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Development of PSCAD Solar Farm EMT Models Based on PSS®E RMS Models: A Step-By-Step Guide

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SUMMARY

This paper details the current methodology adopted at Dominion Energy Virginia for the implementation of electromagnetic transient (EMT) models utilizing PSCAD. The goal of this work is to detail the lessons learned during the implementation and validation of PSCAD-based EMT models of a Dominion-owned large photovoltaic plant and to delineate the success as well as the current challenges faced. Due to Dominion Energy's Net-Zero Commitment, the increased economic viability of PV generation, and the influx of solar developers, IBR penetration will continue to grow. As a result, Dominion Energy will rely more on EMT-based models of inverter-based resources to analyze issues related to ultra-fast switching dynamics.

KEYWORDS

Electromagnetic Transient Model (EMT), Phasor Dynamic Simulation, PSCAD, Large Photovoltaic Plant, Inverter-Based Resources

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1. BACKGROUND

Renewable energy sources are at the forefront of a worldwide initiative to reduce the amount of CO_2 emissions in the atmosphere. The United States is currently experiencing a steady reduction in its CO_2 emissions per capita since the early 2000s, going from roughly 21 tons in 2000 to less than 15 tons in 2021 [1]. One of the many reasons why the US is experiencing a reduction in CO_2 emissions is due to a shift in its energy portfolio, moving away from traditional coal-based power plants to cleaner gas-based and renewable-energy sources.

In 2020 Virginia passed the Virginia Clean Economy Act, policy requires a complete shift in Dominion's energy production and the ambitious goal of achieving 100% renewable and clean energy production by 2045 [2]. Concomitantly, Dominion Energy implemented its Net Zero Commitment program, intending to achieve CO^2 net zero emissions by 2050. Since 2005, Dominion Energy has reduced carbon emissions from power generation by 46% and will continue to improve its carbon footprint in the years to come.

Dominion Energy has deemed the transition to a cleaner energy portfolio as necessary, but this shift and the increase in inverter-based resources in the electrical grid comes with engineering challenges. Inverter-based resources are known for being inertia-less, purely driven by power electronic components and controlled through digital signaling. They are also associated with power quality issues including but not limited to harmonics. Another important characteristic of inverter-based sources is their relative novelty, considering that engineers have more than one hundred years of experience with synchronous generators and turbines. Thus, modeling and simulation of inverter-based resources becomes an even more important task within utility companies.

The Western Electricity Coordinating Council (WECC) Renewable Energy Modeling Task Force developed the first solar power plant dynamic modeling guidelines for interconnection and transient stability studies back in 2014. Since then, they have been continuously improving models and proposing new updates to older versions of their renewable energy models, to keep up with the current status of the inverter technologies in the field. The models are designed in such a way that they are generic, intended for power system dynamic studies, and able to represent most PV plants in the Western Interconnection [4]. However, such generic renewable energy models are limited in their modeling scope, as they represent solar farm dynamics only in positive-sequence form.

As the penetration of renewable energy sources continues to rise, utility companies will need to ensure that new solar farm projects and increased power production from inverter-based resources do not impact the electrical grid's reliability. Therefore, the best approach to modeling and simulation is to also model the current and new solar farms in electromagnetic transient software tools, such as PSCAD, for increased detail and fidelity. For all the reasons mentioned, it is crucial that utility companies start to implement EMT-based models of their inverter-based resources so that high frequency phenomena can be modeled and better understood.

Currently, utilities do not lean on EMT-based models as they were not conventionally necessary when the grid was different, but such studies will becoming increasingly critical for modeling the impact of switching-based resources. To gain a head start on the development of EMT-based solar farm plant models, Dominion Energy has invested in implementing EMT-based system examples, using models of vendor-specific equipment currently in the field. This paper explores the implementation and validation process of one of Dominion's major photovoltaic plants utilizing PSCAD software, and details the current methodology and its drawbacks. The objectives of our work is to:

1) Describe and model a major photovoltaic plant from Dominion's grid with vendor-specific inverter and controller models, utilizing the PSCAD software.
2) Validate and compare the simulation results from both PSS®E and PSCAD.
3) Develop a modeling template for future EMT-based model implementations.

This paper is structured as follows: Section 2 describes the differences between RMS and EMT modeling philosophies. Section 3 describes the current modeling philosophy and details the generic photovoltaic model. Section 4 describes the new EMT model implemented in PSCAD. Section 5 describes the validation and simulation comparisons, and lastly, Section 6 explains the conclusions and highlights the importance of understanding the generic PSS®E model.

