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### **Impacts of Photovoltaic Generation and Natural Gas-fired Generation on Large-scale Power Systems**

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#### **SUMMARY**

Growing interest in renewable projects has led to the replacement of conventional generation with inverter-based resources (IBRs). With the increasing penetration of renewable resources, grid characteristics of large-scale power systems, including steady-state and dynamic performance, could experience changes. This paper aims to compare the impact of photovoltaic (PV) generation and conventional natural gas-fired generation on short-circuit level, voltage profile and dynamic performance in the territory of Dominion Energy Virginia. Future PV projects were selected from PJM's interconnection queues and added to the system to replace a portion of conventional generation. Case studies were carried out using an 80k-bus Eastern Interconnection (EI) model. Results identify the impact of PV and natural gas-fired generation on both static and dynamic grid performance.

#### **KEYWORDS**

renewable energy, natural gas-fired generation, short-circuit analysis, dynamic characteristics

## 1 INTRODUCTION

With the increasing need for clean and renewable energy, conventional fossil-based generation is gradually being replaced by inverter-based renewable resources (IBRs), among which photovoltaic (PV) generation plays a significant role. PV generation can be installed at both small-scale (normally rooftop PV panels, closer to load customers) and at large-scale (usually away from load centers). Regarding the interconnection to grid, small-scale PVs are normally connected to distribution systems and modeled as negative active power loads, while large-scale PVs are connected to the system at the transmission level and modeled as generators.

The increasing penetration of IBRs has raised challenges to secure and reliable operation of large-scale power systems. Previous studies focused mainly on the impact of photovoltaics (PVs) on distribution systems [1]–[5], where the small amount of distributed PV installation at the time had negligible effects on transmission systems. These studies did report that higher PV penetration would have an impact on system voltage profiles, and they suggested that existing voltage regulation resources may be insufficient to accommodate the intermittency nature of the IBRs. In addition, since most distribution-level PVs are not required to participate in voltage regulation [6], the lack of reactive power support from these IBRs raised further concerns regarding voltage regulation.

While a number of focused on the impact of IBRs on distribution systems, there has been limited discussion about IBR impact at the transmission level [7], which is nonnegligible as the penetration of IBRs increases. Ref. [6] studied the impact of increased penetration of PV systems on static performance as well as transient stability of the Western U.S. interconnection, in particular the transmission system. Ref. [8] compared transient voltage behavior in cases with and without solar generation and concluded that the impact depends on the size and point of interconnection of the renewables. However, existing studies did not utilize actual large-scale interconnected models, and the locations of the added renewables did not necessarily reflect future trends.

To address these issues, we conducted our analysis using the actual model of the 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). We created future PV scenarios by integrating PV projects from the generator interconnection queue of Independent System Operators (ISOs) reviewed by the end of 2020.

The paper is organized as follows. Section II introduces the study model and target scenarios. The modeling of PV generation, including both power flow and dynamic models, is also discussed. In Section III, different analyses investigate the impacts of both PV generation and gas-fired generation on system characteristics. Section IV presents the case study results of the EI model from different perspectives, including both static and dynamic performances. Section IV summarizes our key findings.

## 2 MODELING OF THE STUDY SYSTEM

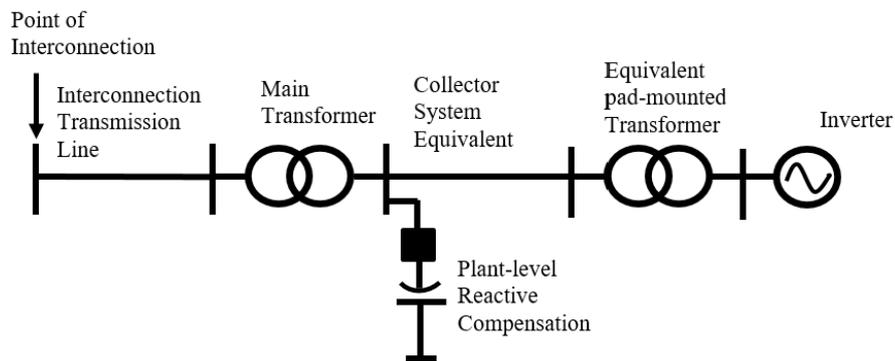
### 2.1 SUMMARY

The system we chose to study was the 2024 Eastern Interconnection spring light load model developed by MMWG, representing the light load conditions of EI with less dispatched generation during spring season. The model represents transmission voltage levels ranging from 69 kV to 765 kV. Dominion Energy Virginia (DEV) was selected as the study area.

