EMT Model Validation of a 2 MVA PV Inverter Using Transient and Frequency-Domain Hardware Testing

Preprint

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EMT Model Validation of a 2 MVA PV Inverter via Transient and Frequency-Domain Hardware Testing

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***Abstract*–This paper presents the results and new insights from a hardware test campaign on a 2 MVA PV inverter for validating its vendor-supplied electromagnetic transient (EMT) model. The test campaign was conducted using a 7 MVA grid simulator and a 2 MW PV emulator. It considered both time-domain transient tests and frequency-domain impedance scan tests. The paper highlights the inadequacy of the transient tests in capturing all critical resonance modes of the inverter and the effectiveness of the frequency scan testing in addressing this problem. The paper shows the frequency scan testing as an effective tool for the EMT model validation of IBR units, which can highlight inaccuracies that are easy to overlook when the model validation is performed using only the time-domain transient tests, such as low voltage ride-through and phase jump tests.**

I. Introduction

Stability has emerged as a major challenge in operating power systems with high levels of inverter-based resources (IBRs) [1]. It is important to use models of IBRs that can accurately capture their performance for various system stability studies. The most sophisticated form of an IBR model available today is the electromagnetic transient (EMT) simulation model based on the actual firmware used inside the IBR products. There are two main factors that make EMT models more effective at representing the dynamics of IBRs than phasor-domain transient (PDT) models: (1) The fast and complex controls of power electronics equipment used inside IBRs cannot be captured by PDT models because of their inherent inability to capture fast dynamics beyond about 2-8 Hz (depending on model details). (2) It is quite difficult, if not impossible, to translate all control functions implemented inside IBRs using software codes to a PDT model as the PDT models represent three-phase quantities by their magnitudes and angles instead of their instantaneous values. Many system planners and operators have started requiring EMT models of IBRs from the generator owners for performing reliability studies for evaluating subsynchronous control interactions and oscillations, control instability, ride-through capability of IBRs and transient performance during grid disturbances, high IBR penetration or low system strength conditions, and system protection [2]. In fact, clause 10 of the new IEEE 2800-2022 focusing on the performance of IBRs says that "the IBR owner shall provide [...] an EMT model" and "It is critical that models provided for IBR plants [...] reflect the actual installed equipment [...] for reliability study purposes and to help ensure reliability of the BPS".

Despite of the growing interest in EMT models of IBRs, limited information is available on how to validate EMT models to ensure that a model accurately represents the actual equipment. The latest EMT model validation requirements from a couple of system operators are summarized in the following:

1) The power system operator for Texas (USA), ERCOT, revised its EMT model validation requirement for IBRs in 2024 [3]; it requires generator owners to benchmark EMT models of units inside an IBR plant (i.e., individual inverters and wind turbines) against actual hardware. The tests required for performing model validation include a small voltage step test, a voltage ride-through or dip test, system strength test, phase jump test, and subsynchronous frequency scan test.

2) The EMT model validation guidelines released by AEMO, the system operator for the Australian grid, described model validation in a qualitative manner without defining specific test procedures or model validation metrics [4].

EMT model validation requirements from other system operators are similar to these two examples. It is easy to miss errors in the EMT models when they are tested against the existing EMT model validation requirements.

This paper presents the results from a collaboration between a power system utility, a PV inverter original equipment manufacturer (OEM), and a national laboratory focusing on the comprehensive validation of the EMT model of a PV inverter from a test campaign on a 2 MVA PV inverter. It shows that time-domain transient tests might not be sufficient for evaluating the accuracy of an EMT model; it is important to also perform frequency scan tests on wind turbines and inverters to properly evaluate the accuracy of their EMT models. The paper also demonstrates the importance of the accurate modeling of PV arrays and saturation of the inverter transformer for the overall accuracy of the EMT models of PV power plants.

