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

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Background and Motivation

- The impacts of inverter-based resources on system security and reliability have not been fully investigated.
- Previous studies have mainly focused on the impacts of IBRs on distribution systems. Discussion of the impact on transmission level has been limited.
- High penetration of renewable generation could change the power flow patterns and the distribution of reactive power capability in large-scale systems. Maintaining sufficient reactive power support is significant for the secure and stable operation of the grid.
- Most existing methods of reactive power compensation and related stability indices are validated on small-scale standard test systems, the effectiveness is unknown in actual large-scale systems.

Contribution

- Develop a 2025 high renewable scenario of the Eastern Interconnection (EI) based on MMWG planning model
- Investigate voltage related issues within Dominion Energy territory, including voltage profile and voltage stability
- Identify ideal locations of reactive power compensation and estimate the amount of compensation using indices derived from QV analysis

2025 EI Renewable Model

- Based on MMWG summer peak model, this study developed a 2025 EI Renewable Base case that reflects new generation projects and confirmed retirements till 2025.

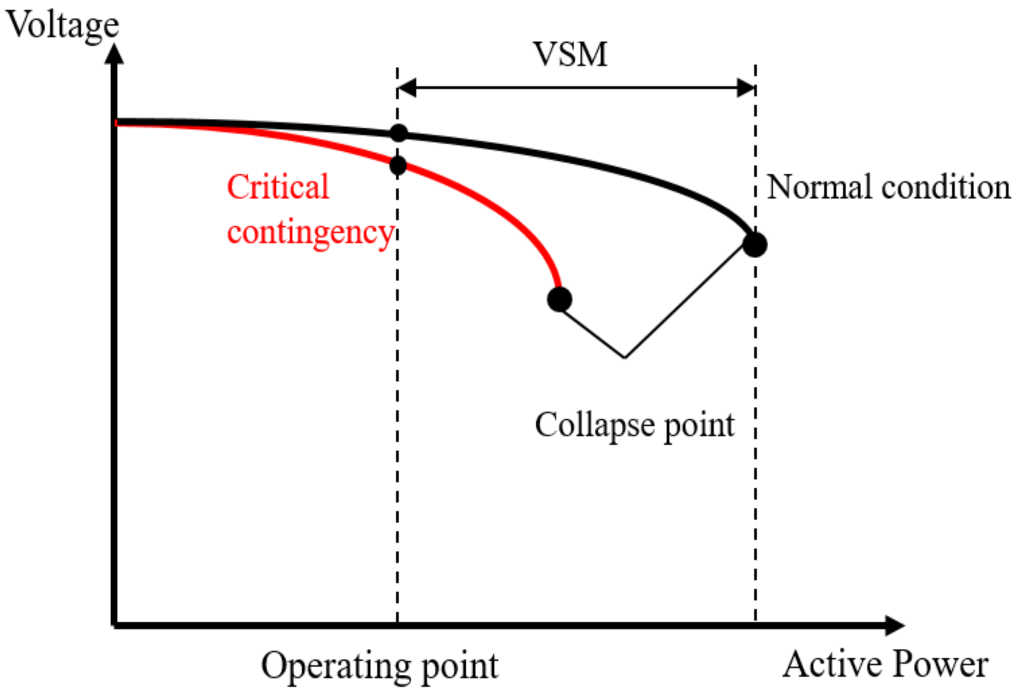
- Information of new generation projects is from generation interconnection queues of ISO and utilities. Only Tier 1 capacity additions are considered, which include under construction projects and projects that have executed interconnection service agreement.

- Confirmed retirements are referenced from U.S. Energy Information Administration (EIA) Form-860.

- The reactive power capability are modeled as recommended in FERC Order 827. New non-synchronous generators are required to provide dynamic reactive power within the power factor of 0,95 leading to 0.95 lagging.

Impacts of renewables on grid voltage

- Voltage profile
  - Bus voltage magnitudes should be maintained within operating limits
  - Integration of IBRs could result in variations in regional voltage profiles
- Voltage stability
  - It describes the ability of a power system to maintain steady voltages at a stable operating under normal conditions and during contingencies.
  - As loading level increases, system reaches the collapse point.
  - Relationship between voltage and loading level is depicted by PV curve.



