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Reactive Power Compensation Analysis of the U.S. Eastern Interconnection with Increased Renewable Penetration

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SUMMARY

The penetration of renewable generation in North America's power grid is expected to increase significantly to replace conventional generation in the next few decades. However, impacts of renewable energy on grid characteristics have not been thoroughly studied. Based on a projected high-renewable scenario of the U.S. Eastern Interconnection (EI), which encompasses the area east of the Rocky Mountains as well as a portion of northern Texas, this paper investigated the impact of renewables on voltage profiles and grid voltage stability. To mitigate the potential voltage issues identified in the analysis, this paper proposed a framework to provide additional reactive power compensation, including the optimal compensation location and size selection strategy based on voltage-stability-related indices, which were calculated using QV analysis. The proposed methodology was validated in the Dominion Energy Virginia (DEV) territory using the EI's future high renewable scenario. Results provide valuable insights into the impacts of renewable integration on grid voltage performance and offer corresponding preventive measures.

KEYWORDS

renewable energy, reactive power capability, voltage stability

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1 Introduction

Environmental concerns have precipitated the increase of renewable energy penetration and the replacement of conventional fossil-fueled generation in today's power grids. While this change has brought challenges to both system planning and grid operation, the impacts of these non-synchronous resources on the system security and reliability have not been fully investigated.

Previous studies have mainly focused on the impacts of PVs on distribution systems [1]–[5] considering a small amount of distributed PV installation and its negligible effects on transmission systems. These studies have discovered the impacts of higher PV penetration on system voltage profiles and suggested that existing voltage regulation resources may be insufficient to accommodate the intermittency nature of inverter-based resources (IBRs). In addition, since most distribution-level PVs are not required to participate in voltage regulation [6], lack of reactive power support from these IBRs brought further concerns regarding voltage regulation.

Discussion of the impact on transmission levels [6], which becomes non-negligible as IBR penetration increases, has been limited. [7] compares transient voltage behavior in cases with and without solar generation, concluding that the impact depends on the renewables' size and point of interconnection. However, existing studies do not utilize actual large-scale interconnected models, and the locations of existing renewables do not necessarily reflect future trends. To address these issues, this paper conducts the analysis using the actual model of Eastern Interconnection (EI) developed by Multiregional Modeling Working Group (MMWG). The EI is one of the two major power grids in the continental U.S. It starts at the Eastern Seaboard and goes westward to Central Canada in the north (excluding Quebec) and west to the foot of the Rockies (excluding most of Texas). To project realistic future scenarios with high renewable penetration, information on future solar and wind projects is incorporated into the model from the interconnection queues of Independent System Operators (ISOs) and utilities.

High penetration of renewable generation could change the power flow patterns and the distribution of the reactive power capability in large-scale systems. It is known that reactive power support is closely related to grid voltage issues and reactive power compensation could help improve system security and stability. Sufficient reactive power support is vital for power grids to operate within limits during normal and post-contingency conditions. It is also significant to maintain adequate reactive power reserve for system voltage stability. Ref. [8] investigates the relationship between generator reactive power reserve and system security in terms of voltage stability margin and voltage violations. Ref. [9] presents a formulation for reactive power resource planning through competitive markets for secure operation. A reactive reserve management program based on optimal power flow is proposed in [10] to manage critical reactive power reserves and improve voltage stability. Ref. [11] presents a comprehensive review on the optimal location and sizing of reactive power compensation for voltage stability improvement and voltage profile enhancement. As the validation of most existing methods and stability indices is based on small-scale standard test systems, their effectiveness is unknown in actual large-scale systems. This paper proposes a methodology to identify locations of reactive power compensation and estimate the amount of compensation using indices derived from QV analysis. The method is validated in the high-renewable EI model.

This paper is organized as follows. Section 2 provides a brief description of the modeling of the EI future high renewable scenario. Section 3 introduces the procedure of voltage related analysis and the methodology of reactive power compensation. Section 4 presents the case study results of the proposed approach in enhancing voltage profile and improving voltage stability. Section 5 concludes the findings of the work and provides useful insights for further studies.