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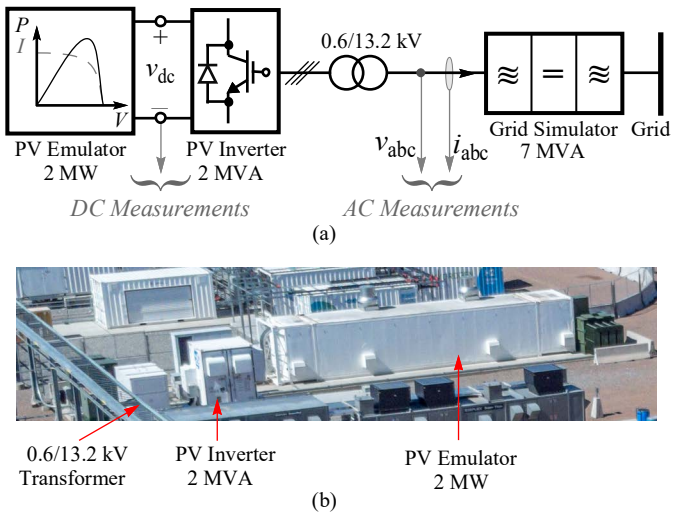

Fig. 1. Experimental test setup at NREL used for time-domain (LVRT, phase jump, and ROCOF) and frequency-domain (impedance/admittance scan) testing of a 2 MVA PV inverter using a 7 MVA grid simulator and a 2 MW PV emulator. (a) Schematic and (b) picture of the test setup (Source: Josh Bauer, NREL).

II. EMT Model Validation: Initial Results & Errors

A. Hardware Test Setup

Fig. 1 shows the test setup used at the National Renewable Energy Laboratory (NREL) for performing various tests on a 2 MVA PV inverter hardware for validating its EMT-PSCAD model provided by the OEM. The inverter is supplied at its dc terminals by a 2 MW PV emulator. The inverter is connected by a 600 V/13.2 kV step-up transformer to a 7 MVA grid simulator, which is used for performing various transient tests and frequency-domain impedance measurements. Three-phase voltages and currents, v_{abc} and i_{abc}, on the ac side and the dc-bus voltage, v_{dc}, on the dc side are measured during hardware tests using a custom-designed medium-voltage data acquisition system (MVDAS). More information on the grid simulator, voltage and current sensors, and MVDAS can be found in [5]. Note that v_{abc} and i_{abc} are used to derive the active and reactor power output, P and Q, of the inverter for comparing their responses with the responses obtained from the EMT model.

B. Voltage Dip Test

For the voltage dip test, the 7 MVA grid simulator shown in Fig. 1 instantaneously reduces the magnitude of the voltages at the ac terminal by a specific amount ranging from 10% to 60% for two different time durations of 50 ms and 200 ms. Fig. 2 compares the response of the hardware inverter with the EMT model for one such voltage dip test when the voltage is reduced by 30% for 200 ms. The EMT model exhibits high accuracy in capturing the response of the inverter during the voltage dip test. All other voltage dip tests confirmed a similar level of accuracy of the EMT model; however, the hardware inverter tripped at the end of the voltage dip event for some of the tests, whereas the EMT model was able to ride-through the event and return to the pre-disturbance level. Fig. 3 shows the response during one such voltage dip test in which the voltage magnitude is reduced by 60% for 50 ms.

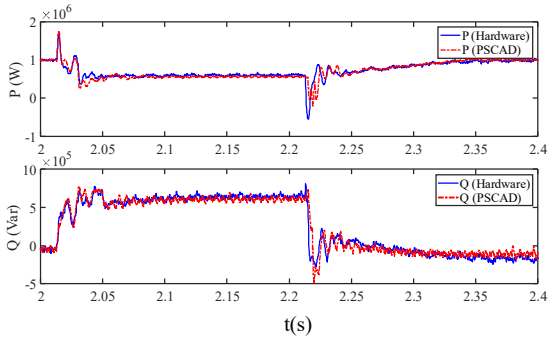

Fig. 2. Response of the active and reactive power output of the 2 MVA PV inverter during an LVRT test with 30% voltage dip of 200 ms duration.

