difficult because they are usually added to the distribution grid and lower voltage levels.

### *B. Transmission and distribution voltage control*

The power plant voltage control should be coordinated with transmission and distribution voltage control. Transmission voltage is mostly controlled by reactor or capacitor banks. Switched shunts and synchronous condensers are also utilized for fast and continuous control in contingencies. Switched shunts are widely used for reactive power control in normal operations and contingencies. These devices can control the voltage and reactive power on the transmission side. If generators control voltage on the high side, voltage coordination between switched shunts and generators is improved [23].

## III. POTENTIAL IMPACTS OF LARGE PENETRATION OF DERS ON VOLTAGE AND REACTIVE POWER CONTROL AND VISUALIZATION STRATEGY

Large penetration of DERs can have a significant impact on voltage profiles of buses in the grid if sufficient reactive power control devices are not added to the power system. In this section, the potential impacts of large penetration of DERs, which are usually added to the lower voltage sides compared to conventional power plants are studied from the viewpoint of the reactive power control in steady state operation performance of the grid and a reactive power visualization strategy is presented to improve the situational awareness of reactive power reserve.

If the overall voltage profile of the power system is improved with suitable reactive power control, the possibility of voltage collapse will decrease, and the system will be more resilient. Reactive power issues in transmission, distribution, and load, create the need to provide reactive power locally. This also explains the need to improve the voltage safety of power system, as well as the increasing requirements for the system security in order to reduce losses and ensure the sufficiency of reactive power control during normal and emergency conditions to prevent voltage collapse [24]. Therefore, it is imperative for operation of power system to have situational awareness of the status of reactive power dispatch in the grid as well as the available reactive power reserve with considering the online and offline availability of reactive power margins, since reactive power controls voltage.

In order to visualize voltage stability and the distance of voltages of buses from voltage collapse we proposed to use reactive power visualization in our previous work [25]. We proposed VAR Ready Reserves (VRRs), to provide a useful tool to enhance the situational awareness of the reactive power and voltage in the power system. This visualization technique can be adapted to demonstrate the dispatch, injection, and absorption capability of reactive power devices (such as generators, shunts, SVCs) to provide users with the awareness of reactive power capability and dispatch in the grid. The proposed VRR presents the following levels of information:

Level 1: Online regional reactive power reserve capability

Level 2: Offline regional reactive power reserve capability

Level 3: The present status of regional reactive power dispatch

Level 1 shows the available reactive power absorption and production capabilities for committed reactive power devices including generators, shunts, and SVCs for a region of the system. This is depicted by lighter colors in the middle of the VRR. Level 2 shows the reactive power capabilities for offline devices. This is depicted by darker colors in the VRR and form the upper and lower bound for the reactive power capabilities within a region of a system. So, the upper line and lower line in VRR graphs are the overall positive and negative reactive power capability in each area or a super area, respectively. Level 3 shows the regional reactive power dispatch at a present state of the system. This is presented by the black line within the VRR. A blue-red color mapping is used within this paper, but any high-contrast color mapping may be applied. Figures 2-8 show sample VRR chart for the studied cases.

## IV. CASE STUDIES

Results of different scenarios are demonstrated on two synthetic electric grids with 7,000 buses and 70,000 buses from [26]. Synthetic grids are created based on the strategy presented in [27] to mimic the main characteristics of the actual cases while includes no critical energy/electricity infrastructure information (CEII). These synthetic grids are created based on publicly available data such as U.S. Census [28] and generators‘ information that is available at Energy Information Administration website [29]. Reference [30] outlines fundamental steps for the creation of synthetic power system models. The overall approach for building these networks is described in [30]. The general process includes substation planning, transmission planning and reactive power planning. Also, these synthetic grids are validated based on important characteristics of actual grids called validation metrics [31, 32] for achieving realistic grids. One important feature of these synthetic grids is the availability of geographic coordinates of system elements. First, the synthetic grid over Texas footprint with the actual generators' data in 2019 is considered and the predicted amount of increase in the penetration of renewable resources by 2030 from [33] is added to the grid. Second, the 70k-bus synthetic grid over the Eastern part of U.S. interconnect is considered and studied in two scenarios including the current grid and the impact of moving the regulating buses of all generators to the low voltage side of GSUs. All simulations are carried out using PowerWorld Simulator [34]. The case studies are further described as follows:

