EMT-Phasor Domain Hybrid Simulation of Distribution Grids with Photovoltaic Inverters

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***Abstract*—This paper presents the hybrid simulation technique to efficiently analyze the impact of high PV penetration on the distribution system. The proposed approach utilizes the multi-domain simulation capability of Matlab/Simulink software to simulate the tested system in the Electromagnetic Transient (EMT) and Phasor domains. The detailed switching models of several PV inverters are modeled in the EMT domain, while the rest, including other PV inverters and the grid, are modeled in the Phasor domain. An interaction method is proposed to handle data transferring between EMT and Phasor sub-systems. The modified IEEE 13-node distribution grid with several units of a two-stage single-phase smart PV inverter is used to validate the proposed technique. Several transient studies are carried out to analyze the accuracy and efficiency of the proposed hybrid method and compared with the full EMT model. Simulation results show that the proposed approach significantly reduces the computation time and retains sufficient accuracy as compared to full EMT model.**

***Index Terms*—Electromagnetic transient model, phasor domain simulation, PV systems, distribution grid, smart PV inverter.**

I. INTRODUCTION

The number of residential photovoltaic (PV) systems in distribution grids is increasing significantly in the US. To study the impact of large-scale penetration of residential PVs in distribution grids, the development of fast and accurate models of the PV-integrated distribution feeders becomes necessary. Although electromagnetic transient (EMT) type models provide detailed and accurate responses, they are complex and computationally burdensome. On the other hand, phasor-type models provide better computational capability [1], [2]; however, they are not suitable for studies that require sufficient details (e.g., fault analysis and transient studies) [3], [4]. To get the benefits of both the EMT and phasor-domain simulations, which are accuracy and speed, respectively, hybrid EMT-Phasor models have been proposed. In the hybrid approaches, part of the system, whose detailed response is of interest, is modeled in the EMT domain, and the rest of the system is modeled in the phasor domain. The hybrid simulation benefits from the fast and accurate simulation offered by Phasor and EMT domains, respectively [5], [6].

The existing EMT-Phasor hybrid models are developed primarily for coupled Transmission-Distribution systems [5], [7], [8], where the transmission systems are modeled in the EMT domain, and the distribution systems are modeled in the phasor domain. However, due to the increasing number of power electronic-based distributed generation units in the distribution systems, the inclusion of the EMT model of some portions of distribution systems in the hybrid approaches may become necessary. In this regard, a hybrid model of distribution systems is included in [6], [9]. On the implementation side, the hybrid model is implemented using two different simulation tools that can solve EMT and Phasor type models [3], [5], [6], [10], [11]. These approaches require specific and complex interfacing protocols to govern accurate data exchange between the EMT and phasor simulation tools. In another approach [12], both the EMT and Phasor models are developed in the same environment, MATLAB/Simulink. Though this enabled the need for a simpler interfacing protocol, such approaches still need two separate models (one in the EMT and one in the Phasor domain) and the development of an interaction protocol algorithm, a series or parallel protocol, in a separate file to handle data exchange between the two models. for instance, in a series protocol at each time instant only one model, EMT or phasor-domain, runs while the other is idle. As for a parallel protocol, both the models run simultaneously, while it requires synchronization [3]. Therefore, even this approach [12] will increase the total execution time of a hybrid simulation.

In this work, a hybrid EMT-Phasor simulation approach is developed in the MATLAB/Simulink environment. Taking advantage of multi-domain simulation capability, the EMT and Phasor models are simulated separately in different sub-systems. An interaction method is proposed to handle data transferring between the EMT and Phasor sub-systems. This approach reduces the existing hybrid models' complexity and execution time, eliminating the need for having two different simulation platforms (e.g. presented methods in [6], [9]) or two separate models/files for the EMT and phasor domain models (e.g. presented method in [12]). Moreover, it simplifies the interaction between the EMT and Phasor sub-systems, as such two sub-systems are run in one MATLAB/Simulink model. In this paper, the proposed approach is used to test PV inverter-dominated distribution grids. The phasor part of the system is built upon a simplified phasor model of the PV inverter systems developed in our previous work [1] which allows for having highly PV-integrated distribution feeders.

