# Hardware-based Advanced Electromagnetic Transient Simulation for A Large-Scale PV Plant in Real Time Digital Simulator


Jongchan Choi
*Oak Ridge National Laboratory*
Knoxville, USA
choij1@ornl.gov

Phani Marthi
*Oak Ridge National Laboratory*
Knoxville, USA
marthip@ornl.gov

Suman Debnath
*Oak Ridge National Laboratory*
Knoxville, USA
debnaths@ornl.gov

Md Arifujjaman
*Southern California Edison*
Westminster, USA
md.arifujjaman@sce.com

Nicole Rexwinkel
*Southern California Edison*
Westminster, USA
nicole.rexwinkel@sce.com

Farzad Khalilpour
*Southern California Edison*
Westminster, USA
farzad.khalilpour@sce.com

Andrew Arana
*Florida Power & Light*
Miami, USA
andrew.arana@fpl.com

Huzaifa Karimjee
*Florida Power & Light*
Miami, USA
huzaifa.karimjee@fpl.com



***Abstract*—Power electronics-based resources, such as high-voltage direct current (HVdc) substations, photovoltaic (PV) plants, wind plants, electric vehicle charging stations, and energy storage systems, are increasingly being integrated within the power grid. Recently, multiple reports have emphasized the necessity for high-fidelity electromagnetic transient (EMT) simulations of these large-scale power electronics-based resources to accurately understand their behavior in power grids. However, performing hardware-based EMT simulations with high-fidelity models for such large power electronics systems is challenging due to the small time-step requirements and the involvement of a large number of states. This paper presents the implementation of hardware-based high-fidelity EMT dynamic model of a large-scale PV plant, accomplished through custom model development using the specific-C language in real-time digital simulator hardware (RTDS) and software (RSCAD).**



***Index Terms*—Electromagnetic transient, hardware-based simulation, inverter-based resources, photovoltaic plant, power electronics, real-time simulation.**


## I. Introduction

The penetration of power electronics-based resources in the power grid is experiencing rapid growth, with the incorporation of various technologies like high-voltage direct current (HVdc) substations, photovoltaic (PV) plants, wind plants, electric vehicle charging stations, energy storage systems, among others. Conducting electromagnetic transient (EMT) simulations of these large-scale power electronics systems is crucial to comprehend the interactions among individual inverters within the power electronics system and to accurately understand their behavior in the power grid [1]. However, performing EMT simulations for such large-scale power electronics systems is exceptionally challenging, as it demands small time-step requirements and the ability to simulate a large number of states in these expansive systems [2].

Hardware-based EMT simulation, utilizing real-time digital simulator (RTDS) hardware or Opal-RT hardware, accelerates power grid simulations [3] and enables real-time or near-real-time capabilities [4]. As the demand for real-time simulation increases due to the high penetration of power electronics in power grids, researchers have explored converting power grid models from offline simulation to real-time simulation, particularly for large-scale power grids [5]. In addition, a real-time simulation of large-scale wind power plants within the Hydro-Quebec power system was modeled and executed [6]. However, these studies have not yet accounted for high-fidelity EMT models of power electronics systems, which are essential for comprehending the interactions among individual inverters within the power electronics systems. For offline simulation, a high-fidelity of large-scale power electronics systems was modeled and simulated to analyze the interactions of individual inverters within the power electronics systems [7], [8].

Real-time co-simulation has been employed to conduct real-time simulations of power grids with power electronics systems, aiming to enhance the fidelity of power electronics systems and the scalability of power grids [9]. However, simulating high-fidelity models of large-scale power electronics systems, such as large-scale PV plants (or inverter-based resources as in IEEE 2800 [10]), remains a challenge due to the difficulty of meeting timing constraints in hardware-based


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simulations [2], [4].