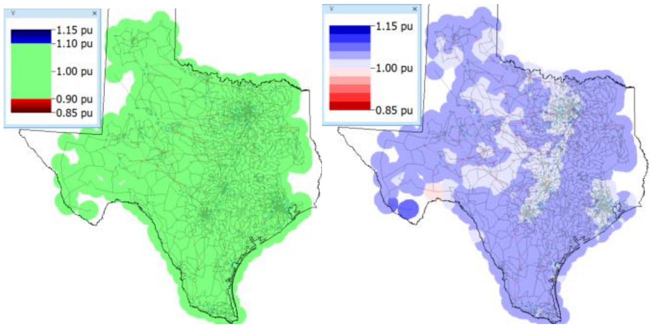
### *A. 7k-bus synthetic grid on the footprint of Texas in the United States with increasing the penetration of renewable resources*

The 7k-bus synthetic grid [26] geographically covers most parts of Texas. This synthetic grid includes 6,717 buses, 4894 substations, 7173 transmission lines, 1967 transformers, 5095 load, 731 generators, 634 switched shunts and 8 areas. The total load is around 75 GW. The transmission network is built using the three nominal transmission voltage levels that exist in the actual grid for this footprint: 345 kV, 138 kV and 69 kV. This grid is studied in two situations:

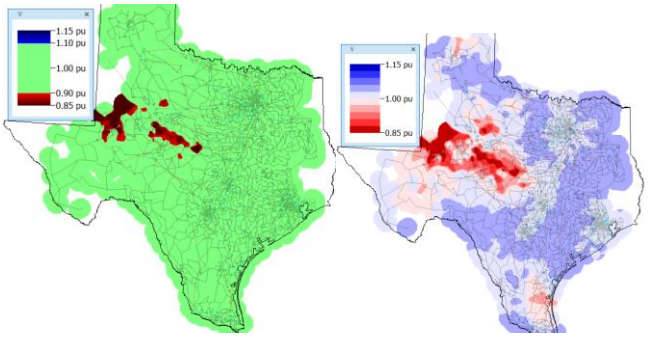
**Case (a):** The 7k-bus synthetic grid [26] in which generator's data are selected of the 7k grid based on actual generators data from year 2019 in [29], where 24.5% of the power generation is from wind and 9% from the sun.

**Case (b):** Generator's data of Case (a) with 36% increase in penetration of wind turbines and 430% increase in PV plants, which is predicted by Electric Reliability Council of Texas Long-Term System Assessment in 2030. [33] The predicted renewable generators are added to the existing substations with the addition of generators buses and some conventional generators are retired as predicted. In this case, 88 buses, 88 GSUs, and 327 renewable generators are added to 7k-bus synthetic grid and two coal power plants are retired.

The voltage profiles of Cases (a) and (b) are compared in Fig. 1 by contouring the bus voltage magnitudes in per unit which is presented in [35] and Table I shows the maximum, minimum, average of pu voltage magnitude (V), and the number of buses with voltage violations for Cases (a) and (b).



Case (a)



Case (b)

Fig. 1. Voltage magnitude (p.u.) contours of all buses of 7k-bus grid in Cases (a) and (b).

TABLE I. THE MAXIMUM, MINIMUM, AVERAGE OF PU VOLTAGE (V) MAGNITUDE, AND THE NUMBER OF BUSES WITH VOLTAGE VIOLATIONS FOR 7K-BUS GRID

| **Case** | **Min pu V** | **Max pu V** | **Ave pu V** | **Number of buses with violation** |
|---|---|---|---|---|
| a | 0.96 | 1.09 | 1.03 | 0 |
| b | 0.75 | 1.07 | 1.02 | 79 |

As it can be observed from Fig. 1, increasing penetration of renewable resources can deteriorate the voltages of buses and cause some low voltage violations in Case (b). However, by adding more reactive power control devices such as switched shunts on these buses, the voltage pu values can maintain voltages in the acceptable range. Therefore, adding renewable devices should be coordinated with adding reactive power devices to avoid voltage issues. This is shown in Case (c).

**Case (c):** We added 8 switched shunts at the buses with the worst low voltage violations in Case (b) and increased the overall capacity of shunts from 43,261 MVAR to 44,101 MVAR so that all voltage violations are removed. In the updated grid, the voltages of all buses range from 0.91 to 1.07 pu and there are no voltage violations out of 0.9-1.1 pu range. The average of all bus voltages remains 1.02 pu.