2 Modeling of EI future high renewable scenario

2.1 2025 EI high renewable scenario

The penetration of renewable energy has been increasing in North America's electric grid in recent years. To better represent the future scenario with integrated renewables, this study first developed an EI system power flow model that reflects new generation and confirmed retirements till the year of 2025. The model was based on 2024 EI MMWG summer peak model in PSSE. Information of new generation projects is from the generation interconnection queues of ISOs and utilities [12]-[17]. Only Tier 1 capacity additions were considered in this study, which include under construction projects and projects that have executed interconnection service agreement. Confirmed future retirements were referenced from U.S. Energy Information Administration (EIA) Form-860 [18].

2.2 Modeling of renewable generation

In the developed 2025 EI high renewable model, new projects of utility-scale solar and wind were considered. The general structure of the inverter-based renewable generation is shown in Fig 1. Utility-scale renewable projects are usually connected to the grid through step-up transformers and interconnection transmission lines. Due to lack of this information in the generation interconnection queues, new renewable plants were directly connected to the point of interconnection. Since this study focused on the impacts of IBRs on regional system performance, the effects of this simplification could be discounted.

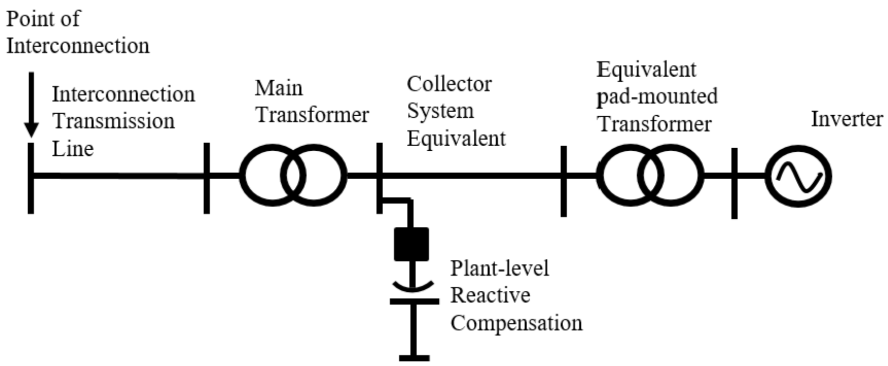


Figure 1 Structure of inverter-based renewables

In PSSE, solar and wind plants are modeled as renewables machines in the power flow model. The main difference in the modeling between conventional machines and renewable machines is the reactive power capability. PSSE offers several options of determining the reactive power limits of the renewable machines: i) standard limits, ii) $+,-$ limits based on constant power factor and iii) fixed Q output based on constant power factor. Interconnection requirements and performance standards of the reactive power capability was set in FERC Order 827[19]. New non-synchronous generators are required to provide dynamic reactive power within the power factor range of 0.95 leading to 0.95 lagging at the interconnection point, unless the transmission provider has established a different power factor range that applied to all non-synchronous generators in its control area on a comparable basis. Therefore, in this study, the reactive power limits of new solar and wind plants were determined by the active power output of the plants and the constant power factor (0.95).

3 Methodology of reactive power compensation

In this section, analysis of the impact of renewable generation on grid voltage is first introduced, including steady-state voltage profiles and voltage stability. Then, the methodology of determining reactive power compensation is proposed to prevent or mitigate the issues identified in the analysis.

3.1 Analysis of steady state voltage performance

3.1.1 Voltage profile

The main focus of voltage profile study is to monitor system voltages under various contingencies. Bus voltage magnitudes should be maintained within operating limits, typically within a ±5% range around the rated value. The integration of renewables could result in variations in regional voltage profiles, mainly because of the reactive power capability difference between non-synchronous generation and conventional generation. Investigation of the impacts of non-synchronous generation on voltage profile could help locate the bus with voltage violations and provide preventive actions.