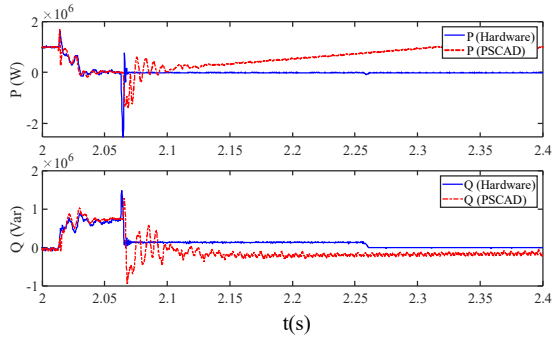

Fig. 3. Active and reactive power output response of the 2 MVA PV inverter during an LVRT test with 60% voltage dip of 50 ms duration. The response of the PSCAD model is almost identical as the inverter during the LVRT event; however, the hardware inverter tripped following the LVRT event, but the PSCAD model inverter was able to ride-through the transient event and continue operation with steady-state power output the same as the pre-disturbance level.

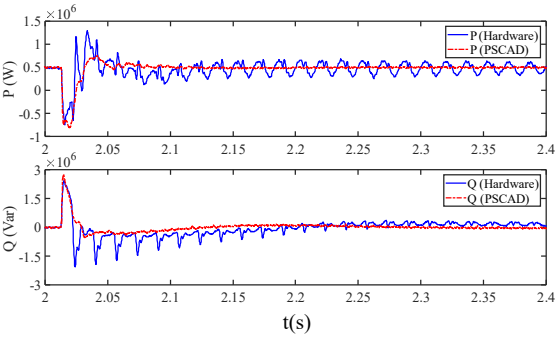

Fig. 4. Response of the 2 MVA PV inverter during a 30° phase jump test. The hardware inverter exhibited large harmonic content in its current output following the event, which was not captured by the PSCAD model.

As shown in the figure, the response from the hardware inverter and the model match well during the event; however, although the inverter tripped during the hardware test at the end of the event, the EMT model continued operation after the event. It is important to evaluate the root cause of this mismatch to effectively use the EMT model for evaluating the performance of the inverter during grid disturbances. The root cause and mitigation of this mismatch are presented in Section III.

C. Phase Jump Test

Fig. 4 compares the response of the hardware inverter with the EMT model for a phase jump test in which a sudden jump of 30° is applied by the 7 MVA grid simulator in the phase of the three-

phase voltages at the ac terminal. Although the EMT model accurately captures the average trajectory of the active and reactive power output of the inverter after the phase jump, it failed to capture temporary harmonics that appeared in the inverter output after the phase jump event. Several other phase jump tests were conducted, and it was observed that the temporary harmonics appeared in the inverter output only when the phase jump was bigger than 20°; however, the EMT model was not able to capture them.

D. *Frequency Scan Test*

Validation of EMT models of inverters using just time-domain transient tests might not be sufficient—they excite the inverter dynamics simultaneously over a broad range of frequencies, which might make it difficult to capture inaccuracies at certain frequencies or certain resonance modes. On the other hand, for the analysis of new stability problems, such as systemwide oscillations and control interactions among IBRs [6], it is important for EMT models to be accurate over a broad range of frequencies. Validation of an EMT model over a broad range of frequencies can be achieved by performing frequency scan testing of the model and the IBR unit; the frequency scan test allows user to separate responses at each tested frequency.