PV curve

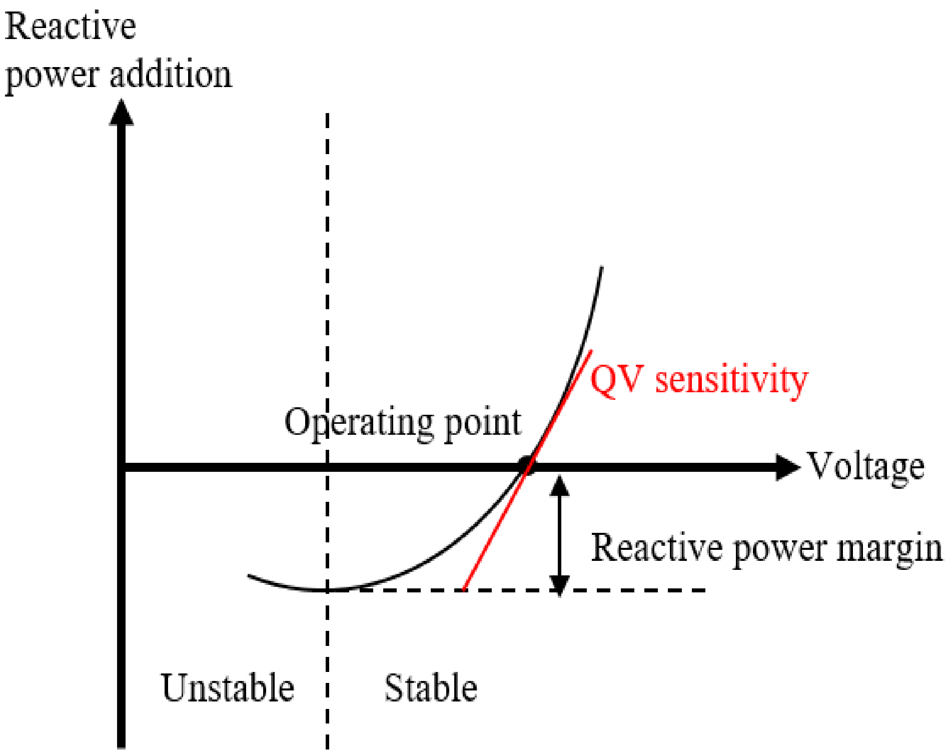
Reactive power compensation

- QV curve
  - It specifies the additional reactive power injection required to maintain the bus voltage at a certain value.
  - Operating point
  - QV sensitivity

- Voltage profile enhancement
  - Eliminate bus voltage violation by adding reactive power compensation
  - Calculate QV sensitivity at the operating point at the violated bus, denoted as QV^{sen}
  - The required amount of the reactive compensation at the violated bus could be approximated as

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

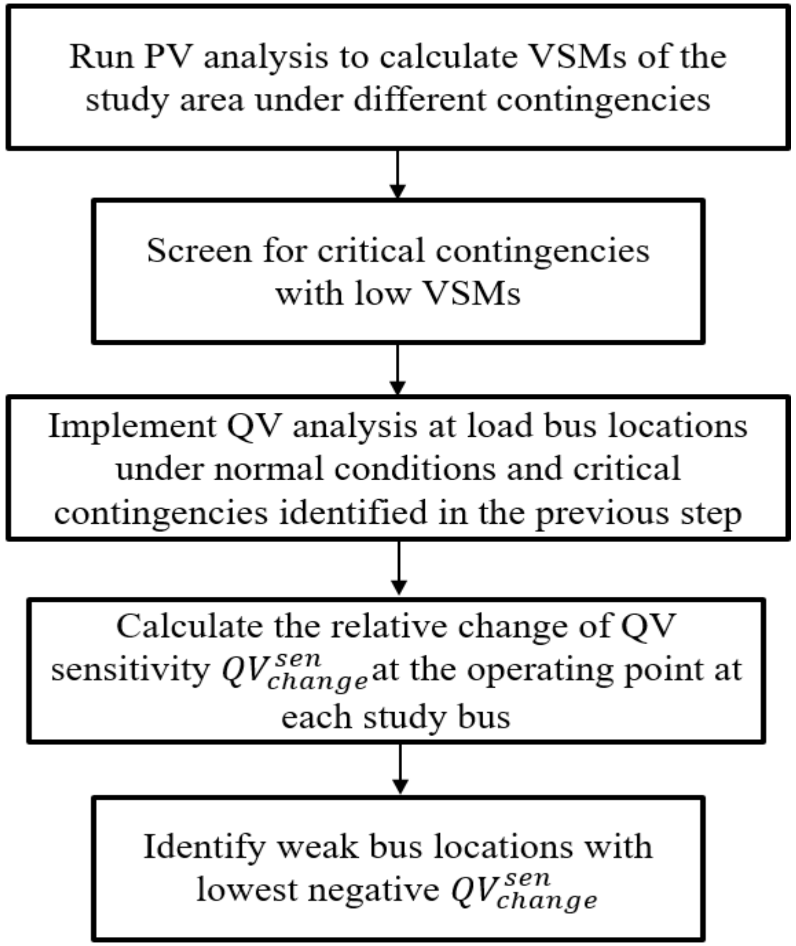
where V^{viol} is the violated voltage, V^{target} is the target voltage