3.1.2 Voltage stability

Voltage stability describes the ability of a power system to maintain steady voltages at a stable operating point under normal conditions and during contingencies. Voltage instability are typically observed at load centers as the loading increases and system reaches the voltage collapse point, also called the 'nose' point. A typical relationship between the voltage at the load buses and the loading level is depicted by the PV curve, as shown in Fig 2. It can be concluded that as the loading level increases, voltage drops gradually and finally reaches the voltage collapse point, where the system could not return to a stable operating point. The additional capacity between the normal operating point and the collapse point is defined as the Voltage Stability Margin (VSM), an indicator of the voltage stability level of the system [20]. According to Fig 2, VSM could be significantly reduced under critical contingencies, which will increase the risk of system instability.

The most common cause of voltage instability is the lack of reactive power capability. Voltage collapse is associated with reactive power demands not being met due to the deficiency in the production and transmission of reactive power [21]. The increasing penetration of renewable generation could result in the change of regional distribution of reactive power capability. Therefore, it is of vital importance to study system voltage stability in the high renewable scenario, identify critical contingencies, and plan corresponding preventive actions to improve system stability.

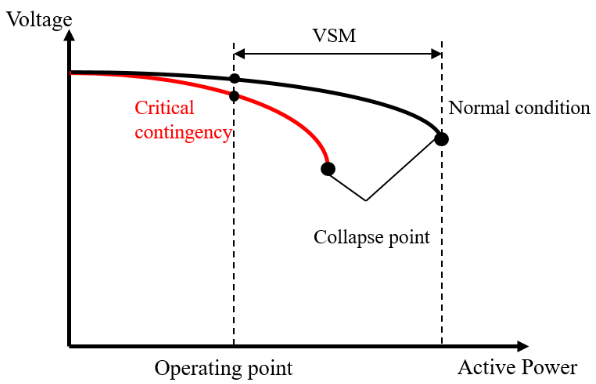


Figure 2 PV curve

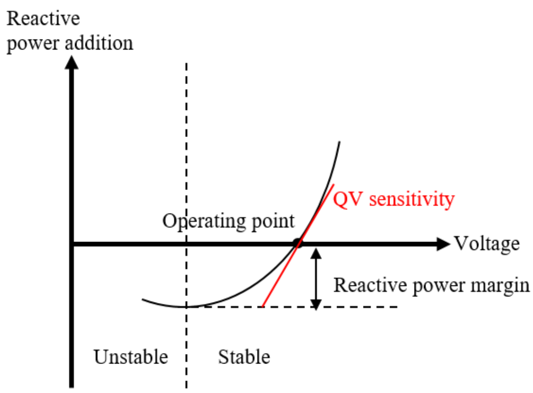


Figure 3 QV curve

3.2 Reactive power compensation

3.2.1 QV curve

QV curve serves as a useful analysis of voltage stability. It depicts the relationship between the voltage at a specific bus location and the additional reactive power injection at the bus, which is shown in Fig 3. The right half of the curve is the stable operating region and the nadir point of the curve indicates the maximum additional reactive load that can be sustained at the study bus, i.e. the reactive power margin. When the nadir is above zero, there is a deficit in reactive power at the bus and no stable operating point could be reached without addition reactive support. To maintain a stable operating point, the nadir should be below zero.

The zero-crossing on the QV curve is the current operating point of the study bus and the slope is defined as the QV sensitivity at the operating point. As the regional loading level increases, QV curve will move upward and QV sensitivity at the operating point will reduce. A lower QV sensitivity at the operating point denotes a less stable system [22]. Therefore, the relative change of the QV sensitivity could also serve as an index of voltage stability margin. In addition, QV sensitivity at the operating point could be used to calculate the amount of reactive power compensation at the study bus to eliminate bus voltage violations identified in the voltage profile study.