Frequency scan testing of an inverter is performed by injecting small perturbations of different frequencies in the voltages at the inverter terminal to measure its impedance or admittance response over a broad range of frequencies. The measured impedance or admittance response can be used not only for the EMT model validation but also for analyzing the stability of the inverter under different grid conditions [1], [6]. The same test setup shown in Fig. 1 is used for the frequency scan testing. The detailed procedure for the impedance/admittance measurement of a utility-scale inverter or a wind turbine is reported in [5]. Fig. 5 compares the dq admittance response, $\mathbf{Y}_{DQ}(s)$, of the 2 MVA PV inverter obtained by a frequency scan test on the actual hardware inverter as well as its EMT model; the inverter output was 0.8 MW, 0 MVAR during this particular scan. The matching is excellent except for the fact that the $Y_{dd}(s)$ element of the dq admittance of the hardware inverter exhibits a severely underdamped resonance at around 5–6 Hz that is not captured by the admittance response obtained from the EMT model†. This underdamped resonance can create instabilities for certain weak grid conditions or it can interact with other IBRs in the vicinity. In fact, several real-world oscillation problems have been reported involving PV power plants around this frequency range [7]. Hence, it is important for the EMT model of the PV inverter to capture the 5–6 Hz resonance mode so that its source as well as impact on system stability can be properly evaluated during power system studies using this model. Section III identifies the cause of the resonance mode and its accurate representation in the model.

E. *Summary*

The results from the voltage dip test, phase jump test, and frequency scan test showed that the EMT model is quite accurate for some events but misses some key dynamics; it failed in capturing certain aspects including: (1) the inverter tripping during certain voltage dip tests, (2) an underdamped resonance mode at 5–6 Hz in the inverter, and (3) nonpermanent harmonics that appear in the inverter output during certain phase jump tests. The first two aspects must be accurately captured by the EMT model so that the model can be effectively used to evaluate if the IBR will be able to ride-through various grid disturbances and if the IBR will create any control interactions or instabilities in the system. The third behavior related to transient harmonics during certain phase jump events results from the saturation of the transformer—it is important to capture the saturation characteristics of the transformer of the PV inverters as it is known to cause ferroresonance problems in PV power plants.

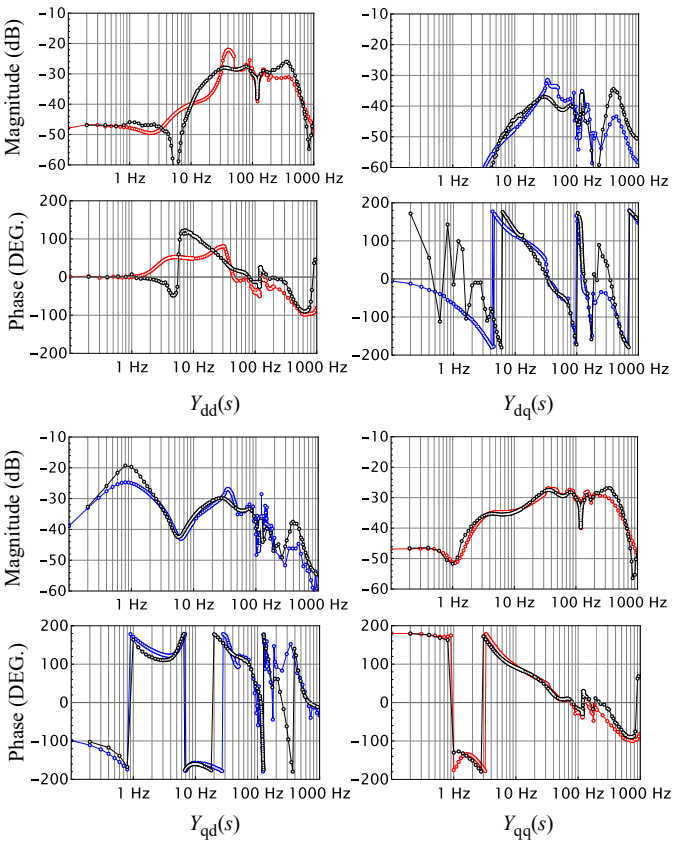

Fig. 5. DQ admittance response of the 2 MVA PV inverter. Black plots represent responses obtained from the hardware measurements on the actual inverter. Red and blue plots represent responses obtained from the PSCAD model of the inverter. The response of $Y_{dd}(s)$ obtained from the hardware inverter showed resonance at around 7 Hz, which is not captured by the PSCAD model.