2. DIFFERENCES BETWEEN RMS AND EMT MODELING PHILOSOPHIES

Before the modeling phase of this project began, consideration was given to the modeling philosophy--the mathematical modeling of the components. Considering that a model is a mathematical representation of the real world, and that each model has limitations based on the goals of the modeling assignment, selecting the optimal approach is essential. Two modeling techniques stood out in the realm of possibilities: models based on phasor domain (RMS) or electromagnetic transient (EMT) [5].

Electrical system overvoltages and overcurrents caused by lightning, switching processes, and fault circumstances can be better understood through electromagnetic transient studies. EMT models rely on waveform representations of currents and voltages to describe electromagnetic disturbances in the system.

In contrast, phasor models are employed to simulate the system's electromechanical oscillations. Therefore, the ultra-fast dynamics of switching components in the inverters are not depicted in full detail; rather, depiction is limited to an averaged switching dynamic representation. The fundamental benefit of using phasor over waveform representation to solve dynamic simulation is practical: the differential equations related to the dynamics of charging and current flow in transmission lines are simplified to algebraic equations. The predicted simulation duration, which is orders of magnitude quicker than EMT simulations, is the second significant benefit of phasor models.

Table I summarizes the peculiarities of each modeling paradigm, including its strengths and weaknesses. Because of the clear disadvantage of EMT models in wide-grid representation, the PSCAD model developed in this work was a single-machine, infinite-bus model (SMIB) of the solar farm. The model included the equivalent collector system, an equivalent pad-mounted transformer, a substation transformer, the interconnection transmission line, and the point of interconnection (POI).

Table I
Comparison between RMS and EMT Modeling

RMS Models	EMT Models
• Positive sequence phasor representation of the grid	• Unbalanced three-phase sinusoidal representation of the grid
• Depicts electromechanical disturbances on the grid	• Depicts electromagnetic disturbances on the grid
• Less detailed representation of the grid	• More detailed representation of the grid
• Is the current backbone of power system transient analysis of wide-grid systems	• Not utilized for wide-grid systems
• Fast simulation speeds	• Slow simulation speeds

3. CURRENT MODELING PARADIGM–RMS MODELING UTILIZING PSS®E

The RMS models implemented in PSS®E were based on WECC's Solar Photovoltaic Power Plant Modeling and Validation Guidelines [4], which detail the second-generation renewable-energy system (RES) models currently used for interconnection and transient stability studies. These models are generic, in the sense that they can reproduce a wide range of control configurations found in real-life inverter-based sources. They are also glass-box models, meaning that the models' equations and modeling rationale can be found in the software's documentation [4, 6, 7]. This is particularly important for transmission planners and grid operators, as it allows modeling without the need for non-disclosure agreements. Fig. 1 depicts the WECC block diagram of the RES for RMS-based dynamic tools.

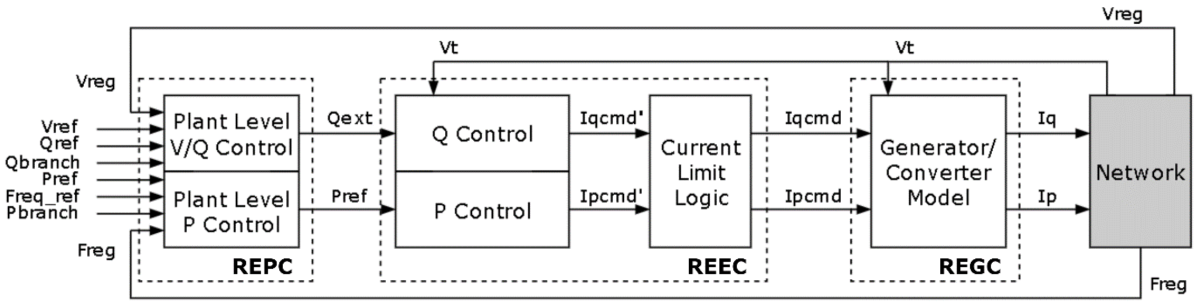

Fig. 1. WECC Block Diagram for RES

The block diagram displays three distinct module families: REGC, REEC, and REPC. The complete RES model is a combination of these three:

- **REGC Module:** Represents the current injection component of the generic renewable energy model. The module does not account for the controls of the renewable energy model, but rather implements logic for both high-voltage reactive current management and low-voltage active current management. WECC has developed two versions of the REGC module: REGCA, and REGCB.
- **REEC Module:** Representing the electrical controller of the generic renewable energy model. It contains two proportional integrator (PI) controllers that allow modelling of constant local power-factor control, constant reactive-power control, local voltage-magnitude control, local coordinated-reactive/voltage-magnitude control, or local

coordinated power-factor/voltage-magnitude control. WECC has developed three versions of the REEC module: REECA, REECB, and REECC.