3.2.2 Voltage profile enhancement

Voltage profile study could help identify bus voltage violations under different contingencies. To eliminate the identified violations and enhance voltage stability, this paper proposed an approach using QV curve to determine the required amount of reactive power compensation to maintain bus voltages within normal operating limits. The procedure is generalized into the following steps:

i) Locate the buses with voltage violations. The current voltage is denoted as V^{viol}

ii) Calculate QV sensitivity at the operating point at the violated bus, denoted as QV^{sen}

iii) Determine the target voltage V^{target} after compensation, which should be within the normal operating limits.

iv) The required amount of the reactive compensation at the violated bus could be approximated as

$$Q^{com} = QV^{sen}(V^{target} - V^{viol})$$

3.2.3 Voltage stability improvement

To improve system voltage stability under critical contingencies, this paper proposed a methodology to locate potential weak buses and determine the amount of reactive power compensation at those locations. The procedure is summarized by the flow chart shown in Fig 4.

As the first step, PV analysis are implemented in the loading scenario of interest and the VSMs of the study region are calculated under various contingencies. Based on the VSM in normal conditions, a threshold of critical VSM could be determined. As a screening metric, the threshold could help identify critical contingencies when VSM significantly decreases. To improve VSMs in critical contingencies, the proposed method first identifies weak bus locations by comparing the relative change of QV sensitivity at the operating point between normal conditions and critical contingencies. Buses with significant reduction of QV sensitivity are considered as the vulnerable buses and ideal locations for reactive power compensation. After fixing the compensation location, the size of compensation could be determined by varying the compensator capacity and comparing the improvement of VSM before/after the compensation. System requirements of stability margin and other factors, such as operating and maintenance cost, should also be considered.

4 Case Study

4.1 Case description

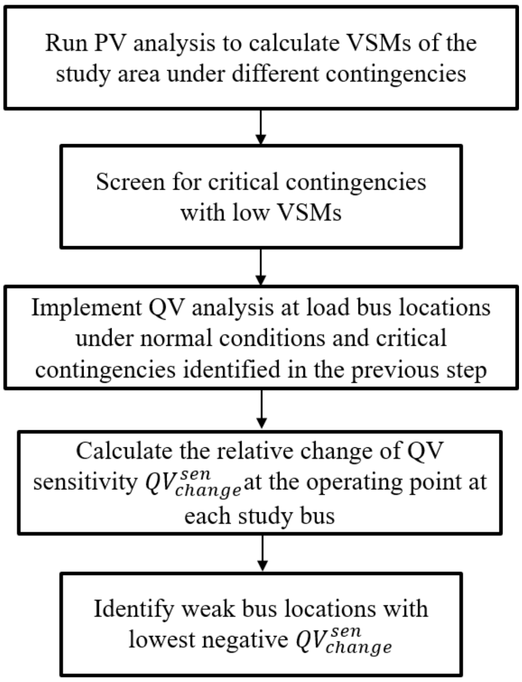


Figure 4 Procedure of reactive power compensation for enhancing voltage stability

The study case used in this paper is the 2025 EI high renewable case mentioned in Section 2.1, which was based on the 2024 MMWG summer peak case. Table 1 shows the amounts of generation additions and retirements in the 2025 Case by regions and fuel types. EI was separated into the following regions: Pennsylvania-New Jersey-Maryland (PJM), Southeastern Electric Reliability Council (SERC), Southwest Power Pool (SPP), Northeastern Power Coordinating Council (NPCC) and Midcontinent Independent System Operator (MISO). The generation additions were selected from the interconnection queues of ISOs and utilities [12]-[17]. In the Dominion Energy Virginia (DEV) territory, new renewable generation replaced some of the conventional generators. The list of candidate generators to be replaced was provided by Dominion Energy. For other regions, power imbalances caused by generation additions and retirements were met by rescaling all in-service generation in that region.