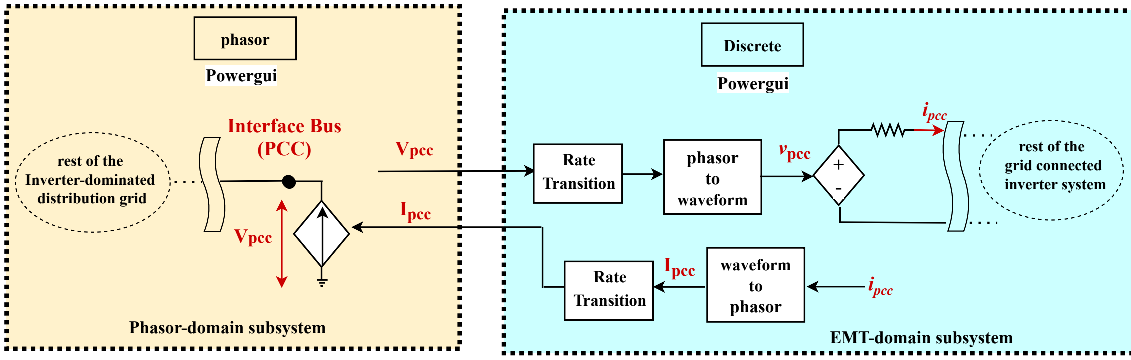

Fig. 1. The Proposed EMT-Phasor domain hybrid model in one MATLAB/Simulink model.

This paper is organized as follows. Section II describes the proposed hybrid approach in detail. In section III various aspects of the implementation are explained in a test system with high PV penetration. The accuracy and efficiency of the developed hybrid model are validated through case studies in section IV. Finally, section V draws the main conclusions of this work.

II. EMT-Phasor Domain Hybrid Model

The proposed MATLAB/Simulink based EMT-Phasor domain hybrid model of inverter-dominated distribution systems in one MATLAB/Simulink model is shown in Fig. 1, which is described in the following subsections in detail.

A. Partitioning

The first step of developing an EMT-Phasor domain hybrid simulation is selecting the part of the system whose fast dynamics are of interest (e.g. smart PV inverter system) to be modeled in the EMT domain. The bus interconnecting it to the rest of the grid is the point of common coupling (PCC) of the grid-connected inverter, which is referred as the 'interface bus' in Fig. 1.

B. Splitting Model into EMT and Phasor Domain Sub-Systems

In this stage, the MATLAB simulation environment's capabilities (i.e., Simulink) to accommodate multiple sub-systems with their own 'powergui' solver blocks and sampling times in a single model are used to split inverter-dominated distribution grids in the phasor-domain and EMT-domain sub-systems from the selected interface bus. To do so, the EMT portion of the system (e.g, a PV inverter) is located in the EMT-domain sub-system with the discrete solver and its corresponding sampling time. Subsequently, the rest of the system is located in the Phasor-domain sub-system to be solved by the phasor solver. The sampling time of the phasor sub-system is an integer multiple (between 50 to 100) of that of the EMT-domain sub-system.

C. Sub-Systems Equivalent Models at the Interface Bus

Since the EMT and Phasor sub-systems are being solved independently, each must be represented by an equivalent model to the other at the interface bus. In this hybrid model,

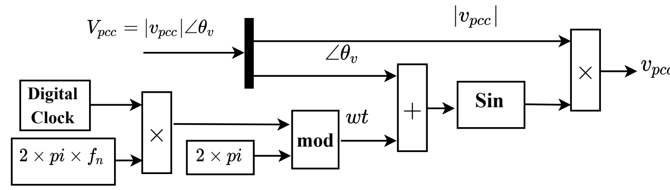

Fig. 2. Phasor-to-waveform block in detail.

the equivalent of the EMT sub-system (e.g. PV inverter) in the Phasor-domain sub-system (rest of the grid) is represented by a current source. As for the phasor-domain sub-system, its equivalent model in the EMT sub-system is represented by a voltage source.

D. Data Conversion

As shown in Fig. 1, (I_{pcc}) the current of the EMT sub-system equivalent model in the phasor-domain sub-system,a current source, is the fundamental frequency component of (i_{pcc}) the instantaneous output current of the EMT model at the interface bus. The waveform-to-phasor block calculates the I_{pcc} using the Fast Fourier Transform (FFT) [13]. The voltage of the voltage source (v_{pcc}), which is the equivalent model of the Phasor sub-system (rest of the grid) in the EMT sub-system, is the waveform representation of the phasor voltage (V_{pcc}) at the interface bus (PCC) through the phasor-to-waveform block shown in Fig. 1. The phasor-to-waveform block obtains the waveform of the voltage from its phasor representation by time interpolation [5]. Fig. 2 depicts this block in detail.