QV curve

Reactive power compensation

- Voltage stability improvement
  - Critical contingencies where VSMs are relatively lower needs to be identified.
  - Weak bus identification
    - Relative change of QV sensitivity at the operating point after the critical contingency occurs
    - Buses with significant reduction in QV sensitivity are considered as vulnerable buses
    - Compensation are added at the identified weak location and improvement of VSMs are validated.



Run PV analysis to calculate VSMs of the study area under different contingencies

Screen for critical contingencies with low VSMs

Implement QV analysis at load bus locations under normal conditions and critical contingencies identified in the previous step

Calculate the relative change of QV sensitivity QV_{change}^{sen} at the operating point at each study bus

Identify weak bus locations with lowest negative QV_{change}^{sen}

Case Study

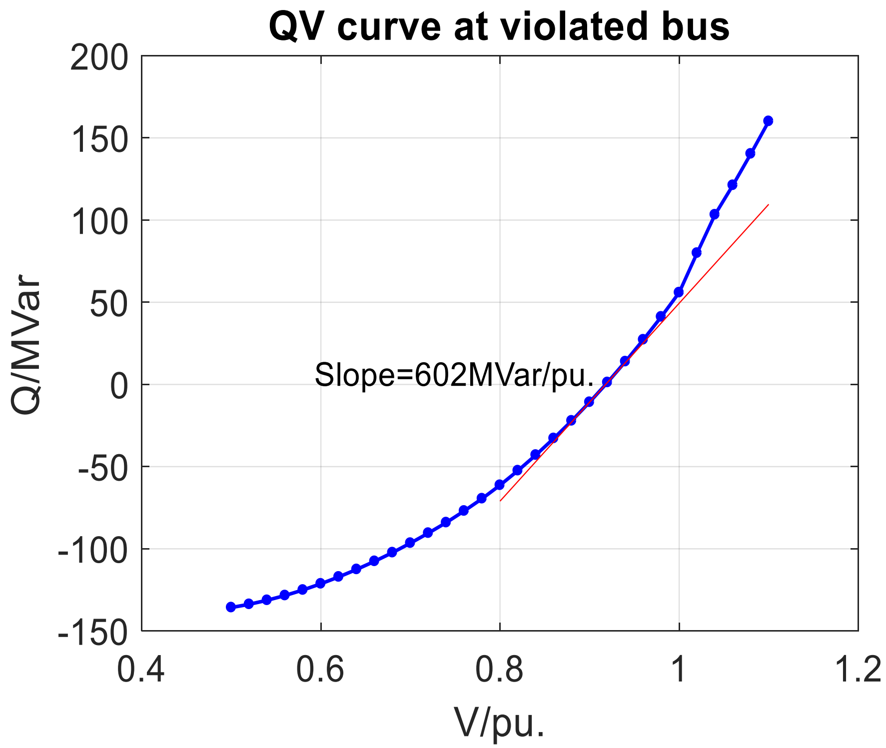
Summary of 2025 EI Renewable Base Case

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

Case Study – Voltage profile enhancement

- Loss of single branch contingencies are studied using the developed 2025 model.
- Low voltage, high voltage and flow violations are identified.
- Below is an example of adding reactive power compensation to eliminate voltage violations.