The spring light load case was selected for this study because it represents lower loads and less dispatched conventional generation. In this case, conventional generation provided less fault current than the summer peak scenario, and the short-circuit MVA level was lower. By replacing synchronous generators, newly integrated IBRs could further reduce the short-circuit level due to its nature of intermittency and its smaller contribution to fault currents. Therefore, the light load case could provide a valid representation of the worst-case scenario caused by the integration of renewable generation.

In this study, utility-scale PV projects within the DEV area were included in the study system. These projects were selected from the PJM interconnection queue, which provides information about point-of-interconnection (POI) and generator capacities.

Projects that are under construction, or that have executed the interconnection agreement, have the priority to be added in the study system. The structure of a utility-scale PV is shown in Figure 1. PV inverters are connected to the POI location through step-up transformers and interconnection transmission lines. However, detailed parameters of step-up transformers and interconnection transmission lines of each utility-scale PV project were not available in the interconnection queue. Therefore, as an alternative, in this study PV plants are directly connected to the POI buses. Since this study focuses on the impacts of IBRs on regional system performance, the effects of this simplification could be discounted.



**Figure 1 Structure of inverter-based renewables**

To compare the impact of PV generation and conventional natural gas-fired generation on system characteristics, this study created a scenario that added a new natural gas-fired plant in the central Virginia area. The location and the generating capacity of the gas plant were provided by Dominion Energy.

## 2.2 MODELING PV GENERATION

### 2.2.1 Power Flow Model

In PSS/E, solar plants are modeled as renewable machines in the power flow model. The main difference in power flow modeling between conventional and renewable machines is their reactive power capability. PSS/E offers several options to determine the reactive power limits of renewable machines: i) standard limits, ii) +, – limits based on constant power factor and iii) fixed Q output based on constant power factor. In this study, the reactive power limit is determined by the active power output of the plant and the power factor range specified in FERC Order 827 [9].

Per FERC Order 827 [9], a large generation facility must be designed to deliver composite power at a continuous-rated power output at the high-side of the generator substation; the power factor must be within the range of 0.95 leading to 0.95 lagging (unless the transmission provider has established a different power factor range that applies to all non-synchronous generators in its control area). In this study, utility-scale PV plants are modeled similarly to conventional generators for steady state analysis. The reactive power limit is determined by the active power output of the plant and the power factor range specified in FERC Order 827.

Another difference in steady state between IBRs and synchronous generators is source impedance. Inverter-based generation is assumed to provide much less fault current during short-circuit conditions. In order to identify the worst effects of the IBRs on short-circuit MVA level, in this study it is assumed

that PV plants do not contribute to fault currents and the impedance of the plants is set to a very large value.

### 2.2.2 Dynamic Model

For dynamic studies, the dynamic model of utility-scale PV is different from the one used in the power flow model. As modeled in PSS/E, the dynamic model of utility-scale PV consists of three modules: a generator/inverter, an electrical control, and a plant controller. The connectivity diagram of the PV plant is shown in Figure 2.

- **The generator/inverter module (REGC)** models the generator's interface with the grid network. It processes the active- and reactive-current command from the electrical control module and outputs active and reactive current injection into the network.
- **The electrical control module (REEC)** models the inverter's electrical control. Using the feedback of terminal voltage and generated power, it processes the active and reactive power reference from the plant controller and outputs active and reactive current command to the inverter module after limiting these commands with the current limit logic.
- **The plant controller module (REPC)** models the plant controller, which emulates active power control and volt/var control. It generates the power reference and outputs to the electrical control module.

A variety of reactive power control modes can be used in a PV plant for reactive power regulation. Plant-level control allows the following control modes: closed-loop voltage regulation, closed-loop reactive power regulation, and constant power factor control. In this study, the PV dynamic model was constructed to maintain voltage at the regulated terminal bus, up to the reactive power capability. The reactive power response from an IBR after a disturbance was provided jointly by the slower plant controller and the much faster inverter control. The reactive power output was limited by the inverter capability and P/Q priority flag, instead of the defined power factor used in the power flow model, which resulted in a wider range of reactive power output. In this study, all newly added PV dynamic models were set with default parameters.