E. Interaction between the EMT and Phasor-Domain Sub-Systems

The proposed hybrid model is a multi-rate MATLAB/Simulink model. Therefore, rate transition blocks are used to handle the data exchange between the EMT and phasor-domain subsystems(i.e. transferring voltage and current signals between the two sub-systems), as shown in Fig. 1. This approach is a parallel interaction protocol, while it eliminates the need for synchronization. Therefore, the proposed hybrid model will reduce the modeling complexity and operation time of the simulation.

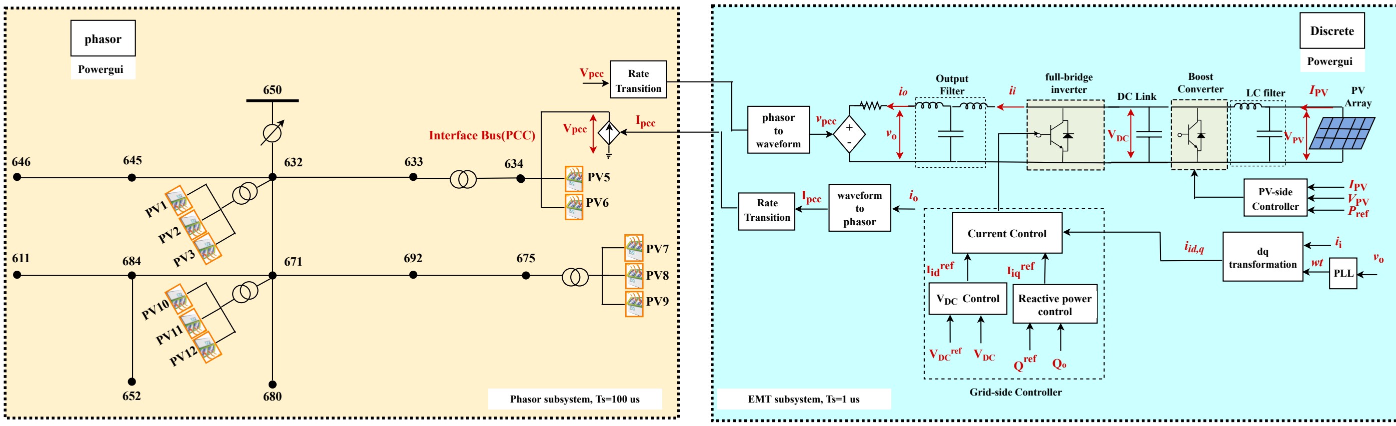

Fig. 3. The proposed EMT-Phasor domain hybrid model of the modified IEEE 13-node test feeder integrated with multiple single-phase smart PV systems.

III. Simulation Setup

A. EMT-Phasor Domain Hybrid Model of a Test Feeder

The modified IEEE 13-node distribution grid with multiple single-phase smart PV inverters is studied in this paper. The penetration of PV inverters in the studied network is high as the total load of the IEEE 13-node test feeder is 3.616 MW and the total rated power of the connected smart PV systems is 1.545 MW. Fig. 3 shows the developed EMT-Phasor hybrid simulation model of the IEEE 13-bus test system. There are two sub-systems of the Simulink model, which are the Phasor-domain sub-system and EMT sub-system. The Phasor sub-system is solved in the phasor domain by the phasor solver with a sampling time of 100 μs, while the EMT sub-system is solved in the EMT domain by the discrete solver with the sampling time of 1 μs. The main grid and most PV inverters are modeled in the phasor domain, while one PV system-of-interest (PV4) is modeled in the EMT domain. The detailed switching model, which can represent the accurate PVs' behavior, including transients and harmonics, is used for the modeling of PV4 inverter [1]. The rest of the PV inverters, which are modeled in the Phasor domain, are based on the simplified phasor model that is developed in [1]. The parameters of the designed 5 kW two-stage single-phase residential PV system are given in Table I. Its output current is scaled up to provide the rated power of each PV inverter in this simulation setup.

B. PV Inverter Model

The PV system consists of a PV array modeled by the well-known single-diode PV model, LC harmonic filter, boost converter, Dc link capacitor, full-bridge inverter, LCL filter, PV-side and grid-side controllers.