- **REPC Module:** Representing the power plant controller of the generic renewable energy model. This module is typically used to represent plant-level control of larger photovoltaic farms, and it contains two PI controllers that model the active and reactive power controllers. The REPCA module allows the user to simulate the following at the plant-level: reactive-power control, voltage control, voltage plus local coordinated-voltage/reactive-power control, and voltage control plus local coordinated-voltage/reactive-power control. WECC has developed two versions of the REPC module: REPCA, and REPCB.

3.1 PHOTOVOLTAIC PLANT MODEL IN PSS®E

The PSS®E model that represents a major Dominion Energy photovoltaic plant is detailed in Fig. 2 and is displayed in a compact form for readability. The compact model combines representations of the three modules: REGCA, REECB, and REPCA. The elements highlighted in green are reference values for the voltage magnitude at the POI bus (V_{ref}), and active power reference (P_{ref}). The (V_{ref}) element, highlighted in yellow, is the voltage measured at the POI bus. Lastly, elements I_q, and I_p highlighted in blue are the imaginary and real currents that are being injected into the grid.

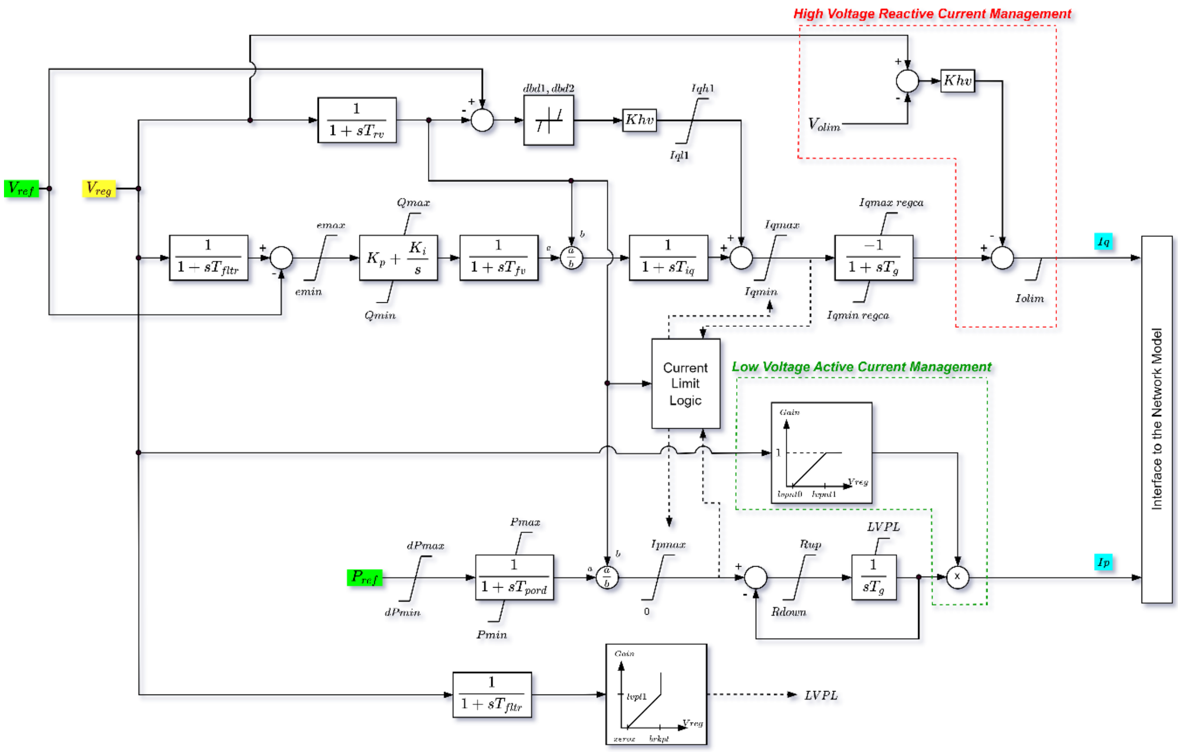

Fig. 2. Compact Photovoltaic Unit, PSSE Model

The PSS®E model in Fig. 2 is constructed with the following elements:

- **Delay blocks:** Mimic filtering and sensor measurement delays added to the response of the controls and output of the real solar module. For instance, $\frac{1}{1+sT_{rv}}$ delay block represents the delay due to voltage or reactive power measurement filtering.