Table 1 Generation additions and retirements in 2025 High Renewable Case

Region	Renewable additions/MW	Natural gas additions/MW	Nuclear additions/MW	Hydro additions/MW	Coal retirements/MW
PJM	3,318	8,216	0	23	1,609
SERC	5,492	52	2,200	0	476
SPP	2,387	66	0	0	198
NPCC	980	672	0	0	684
MISO	7.859	0	-810	119	9,784

4.2 Voltage profile study

Voltage profile studies were carried out using both 2024 MMWG model and 2025 high renewable model. To study the impact of renewables on voltage profile under different contingencies, single line outage (N-1) contingencies within the DEV area were investigated. Results were compared in terms of voltage violations and flow violations. Voltage limits under normal operating conditions specified by voltage levels were provided by Dominion Energy. Branch flow limits were set as 94% of Rate B of line ratings, according to Dominion Energy planning criteria. The comparison between the 2024 MMWG case and the 2025 high renewable case is shown in Table 2. Fewer low voltage violations are observed at 115 kV level in the 2025 high renewable case, while there are also fewer high voltage violations at the 500 kV level in this scenario. The integration of renewable generation and retirements of conventional machines could change flow patterns and also the distribution of reactive power capability, which could result variations in voltage profile. The locations of voltage violations that newly appeared in the 2025 high renewable case are shown in Figure 5.

Table 2 Comparison of violations

Case	Low voltage violations			High voltage violations			Flow violations
	115kV	230kV	500kV	115kV	230kV	500kV	
2024 MMWG	23	0	3	42	31	16	12
2025 high renewable	14	4	1	45	31	6	5

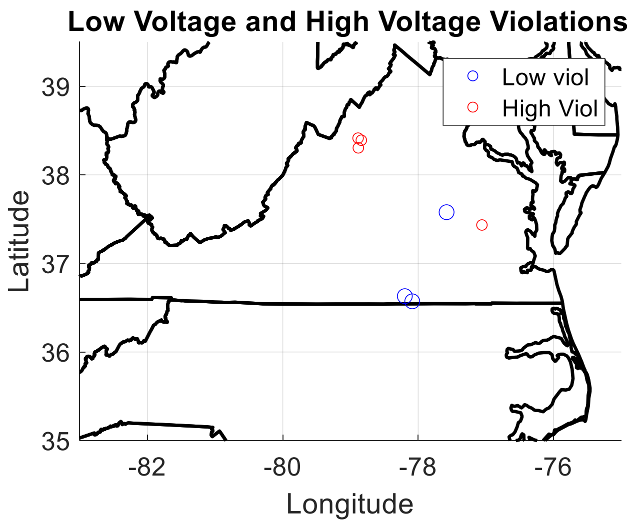


Figure 5 Locations of new voltage violations

To eliminate those voltage violations caused by renewable integration, switched shunt compensation was introduced. The amount of reactive power compensation can be determined by the QV sensitivity method proposed in Section III. This procedure is illustrated using one selected violation as an example. Table 3 shows the voltage before and after compensation at the selected bus with violation after a 115kV branch outage contingency. The QV curve of this bus is shown in Figure 6. The amount of compensation needed to operate within normal limits is calculated as

$$Q^{com} = QV^{sen}\left(V^{target} - V^{viol}\right) = \frac{12.04}{0.02} * (0.9945 - 0.9180) = 46.05MVar$$

QV sensitivity is approximated by the slope between two consecutive points near the zero-crossing on the QV curve. The target voltage after compensation is determined as the midpoint of the normal limits. It can be noted that there is a minor difference between the target voltage and the actual voltage after compensation, which can result from the approximation of the QV sensitivity and the change of Q-V relationship after compensation.

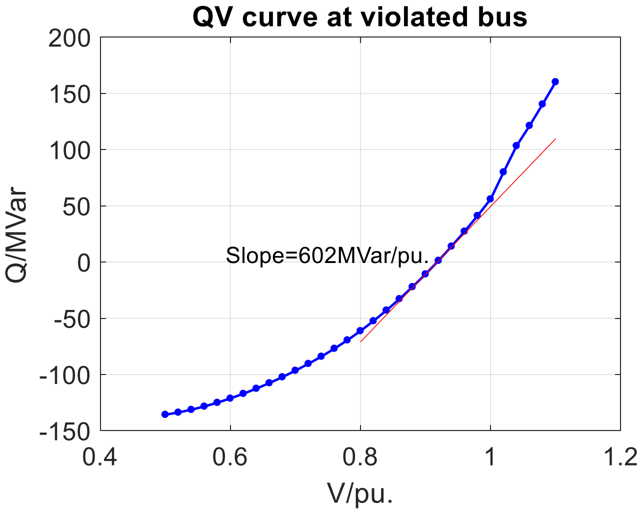


Figure 6 QV curve at violated bus

Table 3 Comparison of voltage before/after compensation

Normal limits	Before Compensation (pu.)	After Compensation (pu.)	Compensation (MVar)
[0.949,1.04]	0.9180	0.9866	46.05