Furthermore, performing hardware-based EMT simulation of large-scale power electronics systems in the power grid demands a thorough understanding of both the hardware and software platforms, as well as expertise in electrical engineering or power systems, as demonstrated in this paper. This paper presents a hardware-based EMT simulation of high-fidelity models of a large-scale PV plant in RTDS hardware. The implementation of the high-fidelity EMT model in RTDS is elaborated in detail, along with potential challenges and techniques to overcome them.

The sections of this paper organized as follows. The system description and components of a large-scale PV plant are presented in Section II. The advanced numerical simulation algorithms applied to the PV plant EMT model are described in Section III. The implementation of hardware-based EMT simulation of a large-scale PV plant, covering both software and hardware considerations, is explained in Section IV. This section also includes discussions on potential challenges and proposed techniques to successfully implement a hardware-based EMT model of a large-scale PV plant. The simulation results obtained from RTDS hardware using the proposed techniques are presented in Section V. The conclusion of this paper is presented in Section VI.

## II. System Description of a large-scale PV plant

A practical large-scale PV plant installed in California is studied in this paper. Under non-disclosure agreement, detailed system description without sensitive information are provided in this section. In Fig. 1, a google map image of the PV plant is displayed to present the actual scale and configuration of the practical PV plant.

A large-scale PV plant is considered as IBR, defined in IEEE Standard 2800-2022 [10]. According to the IEEE standard, the components of an IBR include main IBR transformer, collector system, supplemental IBR device (e.g., compensation device), feeder, IBR unit transformer, and IBR unit. Consequently, the components of a large-scale PV plant in this study comprise PV inverter module (IBR unit), PV system (IBR unit transformer with multiple IBR units), feeder (collector system with compensation device), and power transformer (main IBR transformer). The components and structure of the large-scale PV plant used in this study are presented in Fig. 2. The arrows between the components indicate electrical connections. Thus the power generated from the PV inverter module is transferred through IBR unit transformer, feeder, and power transformer to the main HV grid.

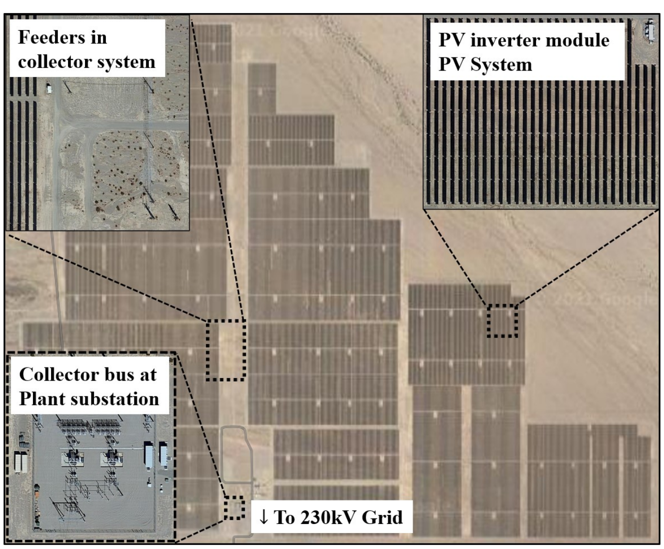



Fig. 1: Aerial perspective of the large-scale PV plant installed in California (from Google Maps. Available at : https://maps.google.com. Accessed: July 2023)

*PV inverter module (IBR unit)*: The PV inverter module considered in this paper consists of a PV array, a DC-AC inverter, a DC-AC inverter controller, and a filter. All the components together are referred to as the PV inverter module, which can also be considered as an IBR unit according to IEEE Standard 2800-2022. There are two different types of inverter and filter hardware configurations present within the plant. Additionally, two different ratings are considered for each type of inverter. All the parameters of the PV inverter module are provided by the manufacturer.