- **Limiter blocks:** Restrict voltage and current signals between permissable minimum and maximum values. An example is the dynamic active and reactive power limits $Ipmin, Ipmax, Iqmin, Iqmax$.
- **Current limit logic:** Mimics the electrical controller setup for either active or reactive power priority. The PSS®E model provided by Dominion's Power Generation group is set up for active power priority.
- **Low-voltage active current management:** Displays a dynamic gain component that presents in a linear form in between two breaking points: $Lvpnt0$, $Lvpnt1$. The regulated voltage (V_{reg}) from the point of interconnection is measured; depending on its magnitude, current management limits the amount of active power injected into the grid. This functionality protects the power electronics equipment and also limits the current injection during low-voltage conditions such as electrical contingencies.
- **High-voltage reactive current management:** Displays a linear response to the difference between the regulated voltage (V_{reg}) from the POI and the inverter's voltage limit for high-voltage reactive current (V_{olim}).
- **Volt/VAR proportional integrator controller:** Displays only one PI controller, responsible for eliminating the voltage-error signal between the regulated voltage (V_{reg}) and the POI reference voltage (V_{ref}).

Understanding the interaction among the components in this generic glass-box model - models that are open-source and have internal structure knowledge available - is useful in shedding light on the black-box, vendor-specific inverter and controller models. The knowledge acquired from inspecting the block diagram (Fig. 2) and understanding the input-to-output relationship of delay blocks, PI controllers, and limiter blocks increased the authors' intuition while working with the black-box model. An example of such intuition is explored in greater detail in Section 5.

It is important to note that many photovoltaic plants on the Dominion Energy grid are currently set for volt/VAR control, while active power is set for maximum output.

3.2 PSS®E SOLAR FARM SMIB MODEL

The RMS-based, single-machine, infinite bus model for the photovoltaic plant is displayed in Fig. 3.

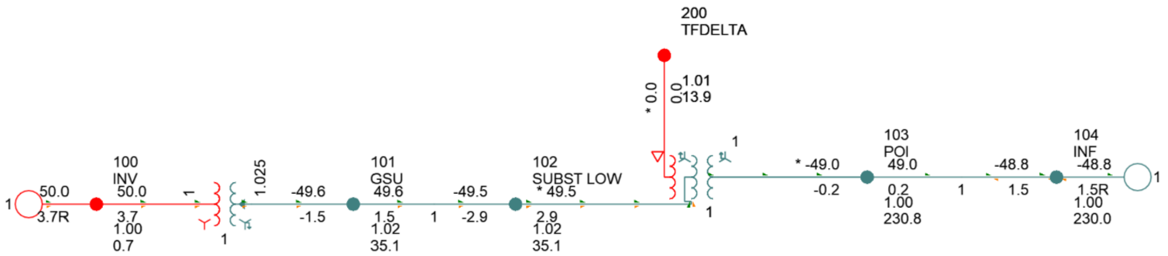

Fig. 3. PSSE Photovoltaic Plant SMIB Model

The SMIB model is designed so that the POI is the regulated bus; therefore V_{reg} from Fig. 2 is the voltage measured at the POI bus. The equivalent PV generator is connected at bus INV. The equivalent pad-mounted transformer is between buses INV and GSU. The equivalent collector system is between buses GSU and SUBST LOW, while the substation transformer is between buses SUBS LOW and POI. Lastly, the Thevenin-equivalent impedance and the infinite source are located on the POI bus. The PSS®E SMIB model was considered as the ground truth model, and it was used for comparison with the PSCAD EMT SMIB model.

4. A NEW MODEL: A BLACK-BOX EMT MODEL UTILIZING PSCAD

Both the PSCAD model of the inverter-based resource and the power plant controller are black box, which limits the overall understanding of the model. The user is restricted to adjusting only certain parameters that are baked into the model. Fig. 4 depicts the IGBT transistor switches and the solar-array current model, which are the only open and unrestricted components of the black-box model.