4.3 Voltage stability study

To study the voltage stability of the DEV area, higher loading scenarios were investigated, where loads inside DEV area were scaled up and active power outputs of generators in the region are correspondingly increased to accommodate the load increase. VSMs are defined as the amount of load increase from the current operating point to the voltage collapse point. Single line outage contingencies within the DEV area were investigated and VSMs were compared, as shown in Fig 7. In this study, the threshold of identifying critical VSM was set as 90% of the no-contingency scenario. Contingencies with VSMs lower than this threshold were considered as critical contingencies. It can be noted from the figure that under some critical contingencies, VSM could drop to less than 70% of the no-contingency scenario, which justifies the need for further investigation into these contingencies for the secure and reliable operation of the system.

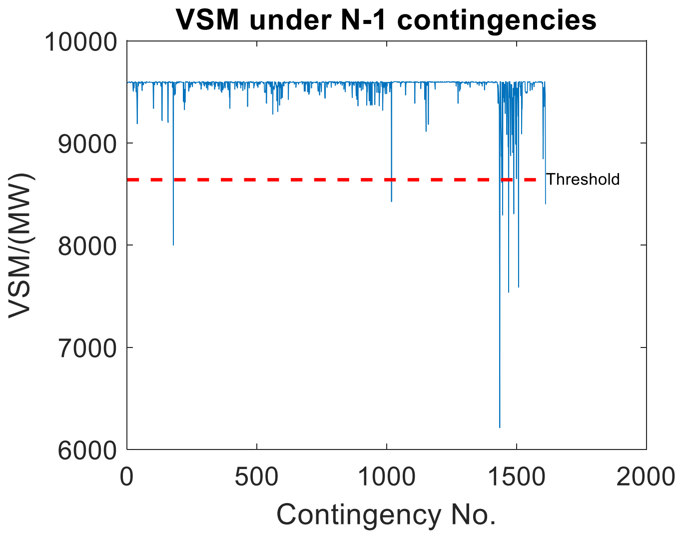
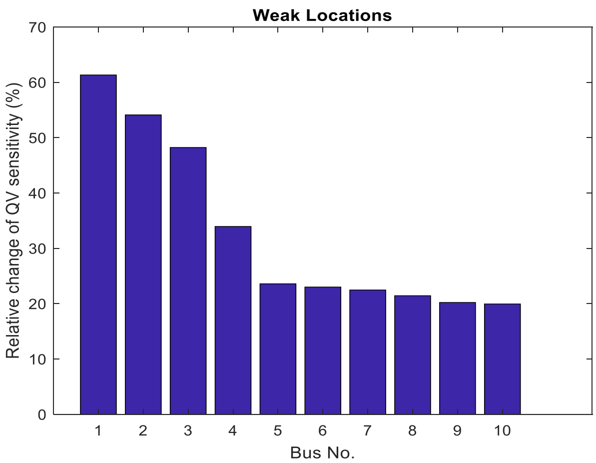


Figure 7 VSMs under N-1 contingencies

To improve regional VSM under critical contingencies, the proposed procedure of reactive power compensation was implemented repeatedly for each identified critical contingency. Due to the page limit, only the results of the weakest contingency (the one with the lowest VSM) are presented as follows. First, QV analysis was carried out at load buses inside the DEV area under both the normal condition and the critical contingency. Then, the relative change of QV sensitivity at the operating point were calculated. Fig 8 shows the top 10 locations with the highest relative change. To validate the effectiveness of the proposed indices in identifying weak locations that require reactive power compensation, switched shunt compensation was installed at each of the 10 locations and the VSMs were recalculated after compensation, as shown in Fig 9. At this stage, the switched shunt compensation was set to work in the continuous mode and could provide any reactive power support needed. It can be seen that additional reactive compensation at the weak locations identified using QV sensitivity indices could significantly improve the VSMs of the DEV area.