*PV system (IBR unit transformer with multiple IBR units)*: The PV system described in this paper comprises multiple PV inverter modules connected through a distribution transformer. This transformer serves as an interface between the IBR units at low voltage (e.g., 480V) and the feeders at medium voltage (e.g., 34.5kV). According to IEEE Standard 2800-2022, the distribution transformer is regarded as an IBR unit transformer. Similar to the PV inverter module, all the transformer's parameters are provided by the plant owner.

*Feeder (within Collector system)*: A large-scale PV plant can deploy and connect hundreds of PV systems through medium voltage feeders using distribution lines/cables. The

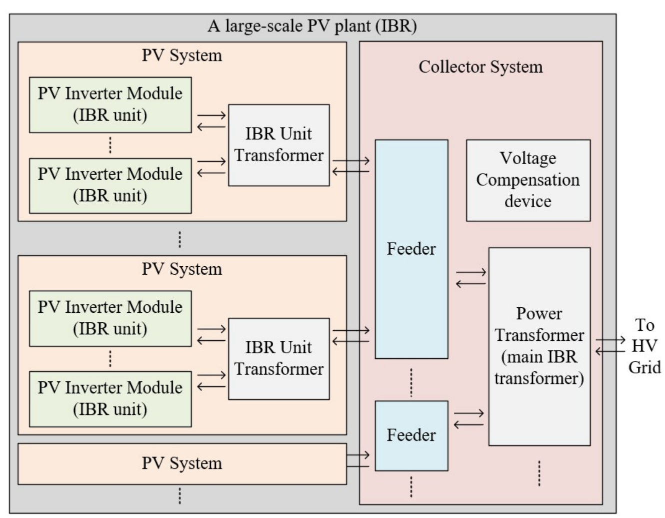



Fig. 2: Components and their structure of the large-scale PV plant

feeders are modeled by a three-phase PI section line model with mutual coupling effects between three phases due to their short lengths. In Fig. 1, the PV plant consists of several dozen radial feeders connected in parallel at the collector bus to create a large-scale PV plant. All the parameters of the distribution lines/cables are provided by the manufacturer.

*Collector system (with power transformers and compensation devices)*: The multiple feeders within the PV plant form a collector system. The configuration of the collector system may vary across PV plants, depending on the number of PV systems within the PV plant and geological characteristics. Multiple feeders are connected at the collector bus to a power transformer, serving as an interface between the medium voltage collector system and the high voltage (e.g., 230kV) transmission grid. Furthermore, shunt capacitor banks may be present at the collector bus as voltage compensation devices.

## III. Advanced EMT Simulation Algorithms for a large-scale PV Plant Simulation

Several advanced EMT simulation algorithms are employed to accelerate the simulation of the developed PV plant model. These algorithms include numerical stiffness-based hybrid discretization, differential algebraic equations (DAEs) clustering and aggregation, multi-order discretization, and matrix splitting methods [8]. These algorithms are necessitated by the computationally demanding nature of EMT simulations, which necessitates substantial computing resources. Moreover, large-scale PV plants comprise a significant number of components; for example, a single plant may deploy over a hundred inverters.

*Numerical stiffness-based hybrid discretization*: The EMT dynamics of a large PV plant can be modeled using DAEs. The DAEs that represent the dynamics of the individual PV inverter module can be segregated based on numerical stiffness characteristic of DAEs [11]. In the PV inverter module, the DAEs representing the dynamics of the inductor current of the dc-dc converter, the dc-ac inverter current, the filter voltage, and the filter current exhibit the numerical stiffness characteristic. Therefore, the DAEs with the numerical stiffness property are discretized by the backward Euler method. Conversely, the DAEs that represent the dynamics of capacitor voltages in the dc-dc boost converter have non-stiff property. Hence, the DAEs with non-stiffness are discretized by the forward Euler method. By segregating the DAEs based on the numerical stiffness property, the EMT simulation can achieve increased speed while maintaining high accuracy and numerical stability.