III. EMT Model Errors: Sources & Mitigation

A. *DC-Side Network Model*

It is generally difficult to identify the root cause of EMT model errors because the EMT models are generally supplied by OEMs in the blackbox format. Frequency scan testing can provide some insights into the modeling errors depending on the frequency range where the errors are detected. As shown in Fig. 5, the EMT model errors in the frequency scan test of the 2 MVA PV inverter are concentrated within the frequency range 1–10 Hz. The ac-side

†. The mismatch in the phase of $Y_{dq}(s)$ at frequencies below 5 Hz is result of a poor signal-to-noise ratio and it is not important because the magnitude of $Y_{dq}(s)$ is negligible at these frequencies compared to other elements.

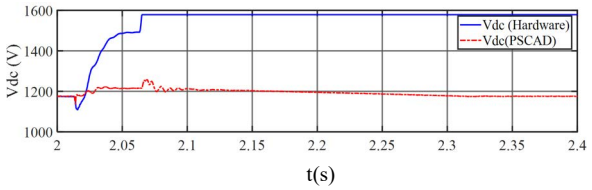

Fig. 6. DC-bus voltage response of the PV inverter during an LVRT test with 60% voltage dip of 50 ms duration. The PSCAD model is not able to capture the dc-bus overvoltage experienced by the inverter during the transient event.

admittance of an inverter is strongly coupled with the dynamics of the dc-side network at frequencies below a couple tens of Hertz [8]. Additionally, the fact that the EMT model errors are present primarily in the $Y_{dd}(s)$ element of the dq admittance matrix point to the dc-side network model as the potential source of the mismatch between the hardware and EMT model frequency scan results; this is because $Y_{dd}(s)$ is strongly dependent on the active power control dynamics of the inverter, which is particularly impacted by the dynamics of the dc-side network.

Based on the insights from the frequency scan test, it was decided to further evaluate if the representation of the dc-side network in the EMT model is the main source of errors. Fig. 6 compares the dc-bus voltage response during the same voltage dip test as shown in Fig. 3 for the hardware inverter and the EMT model. As shown, the EMT model did not experience the dc-bus overvoltage, which allowed it to ride-through the event, whereas the hardware inverter tripped at the end of the event because of the dc-bus overvoltage. This result further confirmed the suspicion that the dc-side network model might be the main source of the error detected in the frequency scan test. It also shows that the improvement in the dc-side network model might also enable the EMT model to capture the inverter tripping observed during some of the voltage dip tests.

B. PV Emulator Model

The 2 MW PV emulator used for the hardware testing consists of eight 250 kW, 1600 V dc power supplies [9]; they can be connected in parallel and configured to emulate any desired *I-V* characteristics to represent PV arrays at the dc terminals of the 2 MVA PV inverter. The testing team closely evaluated the model used to represent the PV emulator in the EMT model of the PV inverter once it became clear that the dc-side network model might be the major source of the modeling errors. After investigation, we determined that the model used for representing the PV emulator was not properly parametrized.