Fig. 2 shows the VRR charts for the super area of Cases (a), (b) and (c). Figs. 3 and 4 show the VRR charts in two areas with the most voltage violations including Far West and West areas in Texas 7k grid. Since the difference of reactive power dispatch is not obvious Figs. 2-4, the VRR charts of buses with voltage violations in Case (b) are shown for Far West and West area in Figs. 5 and 6, respectively and compared to the reactive power situation on the same buses in Case (c), where voltage violations are removed. Please note the difference between reactive power dispatch and reactive power reserve in Cases (b) and (c) of Figs. 5 and 6.

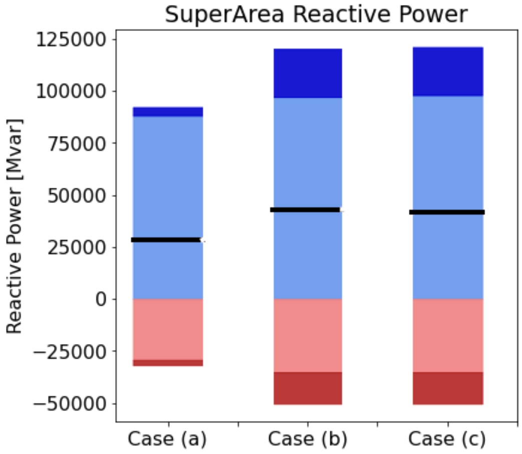


Fig. 2. Super area VRR charts for Cases (a), (b) and (c).

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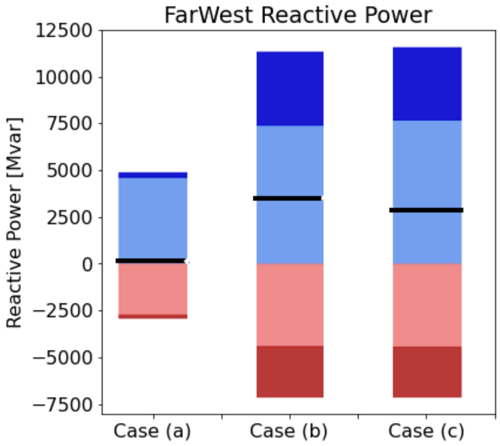

Fig. 3. Far West area VRR charts for Cases (a), (b) and (c).

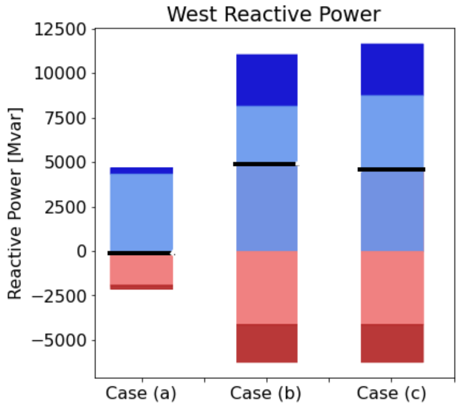

Fig. 4. West area VRR charts for Cases (a), (b) and (c).

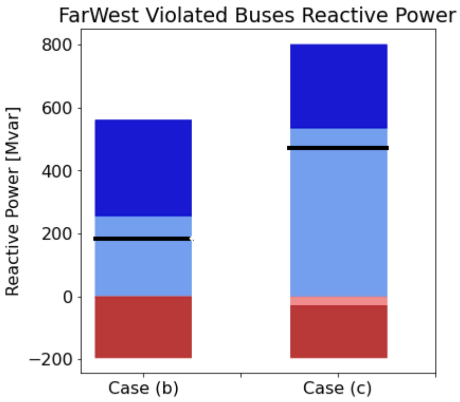

Fig. 5. Far West area VRR charts for buses with voltage violations in Cases (b) and compared to the same buses in Case (c).

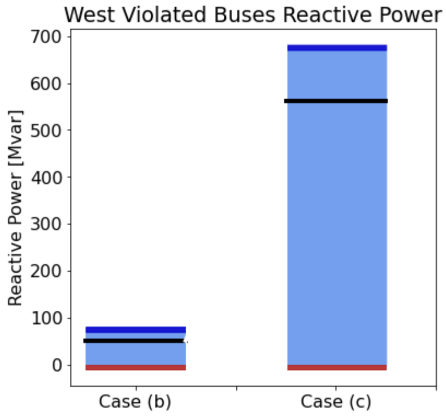

Fig. 6. West area VRR charts for buses with voltage violations in Cases (b) and compared to the same buses in Case (c).

As it is observed from Figs. 5 and 6, additional positive reactive power was required in Case (b) to remove low voltage violations by adding more reactive power resources as in Case (c) the current dispatch and reserve of reactive power is increased.