*DAEs clustering and aggregation*: The dynamics of the multiple PV inverter modules and the IBR unit transformer in the PV system can be aggregated by clustering similar dynamics across the multiple PV inverter modules. Similar dynamics of PV inverter modules can be grouped through the IBR unit transformer, thereby reducing the size of the large matrix required to be operated in computations for the PV system including multiple PV modules. This approach also enables the application of multi-order discretization approaches in both the aggregated module (e.g., IBR unit transformer) and the individual module (e.g., PV inverter module). The reduced computations required in the linear solvers (due to the smaller size of the operated matrices) and the use of multi-order discretization approaches contribute to a reduction in the EMT simulation time necessary for simulating a large-scale PV plant.

*Matrix splitting method*: The matrix splitting method can be applied to reduce the size of the matrix required for computations in the collector system, which includes multiple feeder modules. This approach involves modularizing the collector system into multiple subsystems that exhibit similar dynamics across the multiple feeders. Through this approach, the matrix operated for the collector system can be transformed into a block diagonal matrix. Consequently, only smaller linear equations-based block diagonal matrices need to be solved, as the diagonal blocks can be managed individually. Moreover, there are numerous computationally effective methods available for operating on block diagonal matrices. As a result, the size of the operated matrix can be significantly reduced, thereby accelerating the simulation speed of the EMT simulation. Furthermore, the matrix splitting method enhances modularity and scalability for the collector system. Modularity facilitates the easy implementation of collector systems with different sizes of PV plant. It also enables parallelism in the implementation of the high-fidelity EMT model of the PV plant with high-performance computing. This aspect becomes crucial in hardware-based EMT simulation, where the PV plant model must be divided into multiple blocks and allocated across multiple computing processors. A detailed discussion of this topic can be found in Section IV.

An overview of the multiple advanced EMT simulation algorithms applied to each components of a large-scale PV plant are presented in Fig. 3. Multiple advanced algorithms,

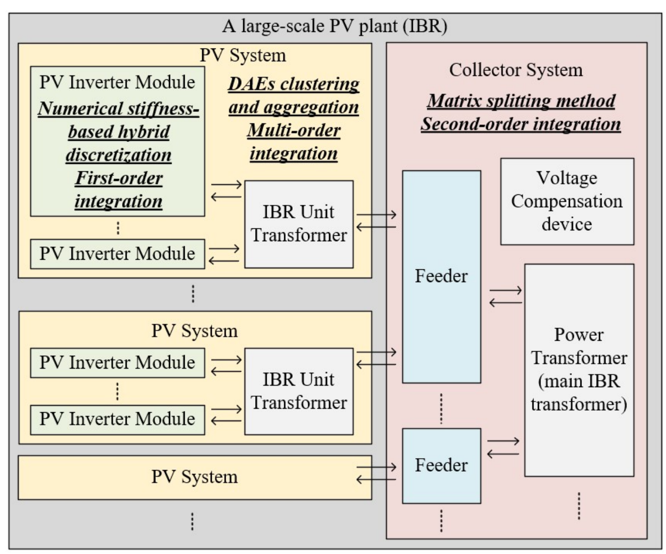



Fig. 3: Overview of the multiple advanced EMT simulation algorithms applied to each module within a large-scale PV plant

including DAEs' numerical stiffness-based hybrid discretization, multi-order integration, and matrix splitting method are applied to solve the DAEs representing the EMT dynamics of a large PV plant. These simulation algorithms have shown speed-up of the order of 326 times in the offline simulation of a large PV plant in PSCAD software [8]. Using these EMT simulation algorithms, the EMT dynamics of large PV plant are simulated in this paper on an RTDS hardware that is explained in the next section.

## IV. Implementation of Hardware-based EMT Simulation of a Large-scale PV plant in RTDS

### A. Software Consideration

The software used to build models and run simulations on RTDS is RSCAD. To apply the advanced EMT simulation algorithms described in Section III to the custom EMT model of a large-scale PV plant described in Section II, customized control components need to be used.