1) Detailed Switching Model: The detailed switching model of the PV system is shown in Fig. 3. As can be seen, the detailed model uses the switching devices for the boost converter and the full-bridge inverter. The grid-side controller is responsible for the regulation of DC-link voltage and managing output reactive power. The DC-link voltage and reactive power controllers generate dq current references for the inner current control loop. The dq components of single-phase current and voltage are obtained in dq transformation block using the phase angle of utility grid voltage given by the phase-locked loop (PLL) block, as shown in Fig. 3. More details of the detailed model are available in [1].

TABLE I
PV and Controller Parameters.

Component	Parameter	Value
PV Array	Photo current at STC, $I_{ph,STC}$	6.24 A
	Saturation current, $I_{0,STC}$	2.18e-12 A
	Series resistance, R_s	0.52 Ω
	Shunt resistance, R_{sh}	431 Ω
PV-side Converter	Rated power, P_{rated}	5 kW
	Rated DC voltage, V_{rated}	600 V
	Switching frequency, f_s	20 kHz
	PV-side capacitance, C_{PV}	4 μF
	DC-link capacitance, C_{DC}	1200 μF
	PV-side inductance, L_d	5 mH
Grid-side Converter	Rated power, S_{rated}	5 kW
	Rated AC voltage, V^G_{rated}	277 V
	System frequency, f	60 Hz
	Switching frequency, f_s	10 kHz
	LCL filter, L_i, C_f, L_g	2.6 mH, 8.64 μF, 1.5 mH

2) Phasor Model: Fig. 4 shows the simplified phasor model of the PV inverter system, which is used in phasor model of the network. In the simplified phasor model, the fast dynamic components, such as the inner current control loop and DC-side harmonic filter, are removed while the slow dynamic components, such as the outer control loop, are kept. The mathematics and more details of the phasor model of PV inverter have been presented in our previous work [1]. It should be noted that, both detailed switching and simplified phase models are in compliance with the IEEE-1547 standard [14].