The PV emulator is modeled in PSCAD as a controllable current source supplying to the dc terminals of the inverter in parallel with a capacitor. The controllable current source is programmed to have the same *I-V* characteristics as programmed in the PV emulator used for the hardware testing. The capacitor used in parallel with the controllable current source represents the output capacitors of the dc power supplies used inside the PV emulator. In addition to appropriately sizing the capacitor depending on the number of dc power supplies used in the PV emulator, it is important to parametrize the *I-V* characteristics of the PV emulator in the PSCAD model to exactly match that

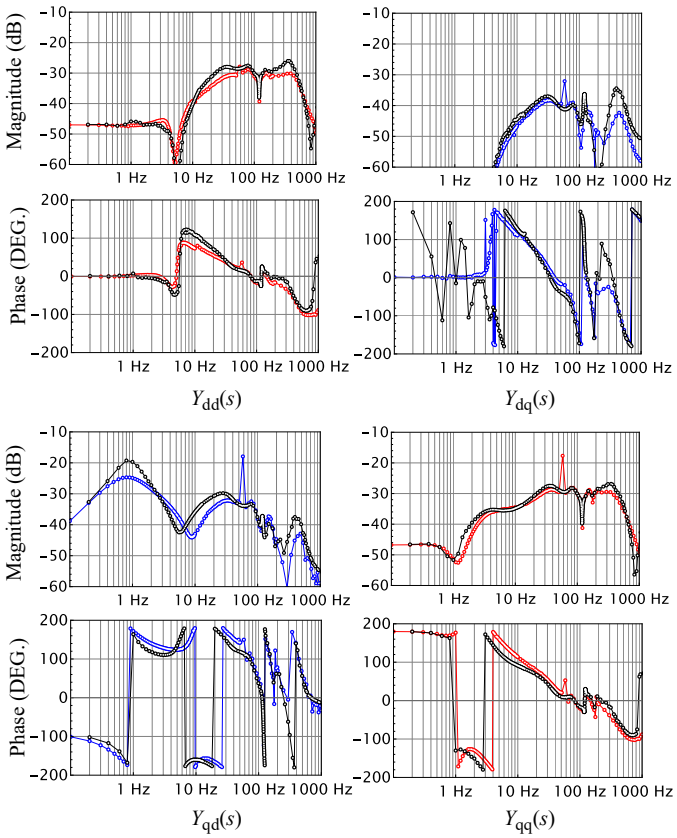

Fig. 7. DQ admittance response of the 2 MVA PV inverter. Black plots represent responses obtained from the hardware measurements on the actual inverter. Red and blue plots represent responses obtained from the PSCAD model of the inverter after improving the accuracy of the dc-source model, i.e., the model of the PV emulator used in the test setup.

implemented in the hardware.

The voltage-dependent current source acts as a resistance during a disturbance depending on the steady-state operation point on the *I-V* curve. The equivalent resistance is very high representing an open circuit or an ideal current source if the dc-bus voltage of the inverter is sufficiently lower than the maximum power point (MPP) voltage, where a small change in the dc-bus voltage will not induce significant change in the output current. On the other hand, the equivalent resistance is very small if the dc-bus voltage is closer to the open-circuit voltage of the emulated PV array. Because of this large variation in the small-signal resistance of the PV emulator, it is critical that the *I-V* characteristics used for its modeling are properly parameterized in accordance with the settings in the actual hardware.

C. Validation of the Revised EMT Model

Fig. 7 compares the dq admittance of the 2 MVA PV inverter obtained from the hardware testing with that obtained from the EMT model after the model of the PV emulator is properly tuned to match the settings in the hardware test setup. The revised EMT model is able to accurately capture the 5–6 Hz resonance mode in $Y_{dd}(s)$. Fig. 8 compares the hardware and the model response for the same voltage dip test as described in Fig. 3 after revising the PV emulator model. The revised EMT model is able to accurately capture the tripping of the inverter at the end of the 60% voltage