The customized control components can be developed in CBuilder in RSCAD using a specific C language. The C language used in RSCAD has a similar syntax as standard C language but has certain framework. For example, there are multiple sections, such as STATIC, RAM, and CODE that need to be used as shown in Fig. 4. Each section has a specific purpose for hardware-based EMT simulation. The scripts placed in each needs to be optimized for real-time implementation to avoid over-runs. Variables used in the model are declared only in the STATIC section. Initialization of the declared variables by certain values or parameters are defined in the RAM section. These two sections are only executed once before the real-time simulation occurs. The rest of the algorithm and variables that update with time are placed in the CODE section. The CODE section runs at every time-step during the real-time simulation. By optimizing the scripts placed in these three sections, efficient hardware-based real-time simulation can be performed in RTDS. That is, a knowledge of EMT modeling, EMT simulation algorithms, and an understanding of the specific C language with the sections in RSCAD are required for hardware-based EMT simulations in RTDS.

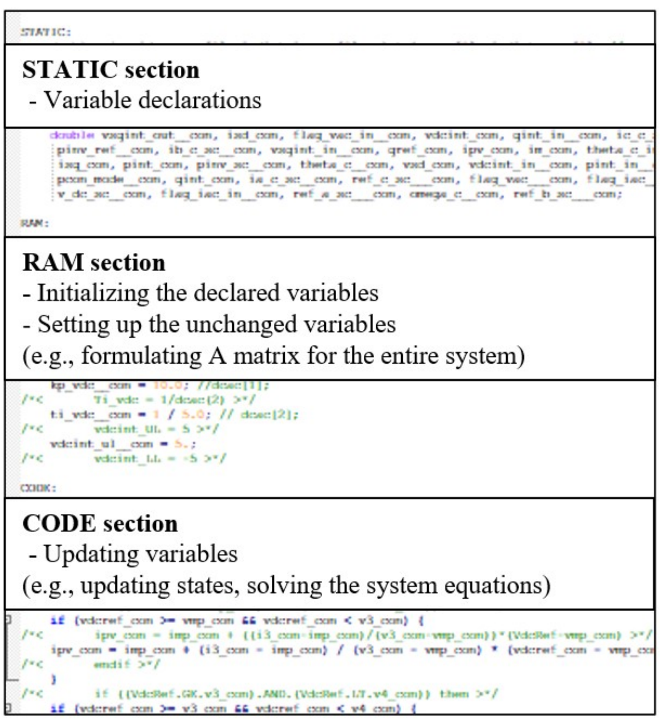



Fig. 4: Example of specific C language for the customized control components in CBuilder(in RSCAD)

An important idea on the implementation of the hardware-based EMT simulation in RTDS is to optimize the specific C script in the three sections. There are three main steps during the EMT simulation such as formulating system linear equations, updating system states, solving the system equations with the updated states. Since both updating system states and solving the system equations need to be performed at every simulation time-step, the scripts must be placed in the CODE section. However, formulating system equations can remain the same when there are no changes in the system. Therefore, the script can be deployed in the RAM section instead of placing in the CODE section. This method improve the efficiency of the EMT simulations by removing the computations from the CODE section.

The use of the advanced EMT simulation algorithms in hardware-based simulations enables the capability to simulate larger systems (as opposed to the offline simulations where speed-up is observed). Moreover, the hardware-based simulations require further optimization of the scripts used to implement the EMT simulation algorithms on the EMT dynamic models.

### B. Hardware Consideration

The hardware structure of RTDS for hardware-based EMT simulation can be expressed as shown in Fig. 5. EMT simulation models can be divided and allocated into the cores within the processor cards. Within a rack, up to 6 processor cards can be connected to a rack and communicated by peripheral component interconnect express (PCIe). For large or complex simulation models, multiple racks can be used by inter-rack communication (IRC) cards. By using a IRC switch including 5 IRC cards, up to 60 racks can be connected each other and communicated by optical cables. Understanding the hardware structure is important to implement hardware-based EMT simulations in RTDS.