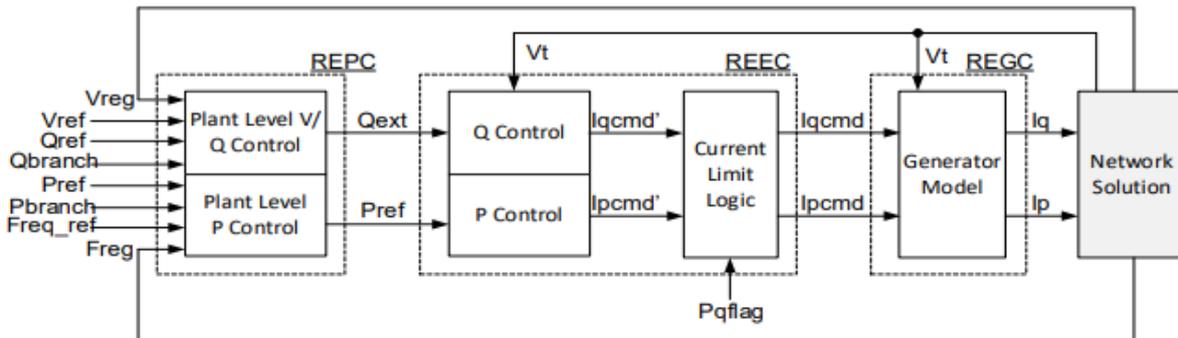


Figure 2 Connectivity diagram of the dynamic model of a generic PV plant

## 3 IMPACTS OF PV GENERATION ON POWER SYSTEMS

For steady state performance, increasing PV resources that replace conventional generation could change the flow patterns of the study system and alter the amount of available reactive power capability. This could result variations in voltage profile and the voltage stability margin under both normal conditions and contingencies. On the other hand, IBRs usually provide less fault current, which could contribute to a lower short-circuit level.

For dynamic characteristics, the change in reactive power capability caused by the integration of PV generation could affect the system's dynamic performance after disturbances, which could further lead

to transient stability and transient voltage issues. The general procedure for steady state and dynamic analyses are briefly discussed in this section.

### 3.1 STEADY-STATE PERFORMANCE

Steady-state analysis is significant to reliable power system operation since it can evaluate the system's ability to maintain steady equilibrium subject to system constraints. Studying the impacts of increased PV generation on steady-state performance could help identify potential issues caused by the IBRs and allow preventive actions to be taken. To understand these impacts, this paper conducted the following analyses:

- **Short-circuit analysis**

Grid strength describes the stiffness of the grid in response to small perturbations. It is related to the sensitivity of the terminal voltage to its current injection changes. In other words, system strength could be quantified as the equivalent impedance seen from the terminal into the system or as the short-circuit current (or MVA) for small voltage variations during normal or contingency conditions.

IBRs normally cannot provide significant levels of fault current. In addition, a weak grid could pose a challenge to integrating IBRs, because these resources rely on adequate grid strength to synchronize power electronics. Therefore, it is important to identify conditions with low grid strength that could significantly affect the operating characteristics of IBR voltage controllers and lead to system instability. In this paper, short-circuit analyses were implemented to calculate short-circuit MVA power at important bus locations. Results were compared under different scenarios to study the impact on grid strength of both IBRs and conventional generation.

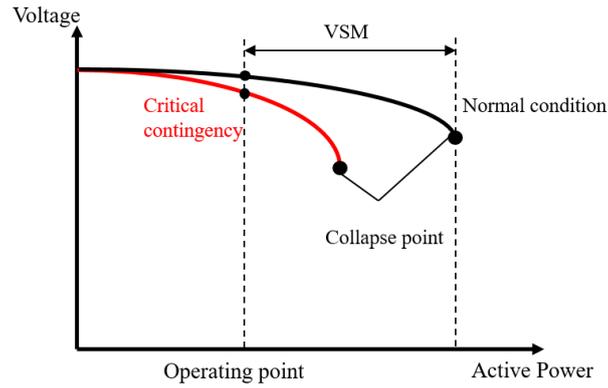
- **Voltage profile**

The main focus of a voltage profile study is to monitor system voltages under various contingencies. Bus voltage magnitudes should be maintained within operating limits, typically  $\pm 5\%$ . The integration of renewables could result in variations in regional voltage profile, mainly because of the differences in reactive power capability between non-synchronous and conventional generation. Investigation of the impact of non-synchronous generation on voltage profile could help locate the bus(es) with voltage violations and allow preventive actions.