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



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

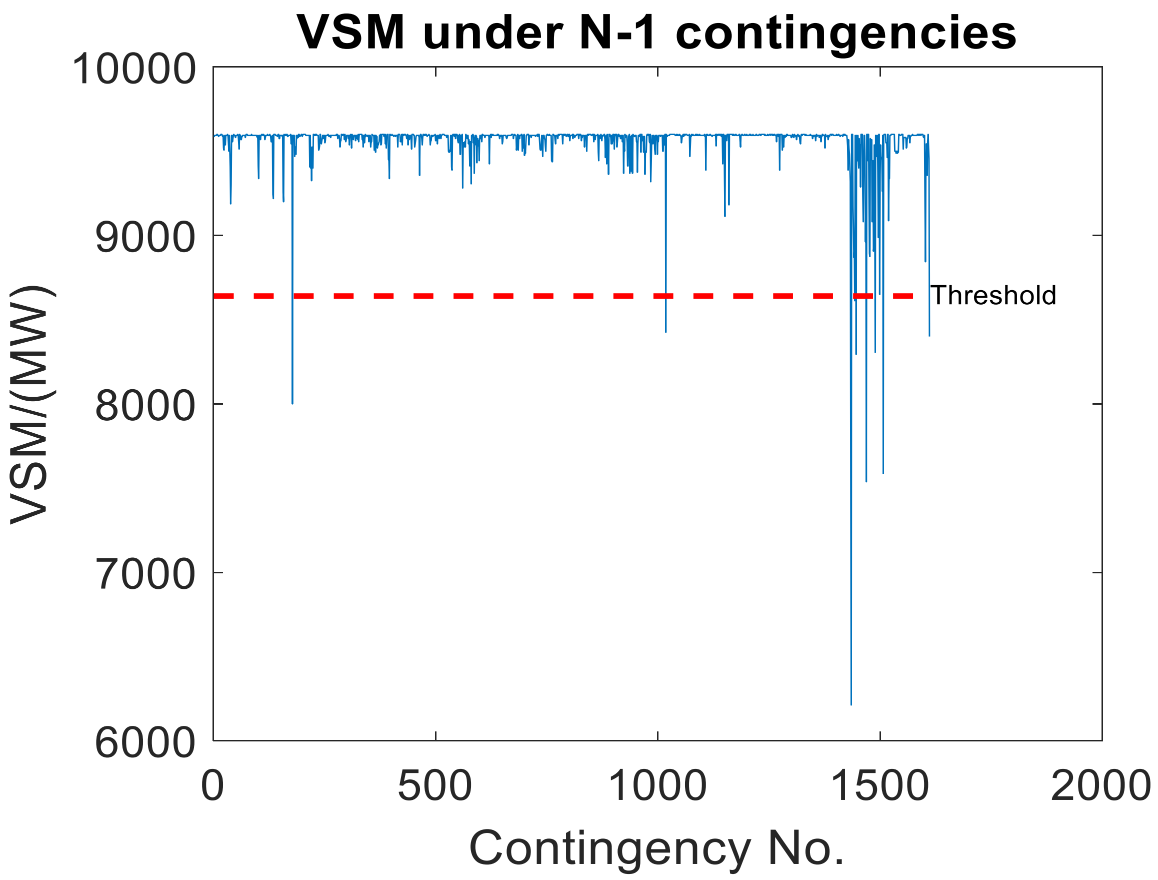
Case Study – Voltage Stability Improvement

- Loading level within the Dominion Energy area is scaled up. VSM is defined as the amount of load increase from the base case operating point to the collapse point.

- VSMs are evaluated under loss of single branch contingencies within Dominion Energy.