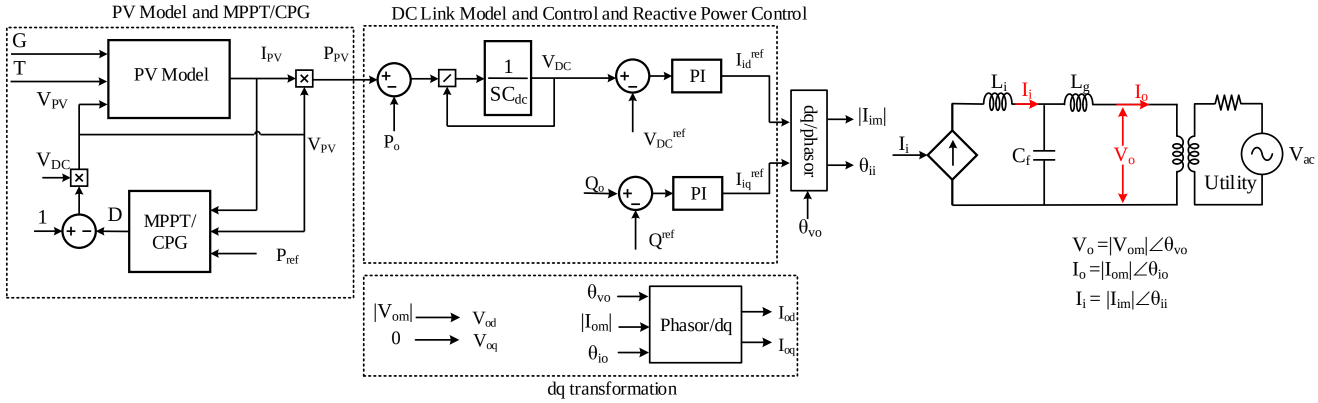

Fig. 4. Simplified phasor model of the PV inverter

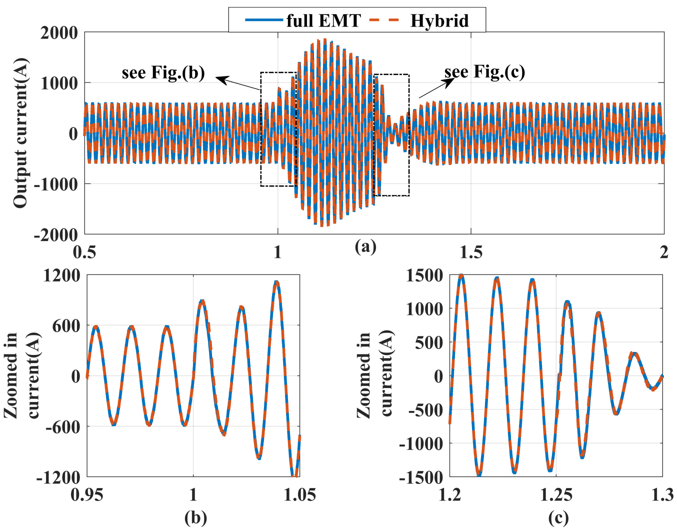

Fig. 5. The PV inverter's instantaneous output current (a) and the zoomed-in figures of the current (b) and (c)

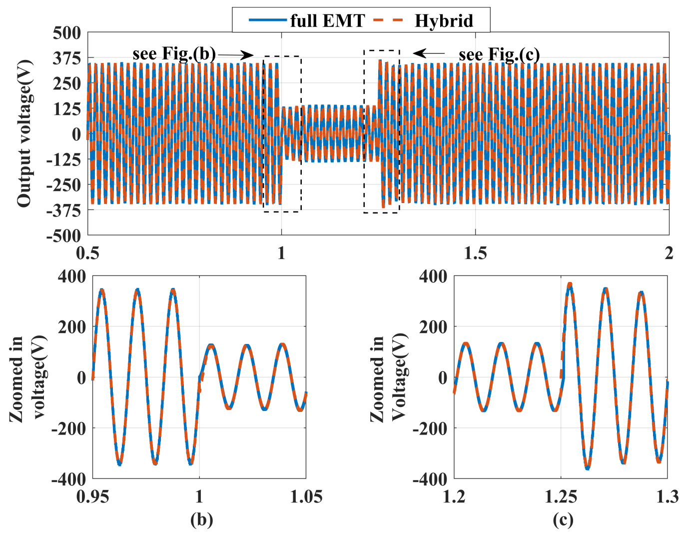

Fig. 6. The PV inverter's instantaneous output voltage (a) and the zoomed-in figures of the voltage (b) and (c).

IV. Simulation Studies

A. Transients During Fault

A single line to ground (SLG) fault is applied to study the transient response of the hybrid model, and the response is compared with the full EMT model. SLG is applied on the PCC point in the Phasor sub-system at 1 s and cleared after 0.25 s. Fig. 5 and Fig. 6 illustrate the PV inverter output current and voltage, respectively. The responses show a good agreement between the instantaneous voltage and current of the inverter in the proposed hybrid model and the full EMT model before, during, and after the SLG fault. To better show the accuracy of the proposed model Fig. 7(a), and (b) depict the error, in percentage, between RMS values of the inverter output voltage and current in full EMT and hybrid simulations, respectively. As it can be seen, the error in steady-state conditions, after and before the fault, is negligible, less than 0.25%, in voltage and less than 0.05%, in current. Similarly, the error during the fault is less than 0.55%, in voltage and less than 0.68%, in current. There are minor errors during transients resulting from a lack of information and approximations at the interface bus.

B. Solar Irradiation Fluctuation

This case study analyzes the performance of the hybrid model under irradiance changes. The PV system is designed to work in MPPT mode. The solar irradiance drops from 1,000 W/m^2 (STC) to 500 W/m^2 at 1 s, as shown in Fig. 8(a). This results in a decrease in the PV inverter active power from 100 kW to 50 kW as seen in Fig. 8(b), and a decrease in current, as well, as depicted in Fig. 9. This case study proves a good agreement between the results from the hybrid simulation and those from the full EMT simulation.

C. Volt-Var Function

This case studies the performance of the smart PV inverter in the time domain under a voltage fluctuation that occurred in the Phasor domain sub-system. The PV system is working in a