In contrast to offline simulations, real-time simulations impose a critical hardware constraint, where computations for simulated models at every simulation time-step must be completed within a given fixed time-step. When a single processor is utilized for large systems, a large simulation time-step is required in real-time simulations to avoid over-runs. However, a long simulation time-step can lead to numerical instability for power electronics systems with small simulation time-step requirement. Hence, to simulate the EMT dynamic model of a large PV plant, the model has to be allocated

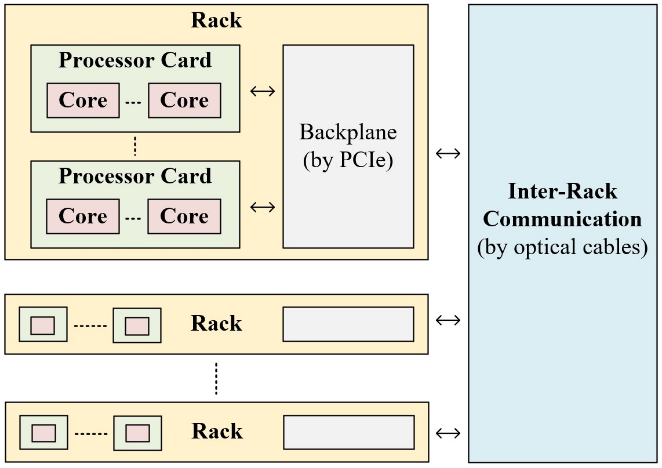



Fig. 5: Hardware structure in RTDS

across multiple processors, processor cards and racks in RTDS hardware. One of the software constraints introduced to meet real-time constraints is that the computation in each processor happens independently at every simulation time-step. And data exchange between processors happens only at the end of each simulation time-step. Thus, splitting a model across multiple processors result in the introduction of multiple time-step delays in the signals exchanged between processors due to the real-time software constraints, hardware structure, and data communication processes. When splitting the EMT dynamic model of a large PV plant across multiple processors, the propagation of the time delay from the grid model that connects to the large PV plant model to the individual inverter models in a PV plant model can result in numerical oscillations.

### C. Proposed Techniques

To address numerical instability in real-time simulation of the EMT dynamic model of a large-scale PV plant in RTDS, multiple hardware-based simulation techniques are proposed in this paper: pseudo real-time implementation with optimizing simulation time-step, appropriate C script partitioning in multiple processors, and equivalencing techniques at boundaries of partitioning.

*Pseudo real-time implementation with optimizing simulation time-step*: The first technique is to optimize (reduce) the simulation time-step to mitigate the impact of time delay propagation from the hardware structure, as this propagation can lead to numerical instability (e.g., oscillations or divergences in states). However, reducing the simulation time-step results in the need to relax the real-time constraints to pseudo real-time constraints. In pseudo real-time implementation, the solution time-step is extended to a larger value than the simulation time-step, while keeping the simulation time-step short to prevent overruns. In the case of the large-scale PV plant discussed in this paper, the simulation time-step is reduced to 0.25 µs, while the solution time-step is extended to 100 µs. The required simulation time-step for offline simulation is 1 µs. This technique is referred to as pseudo real-time implementation.

*Appropriate C script partitioning in multiple processors*: The second technique involves partitioning the C scripts across multiple processors. These C scripts encompass the EMT simulation algorithms applied to the EMT dynamic model. Separate C scripts are created for each PV inverter module, IBR unit transformer module, and feeder module. The partitioning of the C scripts and the development of individual C scripts are based on the utilization of a large time constant found in elements within the EMT dynamic model contained in the respective C scripts. For instance, the presence of a large inductance in the IBR unit transformer facilitates the separation of the C script for the individual PV inverter module and the IBR unit transformer from the C script for the connected feeder model.