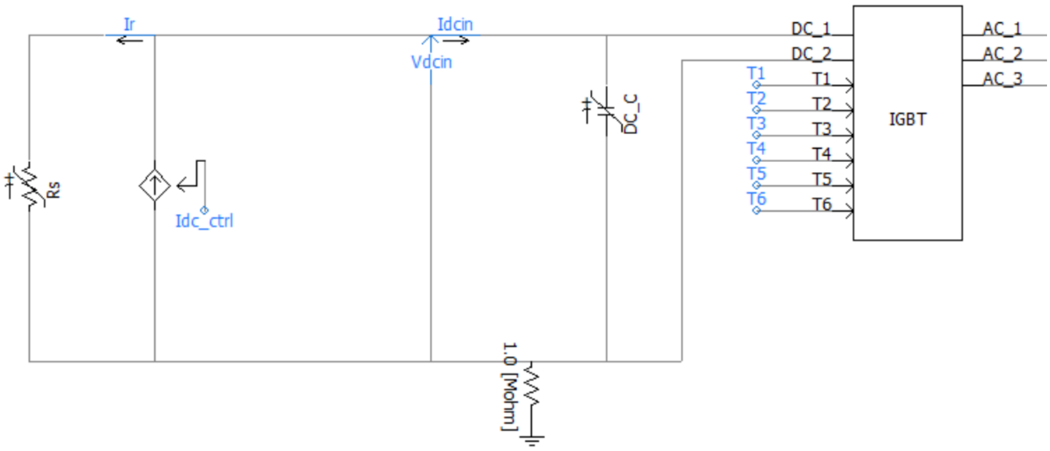

Fig. 4. PSCAD Model of the IGBT and Solar Array

Because it is an EMT model, the IGBT component contains inputs for switching transistors during the conversion from DC to AC voltages and currents. AC_1 through AC_3 are represent the output of the IGBT, i.e. AC three-phases, where an RLC filter is connected to select a narrow frequency range. In other words, it operates as a low-pass filter allowing signals with frequencies below the cut-off to pass. The power plant controller was a vendor-specific model, therefore the user was not able to observe how the model was actually implemented. Fig. 5 displays the adjustable, tuneable parameters.

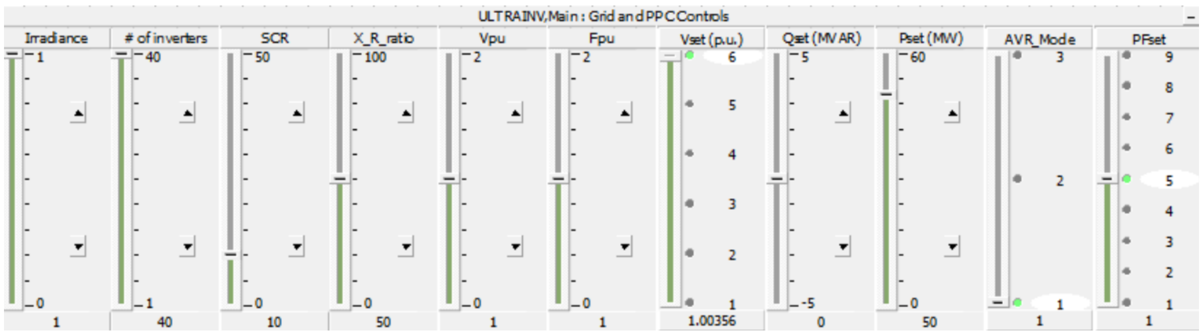

Fig. 5. Power Plant Controller Adjustable Parameters

The parameter selection was chosen to best match the control scheme and reference values of the PSS®E model. The volt/VAR power plant PI controller for the PSCAD model was chosen to match the values of the PSS®E model.

4.1 PSCAD SOLAR FARM EMT MODEL

The EMT-based, single-machine infinite bus model for the photovoltaic plant is displayed in Fig. 6.

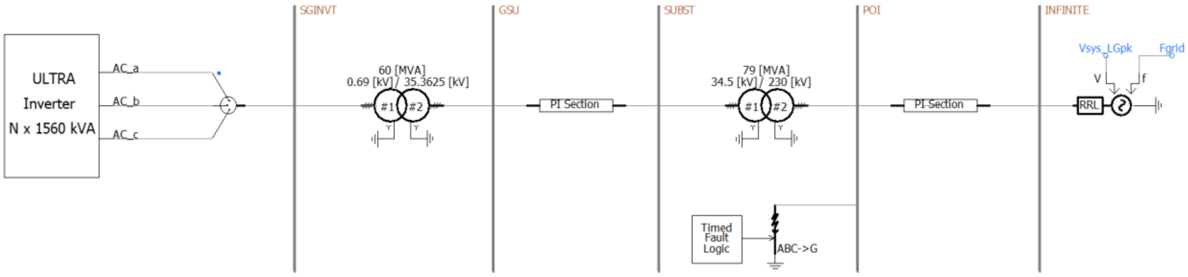

Fig. 6. PSCAD Photovoltaic Plant SMIB Model

The model follows the same structure, parameter values, and rated power in all the components as the PSS®E model.