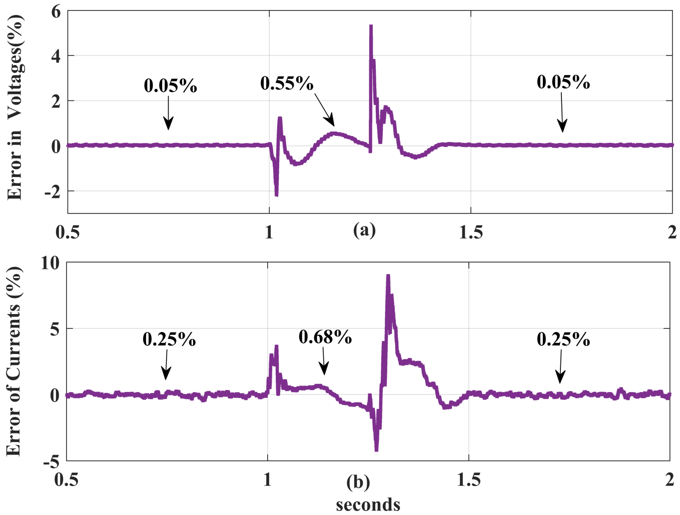

Fig. 7. The error between rms values of the PV inverter voltage (a) and current (b) in full EMT and Hybrid model.

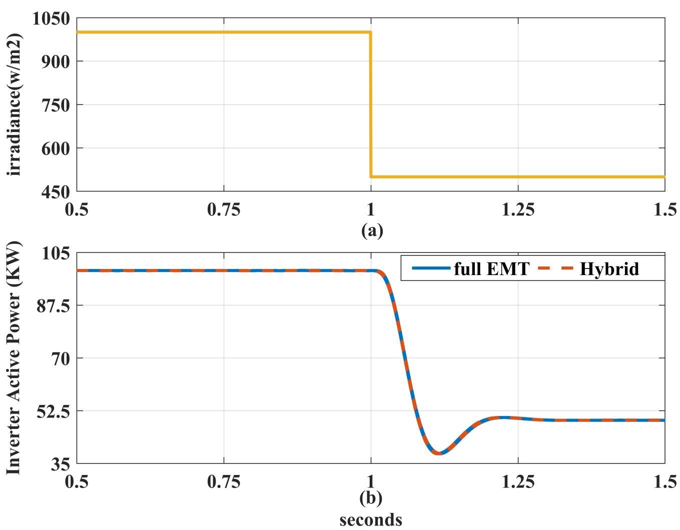

Fig. 8. Solar irradiance (a), PV inverter's generated active power (b).

volt-var mode, whose settings are as per the IEEE-1547 [14], and the solar irradiation is at maximum level. The substation voltage rises from 1 p.u. to 1.05 p.u. at 1 s and then it returns to 1 p.u at 1.5 s. Accordingly the voltage at the interface bus (PCC) fluctuates, as illustrated in Fig. 10(a). Fig. 10(b) and (C) represent the reactive power and generated active power by the PV inverter. Moreover, Fig. 11(a) and (b) show the instantaneous voltage and the zoomed-in voltage of the PV inverter, respectively. The maximum error between the RMS voltage of the inverter in full-EMT and Hybrid simulation is less than 0.2%. This case study verifies that the proposed hybrid model is able to accurately capture the dynamic of distribution grid during the transient. In addition, the measured total harmonic distortion (THD) of the output current signals of the PV inverter (at the steady states) are 1.4% and 1.8% in full-EMT and hybrid simulation, respectively, which are very close.

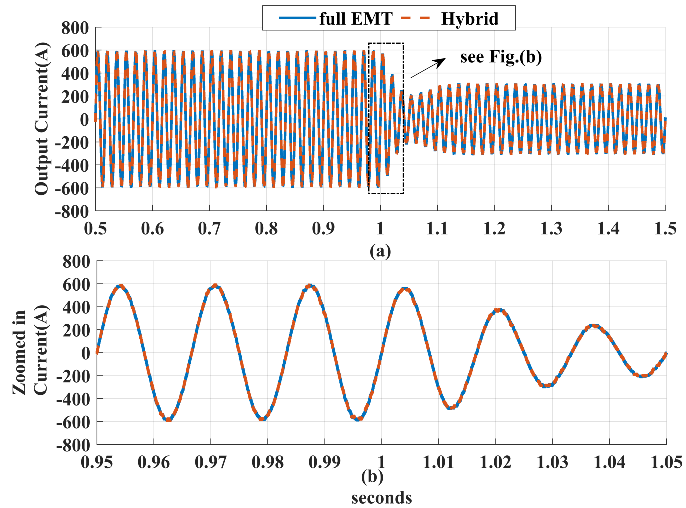

Fig. 9. Inverter's instantaneous output current (a) and the zoomed in figure of the current (b).