- **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 is typically observed at load centers as the loading increases and the 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 in Figure 3. As shown, as the loading level increases, voltage drops gradually and finally reaches the voltage collapse point, where the system cannot 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.

The most common cause of voltage instability is a lack of reactive power capability. The increasing penetration of renewable generation could change the available reactive power capability. Therefore, it is of vital importance to study system voltage stability issues with the integration of renewables and to plan corresponding preventive actions to improve system stability.



**Figure 3 PV curve**

### 3.2 DYNAMIC CHARACTERISTICS

The dynamic characteristics of large-scale power systems could change with the integration of IBRs. This study compared the impacts of PV and gas-fired generation on system dynamics in the following aspects:

- **Dynamic voltage response**

Differences in control characteristics between PV inverters and conventional synchronous generators could affect system dynamic voltage responses. This paper examined these impacts by simulating three-phase branch faults, which were cleared by disconnecting the faulted line. On-fault bus voltages were calculated under different scenarios, which is important for the secure operation of local resources during a fault period. Low voltage during an on-fault period could trigger protection relays in local equipment. Dynamic voltage responses were also compared under different scenarios. Control parameters for the PV converter model were varied to study their impact on the dynamic behavior of the system.

- **Transient stability**

Transient stability describes the ability of a system to maintain synchronism after large disturbances, including line outages and bus faults. Conventional generators contribute to system inertia and can provide sufficient synchronizing capability during disturbances that cause an imbalance between mechanical power and electrical power. However, a PV plant does not have inertia, which could seriously weaken synchronizing capability during disturbances and lead to stability issues. Critical clearing time is a widely-used metric to indicate the transient stability of a power system, and it represents the maximum time a disturbance may continue without losing synchronism. This paper compared the critical clearing times of bus fault under different scenarios.

## 4 CASE STUDY

### 4.1 CASE DESCRIPTION

This paper used the 2024 MMWG EI spring light load model to study the impact of both PV and conventional gas-fired generation on a system's steady-state and dynamic characteristics. The territory of Dominion Energy Virginia (DEV) was selected as the study area. In addition to the base case, two additional scenarios were created: a gas scenario and a PV scenario, as shown in Table 2. In the gas scenario, a newly proposed 1GW natural gas-fired plant in the DEV area was added to the base case. In the PV scenario, new PV projects were sourced from the PJM interconnection queue, and a total of 1GW PV generation was added to the base case for fair comparison. In both scenarios, the imbalance caused by the integration of new generation was accommodated by replacing in-service generators. The list of

candidate generators to be replaced was provided by Dominion Energy. The rest of the power imbalance was met by scaling the active power output of the remaining in-service generators in the DEV area.

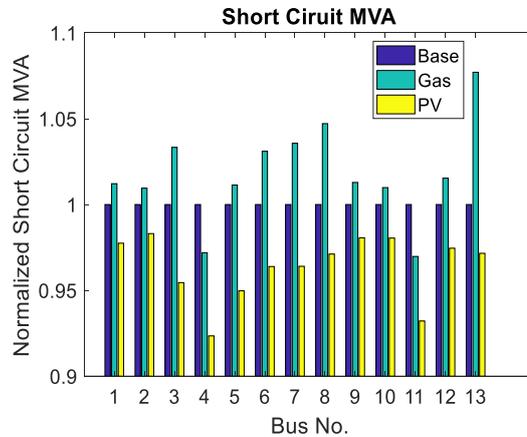
**Table 1 Case description**

Case Scenario	Description
Base Case	2024 MMWG spring light load model
Gas	1GW additional gas generation in DEV area
PV	1GW additional solar generation in DEV area