5. MODEL VALIDATION SIMULATIONS

To demonstrate the features of the PSCAD model, the authors devised a set of simulations split into two categories:

- **Three-phase balanced fault:** Compared the fault response of the PSS®E and PSCAD models.
- **Volt/VAR control comparison:** Compared the volt/VAR controller of both models for a drop in voltage magnitude at the infinite source bus.

Both the PSS®E and the PSCAD SMIB models were initialized with the same initial values, an important condition that allowed comparison of the simulation results.

5.1 THREE-PHASE-TO-GROUND FAULT

A three-phase, phase-to-ground fault was applied at the POI bus in the PSS®E and PSCAD SMIB models to evaluate their dynamic response. The voltage magnitude at the POI bus decreased because of the phase-to-ground fault, which prompted the volt/VAR controller to act and regain the pre-contingency voltage magnitude.

5.1.1 Test 1: FAULT RESPONSE COMPARISON BETWEEN ORIGINAL PSS®E MODEL AND THE PSCAD MODEL

A three-phase, phase-to-ground fault was applied at $t = 6\ [s]$ for a duration of 0.15 seconds. Fig. 7 displays the active power injection at the inverter terminal bus for both models, while Fig. 8 displays the reactive power injection at the inverter terminal.

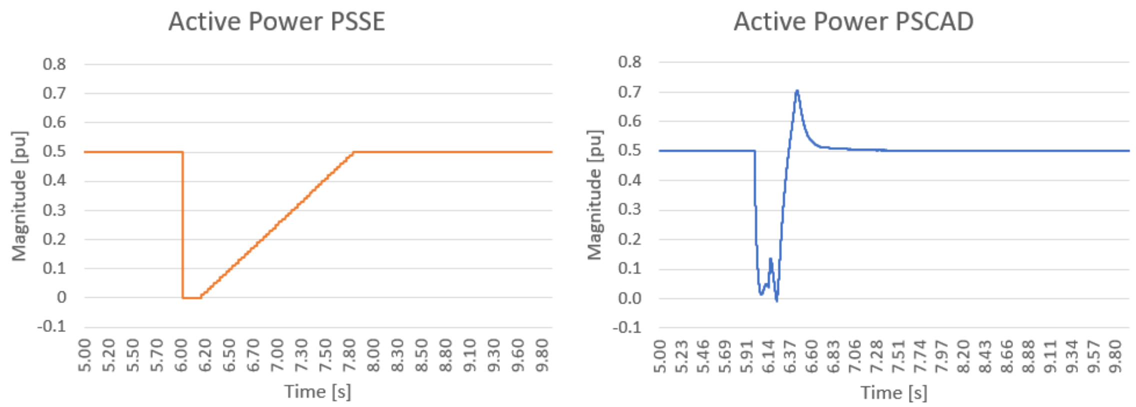

Fig. 7. Active Power Injection at the INV Bus for Test 1

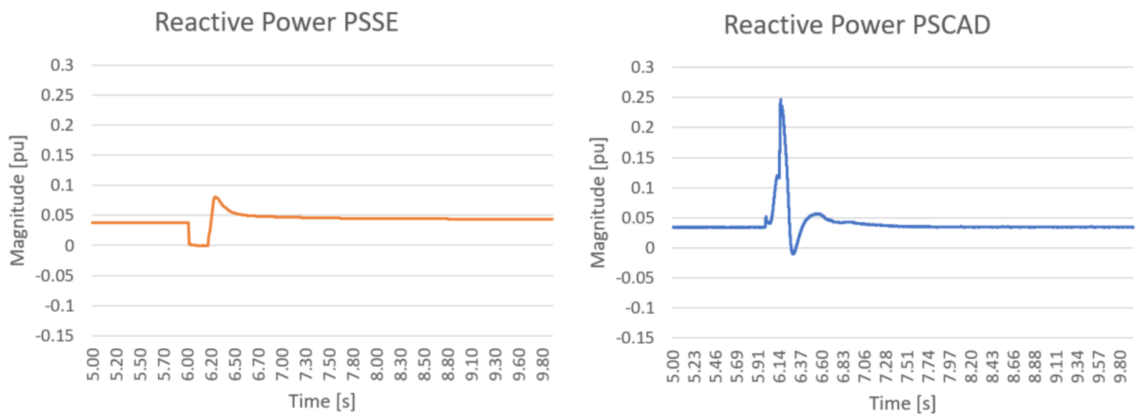

Fig. 8. Reactive Power Injection at the INV Bus for Test 1

The reactive power response from the PSS®E model did not match the response from the PSCAD model with the vendor specific IGBT and plant controller models. The response of the vendor-specific model to the low-voltage magnitude during the contingency did not match the PSS®E model, suggesting some discrepancies in the PSS®E results that might point to incorrect parameterization of the current model. Both active and reactive power simulations for the PSS®E model ceased momentarily, an outcome that is