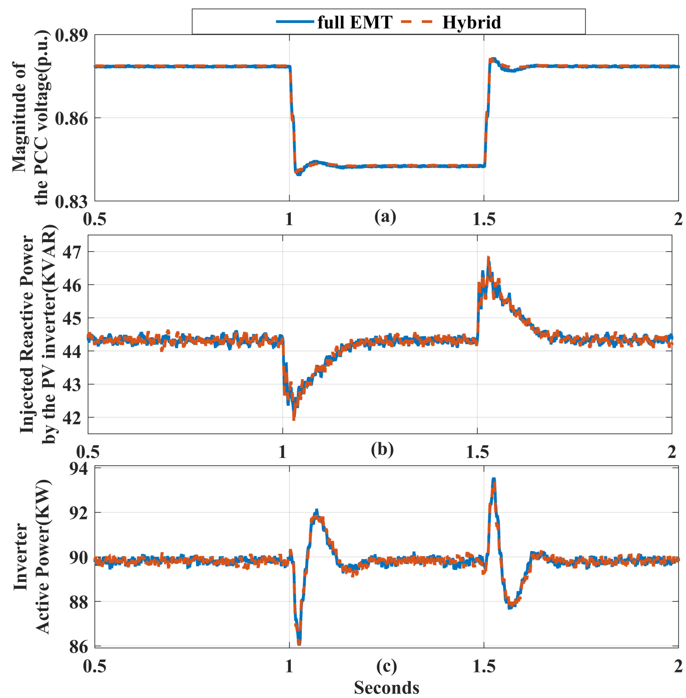

Fig. 10. Magnitude of the voltage at the PCC (a), injected reactive power by the PV system (b), and generated active power by the PV system (c).

D. Computational Performance

The execution time of a 2-second simulation for full EMT and proposed EMT-Phasor hybrid models are given in Table II. The simulation is performed in MATLAB/Simulink R2019b using a PC with 2.9 GHZ CPU and 16 GB RAM. As summarized in Table II, the proposed EMT-Phasor hybrid model reduces the execution time of the simulation drastically compared to the full EMT model. This reduction is almost 92%, from 76 minutes to 5.5 minutes, which is a significant

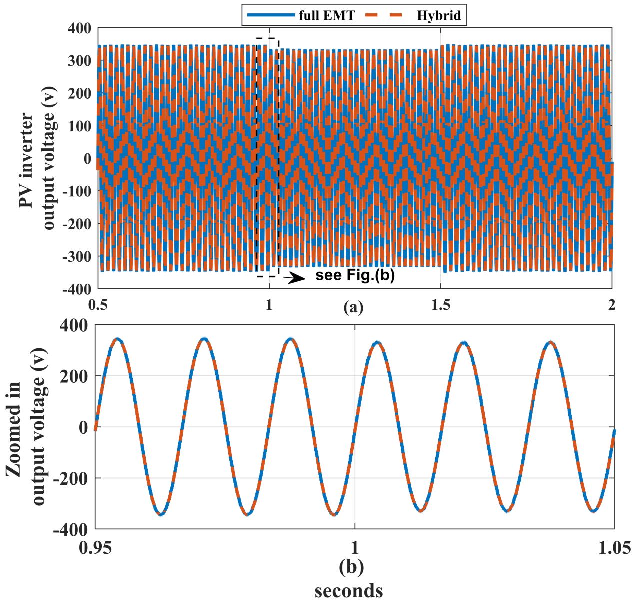

Fig. 11. PV inverter's instantaneous output voltages.

TABLE II
EXECUTION TIME OF BASED ON FULL-EMT SIMULATION VERSUS EMT-PHASOR HYBRID SIMULATION.

Models	Sampling Time, μs	Execution Time
Full EMT	1	76 minutes
Hybrid	EMT sub-system : 1 Phasor sub-system : 100	5.5 minutes

improvement over the hybrid models presented in [6] and [12].

V. CONCLUSION

This paper presented the development of an EMT-Phasor domain hybrid simulation approach for the analysis of the distribution grid with the high penetration of PV inverters. The proposed hybrid method was implemented in Matlab/Simulink environment and validated using various transient analyses. The comparison results showed a very good agreement between the two full-EMT and EMT-Phasor simulations. It is also shown that the proposed Hybrid model is much faster than the full EMT model. In addition, the proposed model is implemented in a single Simulink model, which eliminates the need for two different simulation tools or two separate models and development of a specific interaction protocol to handle data transferring between the two model as used in the existing literature. Future work will include extending this approach for larger distribution feeders.

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