*Equivalencing techniques at boundaries of partitioning*: In the absence of a large time-constant in the EMT dynamic model that enables the split of the C scripts, equivalencing techniques can be utilized at the boundaries of the split for hardware-based EMT dynamic model. The equivalencing techniques are methods to increase the inductance or capacitance at the boundaries of the split in the EMT dynamic model so that there will be a large time-constant for the split of the C scripts. For example, multiple parallel feeder lines can be created for a short single feeder line to increase inductance and hence the multiple lines can be used to split the C scripts. This method is utilized in the split of the EMT dynamic model at the collector bus that connects to multiple individual feeders within the collector system of the PV plant.

In the absence of a large time constant in the EMT dynamic model, which would allow for the partition of the C scripts, equivalencing techniques can be employed at the boundaries of the partition in a hardware-based EMT dynamic model. These equivalencing techniques involve methods to increase the inductance or capacitance of elements at the partition boundaries in the EMT dynamic model, thus resulting in a larger time constant for the partition of the C scripts. For instance, multiple parallel feeder lines can be produced for a short single feeder line to increase inductance. Consequently, these multiple lines can be utilized to divide the C scripts with a large time constant. This approach is applied in the partition of the EMT dynamic model at the collector bus, which connects to multiple individual feeders within the collector system of the PV plant.

## V. Hardware-based Simulation Results

The hardware-based simulation results of the EMT dynamic model of a large PV plant are presented in this section. The EMT dynamic model of a large-scale PV plant in Section II was developed and implemented in RTDS based on the advanced EMT simulation algorithms in Section III and the proposed hardware-based simulation techniques in Section IV. The main focus of these simulation results is to highlight the feasibility of hardware-based EMT simulation for a large-scale PV plant in RTDS. Two use case scenarios such as a steady-state condition and power step change are performed and analyzed in this paper to verify the effectiveness of the proposed hardware-based simulation techniques for a large-scale PV plant. Some important states such as currents and voltages are illustrated in Fig. 6 and 7.

Scenario 1 is performed under a steady-sate condition to identify the numerical stability of hardware-based EMT simulation for a large-scale PV plant in RTDS. Currents and voltages of one PV system within the collector system are monitored and measured from RTDS as shown in Fig. 6a, 6b. Currents, voltages, and active power monitored at the point of connection of the PV plant are illustrated in Fig. 6c, 6d, and 6e, respectively. As can be seen from the figures, the hardware-based EMT simulation model of the large-scale PV plant runs successfully without numerical stability issues. The model would not run at all or be automatically terminated by numerical instability issues and divergences in the states of the PV plant that can lead to overflow errors in RTDS.

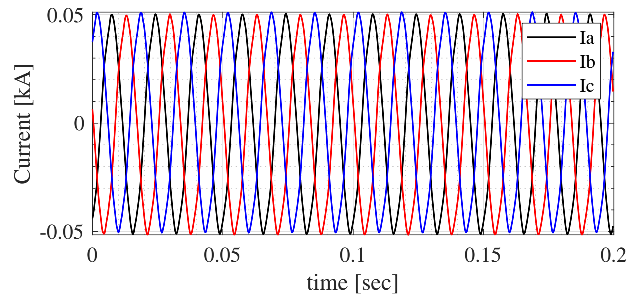
Scenario 2 is performed for a case of power step change in the PV plant by changing the output power of the PV inverter modules from 1.0 pu to 0.5 pu. The power step change is conducted by changing the reference of dc-link voltage in the PV inverter module during real-time simulation. Similar to the scenario 1, currents, voltages, and active power of the PV plant are monitored and measured from RTDS for scenario 2 as shown in Fig. 7. As can be seen from the figures, the currents from the PV inverter module in Fig. 7a decrease, resulting in currents and active power reduction from the PV plant in Fig. 7c and 7e.