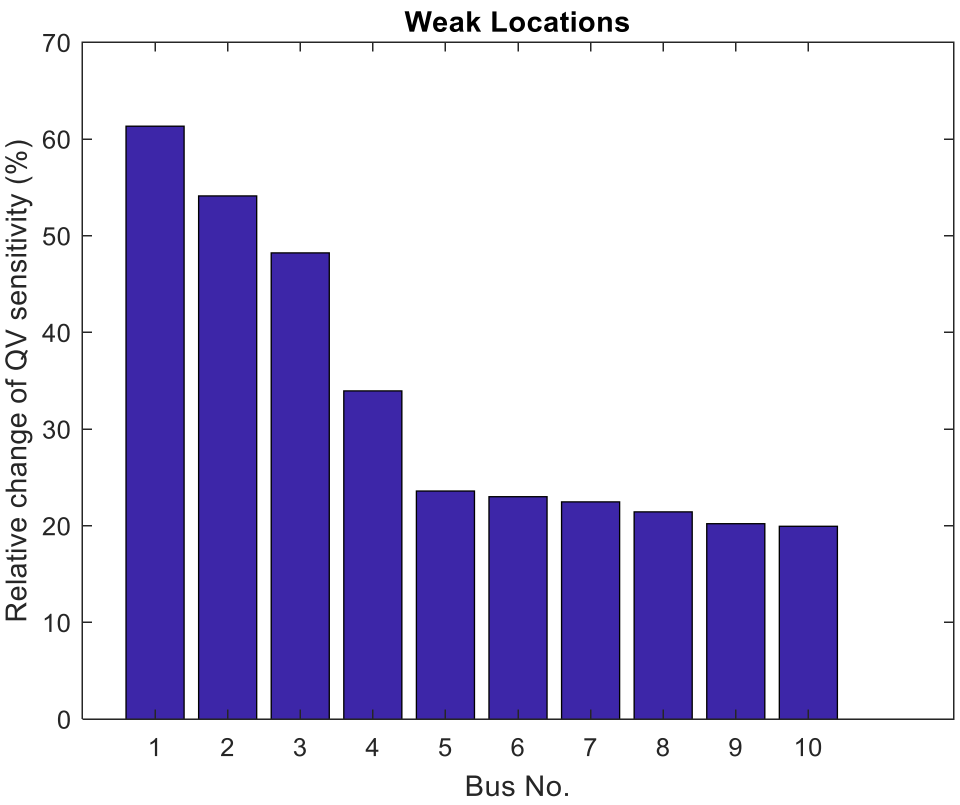
- A threshold of 90% of VSM in no-contingency scenario is established to identify critical contingencies.

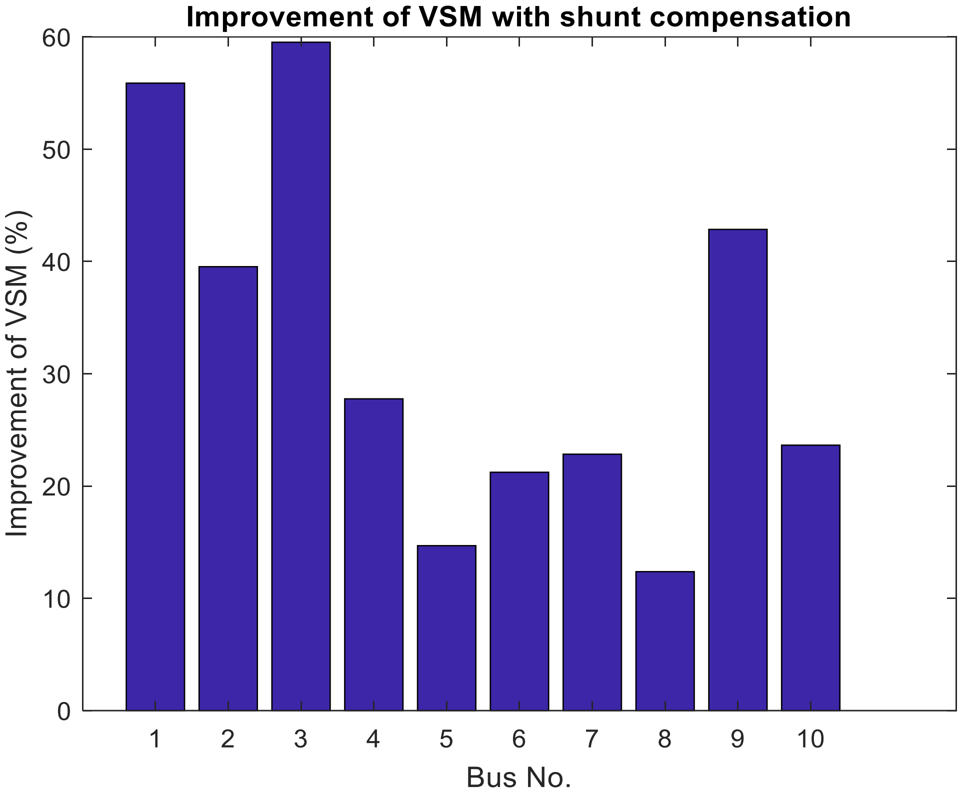
- Weak locations are identified under each critical contingency.