## 4.2 STEADY STATE ANALYSIS

### 4.2.1 Short-Circuit Analysis

Short-circuit analysis was implemented in PSS/E, in compliance with the IEC 60909 standard [10]. Short currents were driven by an equivalent voltage source at the short-circuit location. All network feeders, synchronous and asynchronous machines were replaced by their internal impedances. Short-circuit MVA power, total fault currents and Thevenin impedance were calculated at important bus locations in the Richmond area for three-phase faults. Short-circuit MVA power under different scenarios is compared in Figure 4. Short-circuit MVA values were normalized with respect to the base case values. When compared to the base case, at most bus locations the new gas plant resulted in a higher short-circuit MVA, while new PV plants reduced the short-circuit level. This is because PV machines were modeled to contribute no fault current during a short-circuit, while the new gas plant was modeled to provide significant levels of fault current when a fault occurs in the local area.



**Figure 4 Short-Circuit MVA Comparison**

### 4.2.2 Static Voltage Profile

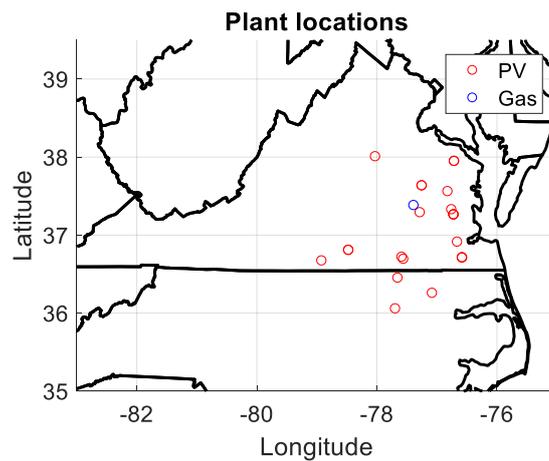
To study the impact of conventional generation and IBRs on voltage profile under both normal conditions and contingencies, single line outage (N-1) contingencies within the DEV area were investigated. Voltage violations and flow violations results were compared. Voltage limits under normal operating conditions specified by voltage levels were provided by Dominion Energy. Branch flow limits were set at 94% of Rate B of line ratings, according to Dominion Energy planning criteria. Identified violations under different scenarios are shown in Table 3.

Results demonstrate similar voltage violations for the three scenarios. The integration of PV generation reduced the overall generation reactive power output and thus eliminated several high voltage violations. However, because several in-service generators in the gas scenario were replaced by the new gas plant, overloads resulted in the local area under some critical contingencies. As shown in Figure 5, PV plants

are more widely distributed over the DEV area. This demonstrates that PV plants are less likely than the added gas unit to create flow violations because active power are injected from different locations instead of a single point of interconnection.

**Table 2 Comparison of violations**

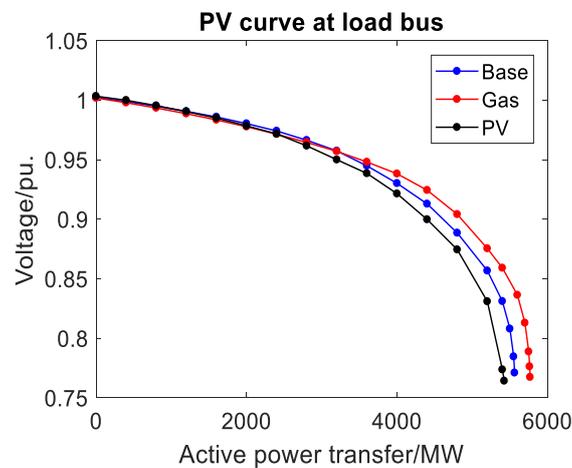
Case	Low voltage violations			High voltage violations			Flow violations
	115kV	230kV	500kV	115kV	230kV	500kV	
Base	4	11	0	35	9	2	3
Gas scenario	4	11	0	34	9	2	6
PV scenario	4	11	0	30	10	2	2



**Figure 5 Plant locations**

### 4.2.3 Voltage Stability

To study the voltage stability of the DEV area, a higher loading scenario was investigated where loads inside the Richmond area were scaled up and active power outputs of generators in the rest of the DEV area were correspondingly increased to accommodate the load increase. The PV curve at an important load bus in the central Virginia area is shown in Figure 6, which depicts the change in bus voltage as the active power transfer between the source and sink region increased. Study results indicated that for the considered transfer path, the integration of the new gas plant improved the voltage stability margin by about 200 MW, while the equivalent new PV generation decreased the voltage stability margin by about 140MW.