### B. *70K- bus synthetic grid on the footprint of the Eastern United States with changing the regulating bus of all generators to low-voltage side of GSUs*

The 70k-bus synthetic grid [26] is built with 70,000 buses on the footprint of the Midwest/Eastern United States. This case includes 52 areas and nine nominal voltage levels including 765 kV, 500 kV, 345 kV, 230 kV, 161 kV, 138 kV, 115 kV, 100 kV and 69 kV. Two scenarios are studies in this grid:

**Case (d):** The 70k-bus synthetic grid [26]. In this grid some generators are regulating voltage on the high voltage side or the low voltage side of GSU.

**Case (e):** All generators' regulating buses are moved to the low voltage side of GSU and voltage set points are not changed.

The maximum, minimum, average of pu voltage (V) profiles as well as the number of buses with voltage violations are compared in cases (d) and (e) and shown in Table II. Figs. 7 and 8 show the VRR charts of the super area and Mississippi area in Cases (d) and (e), respectively.

TABLE II. THE MAXIMUM, MINIMUM, AVERAGE OF PU VOLTAGE (V) MAGNITUDE, AND THE NUMBER OF BUSES WITH VOLTAGE VIOLATIONS FOR 70K-BUS GRID

| Case | Min pu V | Max pu V | Ave pu V | Number of buses with violation |
|---|---|---|---|---|
| d | 0.92 | 1.09 | 1.03 | 0 |
| e | 0.86 | 1.11 | 1.03 | 35 |

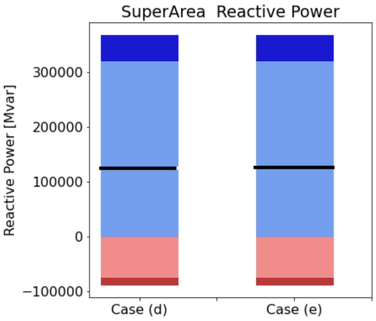

Fig. 7. Super area VRR charts in Cases (d) and (e).

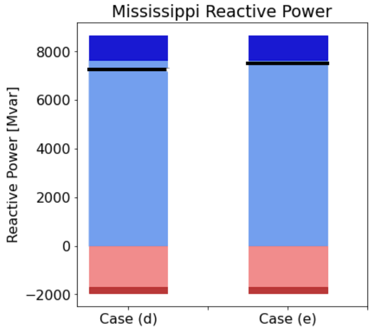

Fig. 8. Mississippi area VRR charts in Cases (d) and (e).

As shown in Table II, moving the regulating buses of generators to the low voltage side without changing their voltage set points causes some voltage violations in Mississippi area and a reactive power mismatch in this area, which results in PF convergence issue in this area. Also, it is observed from Fig. 8 that in Case (e), where reactive power mismatch occurs, the reactive power dispatch is very close to the available reactive power reserve margin in the Mississippi area. This is the main reason that a reactive power mismatch occurs since considering losses, there is not enough reactive power reserve in this area.

In order to avoid this mismatch, the set points of generators should also be updated to the pu voltage of new regulating buses that the reactive power dispatch does not change. Otherwise, the voltage changes and reactive power injection to the regulating buses may not be desired.

This study shows that changing the regulating buses of generators to the low voltage side without updating the voltage set point, can deteriorate the voltage profiles of the grid, and even may cause a reactive power mismatch or voltage collapse. Therefore, the importance of tuning voltage set points of generators is observed. This is due to the fact that when the voltage/reactive power control points of generators move from the high-voltage side of GSUs to the low voltage side, generators which are the primary source of reactive power may generate less reactive power and this makes the power system more dependent on the reactive power control devices. If the capacity of reactive power reserve from control devices is not sufficient, reactive power mismatch or voltage violations can occur.

## V. CONCLUSION

Taking advantage of large realistic but synthetic grids with 7k-and 70k-buses on the geographical footprints of the U.S., which contain no CEII data and include the complicated characteristics of the actual power system, voltage profiles are studied based on different scenarios for voltage regulating buses of generators. The first two scenarios called Cases (a) and (b) study the impact of increase in the penetration of renewable energy resources on voltage profile of the grid. The results show that a significant increase in the penetration of DER without adding reactive power support, can adversely impact the voltage profiles of the grid. This problem can be solved with adding reactive power control devices such as switched shunts as shown as Case (c). In the next two scenarios as Cases (d) and (f), the impact of voltage regulating set points of generators is compared. The results show that when the regulating buses of generators are moved to the low voltage side of GSUs, their set points should be also tuned to avoid voltage violations and even voltage collapse.

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