Case Study – Voltage Stability Improvement

- Example – Critical contingency with lowest VSM



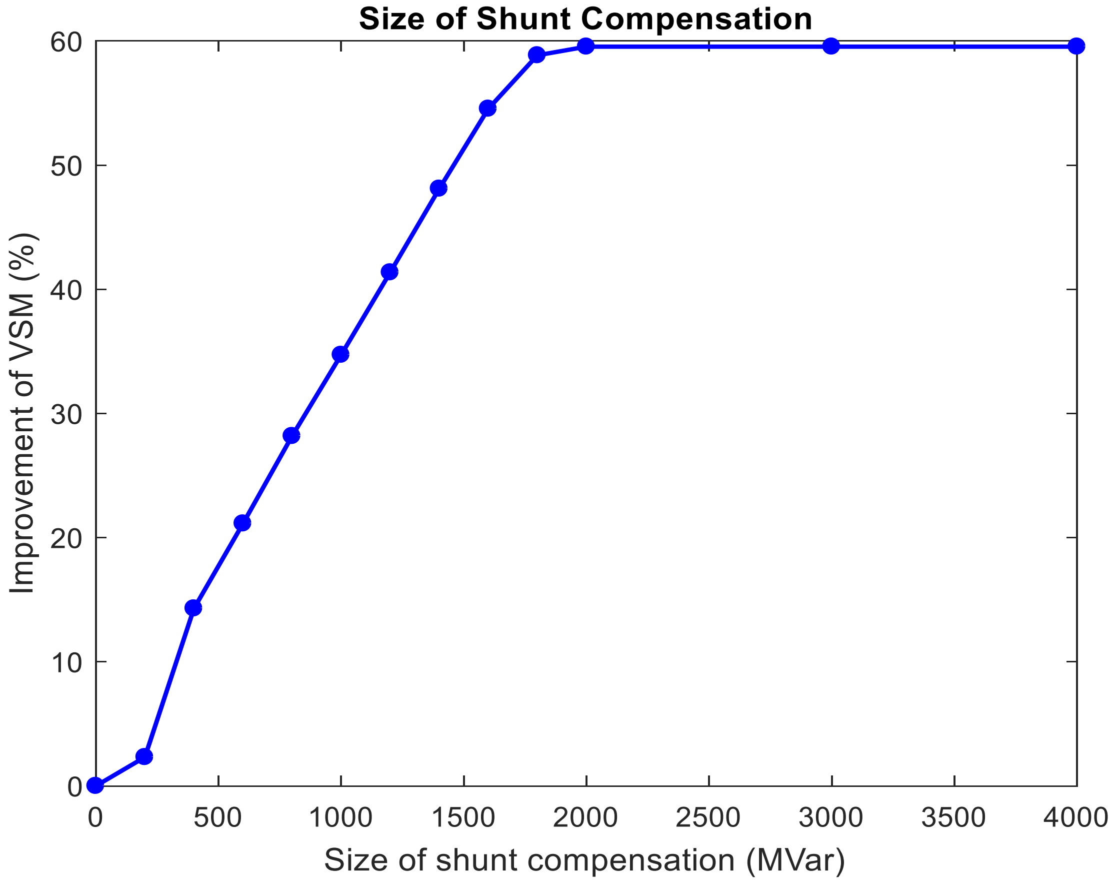


Top 10 locations with large change of QV sensitivity

Improvement of VSM

Case Study – Voltage Stability Improvement

- Size of reactive power compensation varied



Conclusion

- Developed a 2025 EI Renewable Base case based on MMWG summer peak model and incorporate future generation projects from interconnection queues of ISOs and utilities
- Conducts an analysis on the impacts of high penetration of renewables on grid voltage using 2025 EI Renewable Base case
- High penetration of renewables could change the flow patterns and cause new voltage violations
- Proposed an index based on QV curve to identify weak locations that require reactive power compensation to improve voltage stability