**Figure 6 PV curve at load bus**

## 4.3 DYNAMIC STUDY

### 4.3.1 Fault Voltage

In addition to the steady state voltage profile, local voltages during bus faults were compared using the different scenarios. Bus fault voltages were applied at important bus locations in the Richmond area. Figure 7 shows a comparison of bus voltages during the fault-on period under the three scenarios. These bus locations were selected from the bus group that was one level away from the faulted bus. Bus voltages were normalized with respect to the base case. The new gas plant in the central Virginia area provided additional reactive power support when the fault occurred. However, new PV plants were scattered throughout the whole DEV area and did not contribute much to the local reactive power capability.

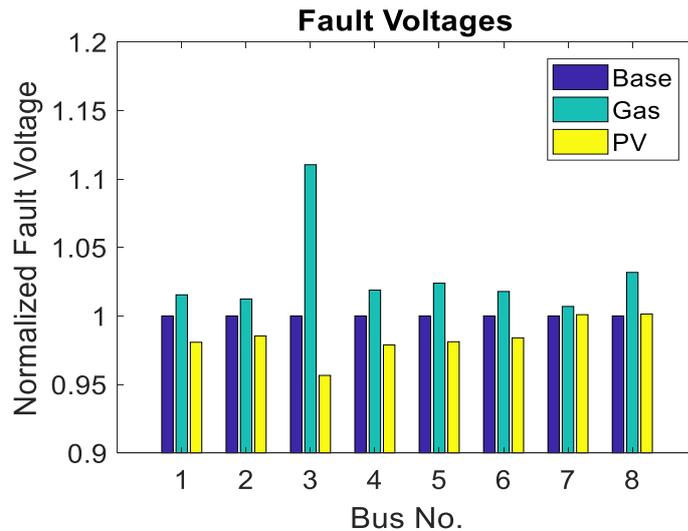
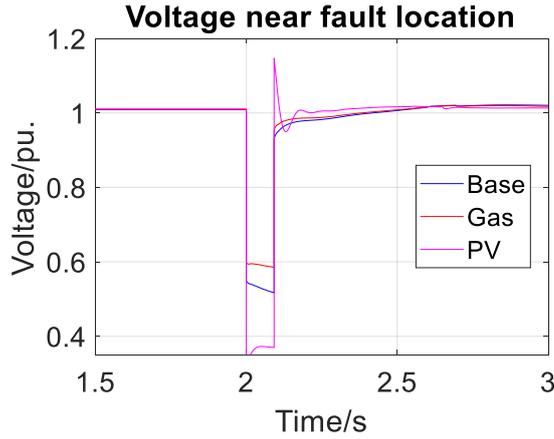


Figure 7 Normalized voltages during the fault

### 4.3.2 Dynamic Voltage Response

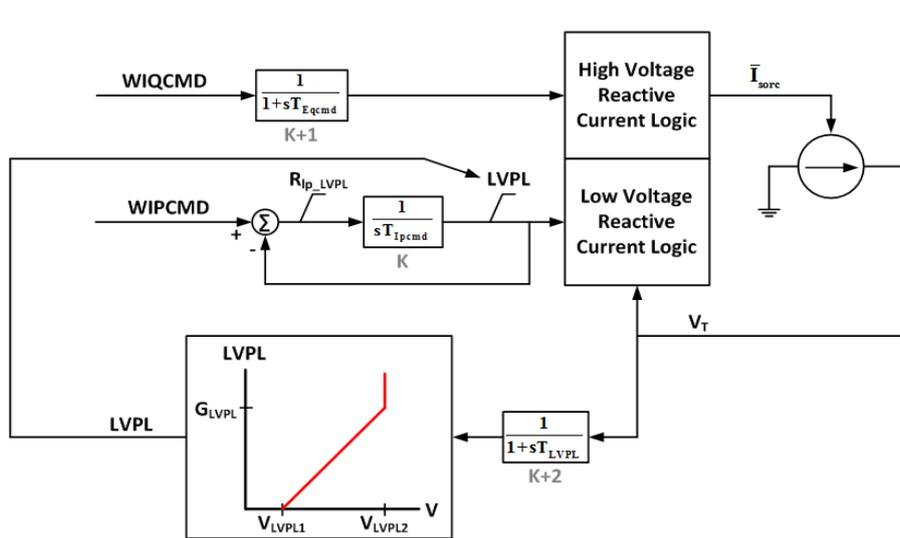
Dynamic voltage responses in the central Virginia area were simulated using a three-phase single branch fault and were cleared by disconnecting the faulted branch after 5.5 cycles. Bus voltages at a neighboring bus are shown in Figure 8 under the three scenarios. It is obvious that additional gas generation in this region could provide significant reactive power support, which would result in higher local voltages. On the other hand, the dynamic reactive power capability of PV plants is limited by the current and terminal voltage rating. In addition, the dispersed locations of PV plants could lead to a lack of local reactive power support and lower bus voltages.