documented in the model manual [4]. The PSCAD model's reactive power response displayed both maximum and minimum peaks, suggesting no momentary cessation, and its peak response was roughly three times greater in magnitude. The active power response for a contingency scenario in the PSCAD model did not indicate the presence of a ramp rate limiter, as was the case for the PSS®E model. Despite that, the active power response of the PSCAD model was not very different than the PSS®E model, keeping in mind that the PSS®E model is overly simplified compared to the black-box model. Their responses will always have differences; the key questions are how much difference and how different are the simulations results?

5.1.2 Test 2: FAULT RESPONSE COMPARISON BETWEEN MODIFIED PSS®E MODEL AND THE PSCAD MODEL

For Test 2, the same three-phase, phase-to-ground fault was applied at the POI bus in both models, but the PSS®E inverter model was set to reactive power priority instead of active power priority. It is worth mentioning that the dynamic model set in PSS®E for the photovoltaic plant was validated and parameterized using the NERC modeling requirements; parameterization errors can occur and can hinder fault analysis. Figs. 9 and 10 display comparison results that appear to be much closer to one another.

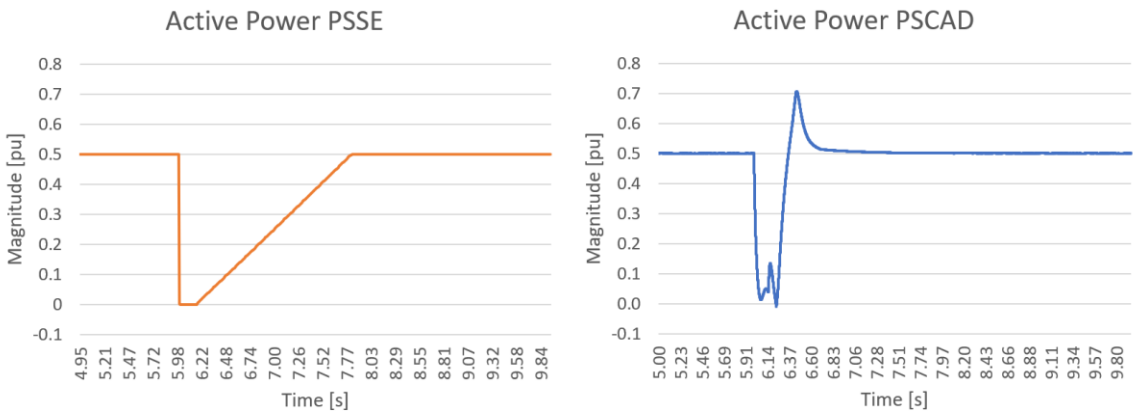

Fig. 9. Active Power Injection at the INV Bus for Test 2

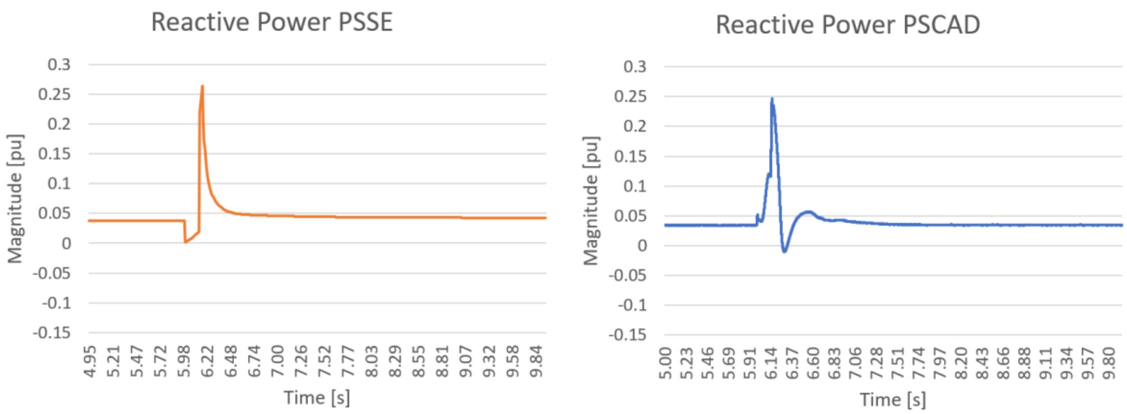

Fig. 10. Reactive Power Injection at the INV Bus for Test 2

In comparison with the Test 1 results, there was a clear improvement in the reactive power input of the PSS®E model. The results also point to an important fact, that although the PSS®E model was verified through MOD 32 tests [8] and is currently utilized to represent the major solar plant, errors in modeling and parametrization are common. A deep understanding of the generic PSS®E model was important to find the error and fix the issue.