To further determine the suitable capacity of the shunt compensation, the capacity of the switched shunt compensation was varied at one of the weak locations and the improvement of VSM is shown in Fig 10. Results indicate that as the capacity of compensation increases, the improvement of regional VSM increases almost linearly with the compensation capacity before it reaches the turning point at about 2,000 MVar. After the turning point, additional reactive compensation at this location could no longer increase the VSM. This relationship could provide insights for lower system planning studies to determine the appropriate size of compensation needed for critical conditions.



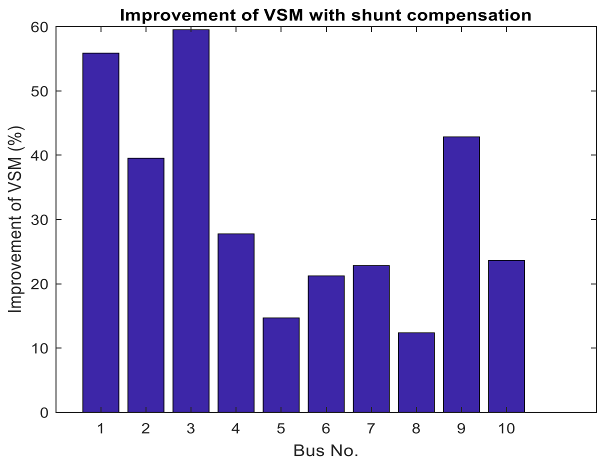


Figure 8 Identified weak locations

Figure 9 Improvement of VSM with shunt compensation

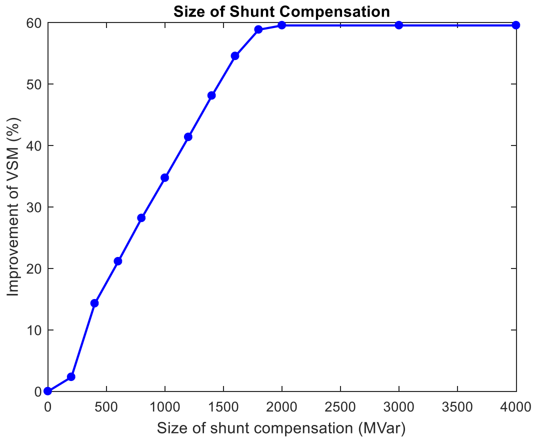


Figure 10 Different sizes of compensation

5 Conclusion

This paper conducts an analysis on the impacts of high penetration of renewables on grid voltage using 2025 EI Renewable Model, which is developed based on the 2024 EI MMWG summer peak model and by incorporating the future renewable scenario using active projects in the generator interconnection queues of ISOs and utilities. To mitigate the voltage related issues identified in the analysis, the paper proposes a methodology to identify weak locations that require additional reactive compensation in order to improve voltage stability. The key findings and potential future work could be summarized as follows,

a) High penetration of renewables could result in voltage magnitude violations and flow violations. Integration of renewables and replacing conventional generation could change the flow patterns and reactive power and voltage regulation capabilities.
b) QV sensitivity at violated bus could be used to determine the amount of reactive power compensation needed to enhance voltage stability.
c) Significant change of QV sensitivity at the operating point under critical contingencies could indicate potential weak locations in terms of reactive power. Compensation at these weak locations could effectively improve voltage stability margins. QV analysis-based stability indices could provide candidate locations of reactive power compensation for planning studies to guarantee secure and reliable operation of the system. Optimization could be further implemented on placement and sizing. Future studies could be focused on approximating QV sensitivity using online measurements, as a useful tool for online stability assessment.

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