Unlike the base and gas scenarios, the PV scenario had a transient overvoltage after fault clearing. The reason is that after a fault clearing, a PV plant may continue to inject reactive power into the grid, while a synchronous generator can instantaneously decrease its reactive power output to reduce the transient overvoltage. Previous studies [8] have discovered that additional conventional generation near the fault location could help reduce the overvoltage magnitude but may not entirely eliminate it.



**Figure 8 Voltage near fault location**

Since the overvoltage protection of PV inverters may trip PV generators during a transient overvoltage period, thereby causing system stability issues, it is desirable to apply control schemes to reduce this overvoltage. Therefore, in this study, the generic PV converter model and its control logic was further investigated. The block diagram of the commonly used generic renewable energy converter model REGCA1 is shown in Figure 9. The inputs to this block are the real power current command and reactive power current command. The outputs are the real and reactive power current interfaced with the network model. High voltage reactive current management (HVRCM) was implemented to limit reactive power current output under high voltage conditions. It has the control property to provide additional inductive current injection to decrease the converter's reactive power output, indirectly reducing the converter's terminal voltage. In previous simulations, the threshold voltage was set at 1.5 per unit, which in fact, deactivates this control logic. To take advantage of HVRCM to reduce transient overvoltage, the threshold was adjusted to a 1.05.



**Figure 9 Block diagram of PV converter model**

To compare the control effects, we varied the threshold voltage for HVRCM. Bus voltages at the fault location and the reactive power output at the terminal of a selected PV plant are shown in Figures 10 and 11. It can be concluded from the simulation results that the transient overvoltage was effectively reduced after the HVRCM was activated and the control effect improved when the threshold decreased.

The transient overvoltage may not be entirely eliminated through this control logic. However, the threshold voltage and overvoltage compensation gain could be tuned to achieve desired voltage performance.