5.2 VOLT/VAR CONTROL COMPARISON

A reduction in the voltage level of the INF bus was applied to both SMIB models to test the reactive power capability of both the PSS®E and PSCAD inverter models. The voltage level was reduced from 1 pu to 0.99 pu at $t = 6\ [s]$. The volt/VAR controller acted to return the voltage magnitude back to its reference magnitude value.

5.2.1 Test 3: FAULT TESTING THE PSS®E MODEL VS. THE PSCAD MODEL FOR VOLT/VAR CONTROL

For Test 3, the voltage reduction was applied at the INF bus of both SMIB models. There was no difference in active and reactive power response for either active power or reactive power priority in the PSS®E simulation, thus one test sufficed for volt/VAR control. The fact that the priority control had no effect could be the reason why the error in the parameterization of the PSS®E model was not captured during validation process.

Fig. 11 displays the active power injection at the inverter terminal bus for both PSS®E and PSCAD models, while Fig. 12 displays the reactive power injection at the inverter terminal.

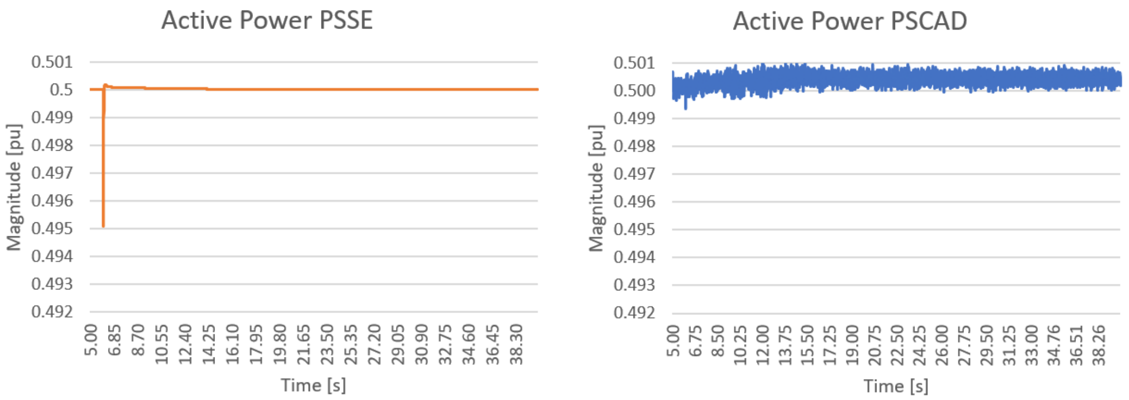

Fig. 11. Active Power Injection at the INV Bus for Test 3

Fig. 12. Reactive Power Injection at the INV Bus for Test 3

The active power curve profiles were similar, while the reactive power curves displayed a somewhat similar volt/VAR PI controller response. The dip in active power from the PSS®E simulation was miniscule. A similar response was also observed in the PSCAD simulation, although it was masked due to embedded measurement noise from the EMT simulations. The key takeaway from Fig. 12 was the discrepancy in the steady-state reactive power value at $t = 40\ [s]$. The simulation results pointed to a mismatch in the reactive power maximum value, which can only be justified by an error in one of the two models. Test 3 results are important not only to demonstrate the differences between the models, but also to raise awareness of the models and their fidelity.

6. CONCLUSION

This work implemented and validated black-box, vendor-specific EMT models in PSCAD against the generic PSS®E phasor model. Utility companies currently do not lean on EMT-based models for transient stability analysis and interconnection studies, despite the increasing number of inverter-based resources on the grid.

For this reason, the step-by-step guide developed in this paper for the implementation and comparison of generic PSS®E and black-box models is extremely valuable. Although the glass-box PSS®E photovoltaic plant model is not ideal, the formulation and block diagrams can help researchers get a sense of vendor-specific inverter models. The fault analysis results pointed to an error in the parameterization of the PSS®E model that Dominion Energy uses. Although this anomaly did not impact results for the volt/VAR controls tests, the PSCAD model improved the parameterization of the widely used PSS®E photovoltaic plant model. Lastly, this paper also highlights the importance of having a working knowledge of the generic PSS®E models so that working with different black-box models in future projects becomes less of a challenge to understand.

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