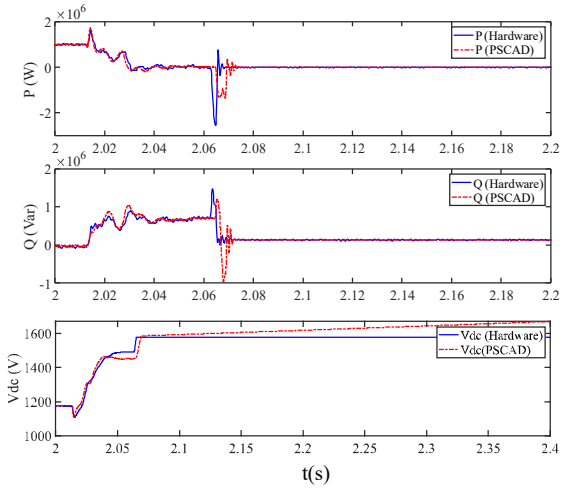

Fig. 8. Response of the PV inverter during an LVRT test with 60% voltage dip of 50 ms duration. The PSCAD model accurately captures the inverter tripping at the end of the LVRT event once the model of the dc source is tuned to accurately capture the dynamics of the PV emulator used in the test setup.

dip event. It also captures the dc-bus over-voltage experienced by the inverter during the event. These results highlight the importance of proper modeling and parameterization of the model used to represent PV arrays in the EMT models of solar inverters.

D. Saturation of Inverter Transformer

Any transformer will saturate when the transformer core is fully magnetized and operating at maximum magnetic flux. Typical causes for transformer saturation include high-voltage or underfrequency conditions, dc offsets induced by additional magnetic flux in the core, phase mismatch, and residual flux. IBRs are often exposed to these conditions during field operation, and they need to provide robust and reliable performance during such transient events; therefore, validating full IBR systems—including not only inverters but also full models of their transformers including saturation and hysteresis—is important.

The voltage recovery after transient events such as voltage sags or phase jumps can also saturate transformers, which, in turn, may cause inrush currents similar to the ones that are produced during transformer energization. Some residual flux always remains in the transformer core during voltage sags and phase jumps. When the voltage is restored, the level of transformer magnetizing current depends on the level of the residual flux. After the voltage recovery, a transient flux is produced and added to the residual flux reaching high-flux magnitudes. At that point, the core is fully saturated. As a result, the air-core inductance of the winding will significantly decrease, causing high-amplitude inrush current.

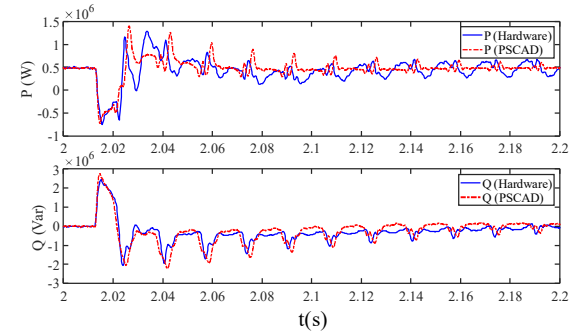

Fig. 9. Response of the PV inverter during a 30^{o} phase jump test. The PSCAD model accurately captures the harmonic content in the output of the inverter once the saturation of the inverter transformer is properly modeled in the PSCAD model.

Fig. 9 compares the response of the hardware inverter during the same 30^{o} phase jump event as presented in Fig. 4 with that from the EMT model of the inverter after the saturation of the inverter transformer is properly represented in the EMT model. The EMT model is now able to accurately capture the harmonics that appear in the inverter output during the phase jump event.

IV. Conclusions

This paper presented a rigorous approach for validating EMT models of inverters and wind turbines, demonstrating results from a test campaign on a 2 MVA PV inverter. The findings indicate that time-domain transient tests alone may be insufficient to capture all model inaccuracies. Frequency scan testing proved effective in identifying resonance modes and diagnosing sources of EMT model errors. Additionally, even a highly accurate vendor-supplied EMT model of a PV inverter might yield inaccurate responses in specific system conditions if the PV arrays at the DC terminal and inverter transformer saturation at the AC terminal are not properly modeled. The combined use of time-domain and frequency-domain testing can significantly enhance EMT model accuracy, supporting more reliable BPS stability and performance studies.

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