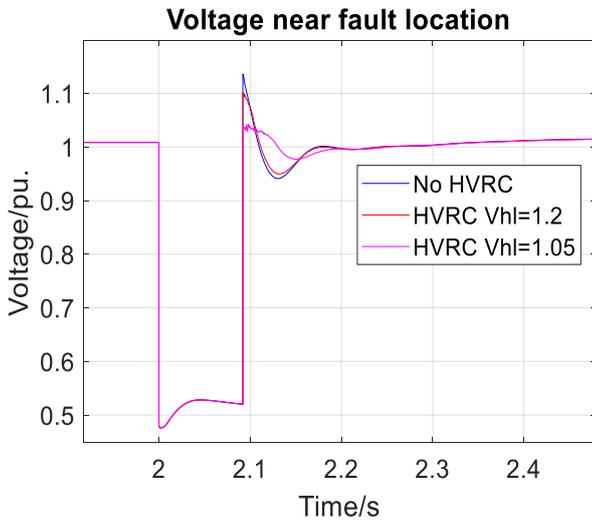


Figure 10 Bus voltage near fault location

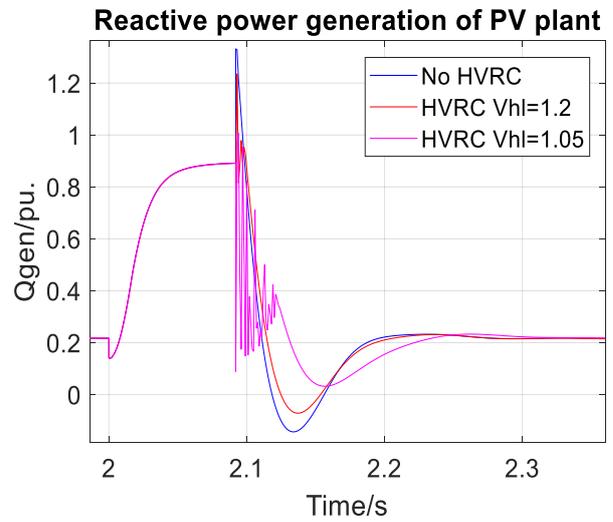
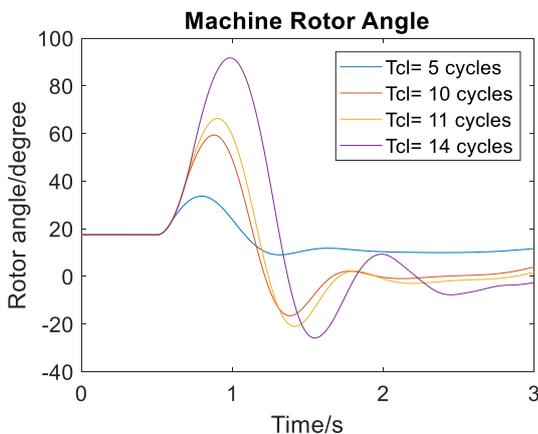


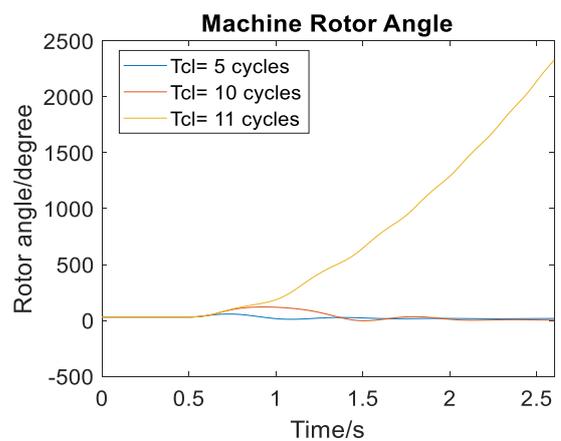
Figure 11 Reactive power output of PV plant

### 4.3.3 Transient Stability

The impact of gas generation and PV generation on transient stability was studied. A three-phase lines fault with different fault clearing times was simulated in the gas scenario and the PV scenario. The fault was cleared by opening the faulted line after the fault clearing time. For both scenarios, the clearing time was gradually increased with a step of one cycle until at least one of generators lost synchronism. The comparison of the rotor angle of the machine that first lost synchronism is shown in Figure 12. It can be concluded that the critical clearing time in the PV scenario was less than 11 cycles, while system was still transiently stable in the gas scenario when the fault remained uncleared till 14 cycles. This was because the gas generator provided more reactive support during the fault-on period, which resulted in higher bus voltages and more synchronizing power output from the generators.



(a) Gas Scenario



(b) PV Scenario

Figure 12 Critical clearing time comparison

## 5 CONCLUSION

In this paper, the impact of PV generation and conventional gas-fired generation on large-scale power systems was studied. Utility-scale PVs within the DEV area (selected from the PJM interconnection queue) were added to the system. A newly proposed natural gas-fired plant in the DEV area was also modeled. The steady state and dynamic behavior of the system under the PV scenario and gas scenario were also investigated and compared.

In the steady state analysis, the system with a higher penetration of PV generation displayed a lower short-circuit MVA than the system with the gas-fired plant because the PV machines could not contribute significant levels of fault current during short-circuit conditions. On the other hand, the analyses on static voltage profile and voltage stability revealed that increased PV generation could lead to smaller voltage stability margins.

In the dynamic studies, dynamic responses of three-phase branch faults were simulated under the different scenarios. It was concluded that conventional gas-fired generation could provide more reactive power support during the on-fault period. Analysis of transient stability also indicated that higher penetration of PV generation could result in a shorter critical clearing time than conventional synchronous generation. In addition, a transient overvoltage issue was identified in the PV scenario, which could be alleviated by tuning the control parameters of the high voltage reactive current control logic.

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