## VI. Conclusions

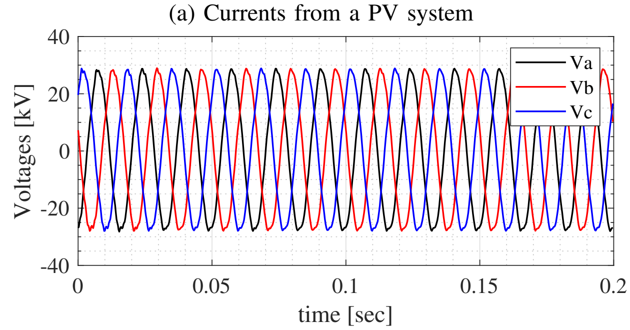
This paper presents the development and implementation of hardware-based EMT simulations for a high-fidelity EMT dynamic model of a large PV plant in RTDS. Advanced EMT simulation algorithms and hardware-based techniques are applied to the high-fidelity EMT model of the large-scale PV plant. The customization of control components using RSCAD-specific C language is discussed, which is necessary for implementing the advanced EMT simulation algorithms in RTDS.

The challenges associated with hardware-based EMT simulations are investigated. To meet the time constraints of EMT simulations and avoid the need for a large simulation time-step, the model needs to be divided across multiple processors. However, splitting the EMT model across processors introduces time delays and can result in numerical oscillations. To overcome these challenges, several hardware-based simulation techniques are proposed, including optimizing the simulation time-step, implementing a pseudo real-time approach, partitioning the C script appropriately across multiple processors, and using equivalencing techniques at the boundaries of the model partition.

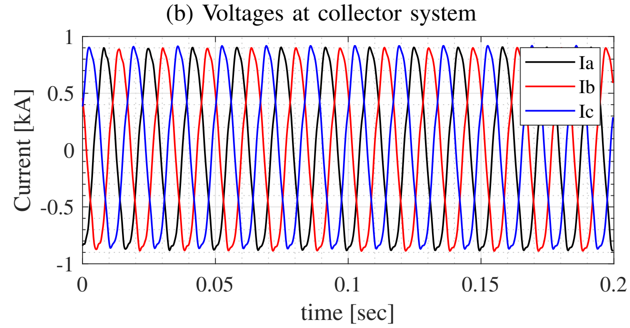
To verify the effectiveness of the proposed techniques, hardware-based simulation results of a practical large-scale PV plant are presented for two use cases: steady-state and power step change scenarios. Based on the obtained results,



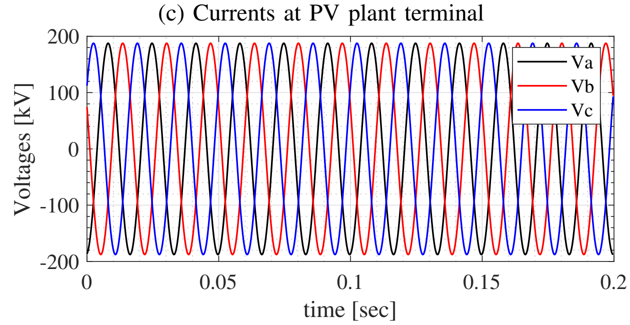
(a) Currents from a PV system



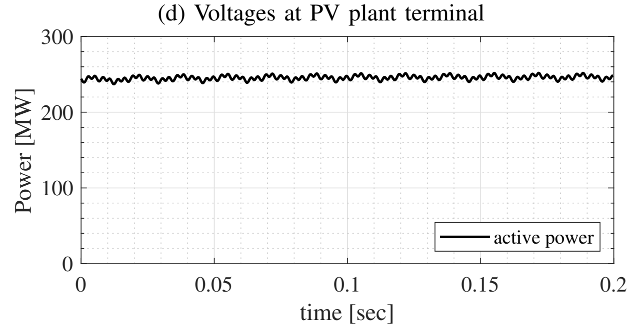
(b) Voltages at collector system



(c) Currents at PV plant terminal

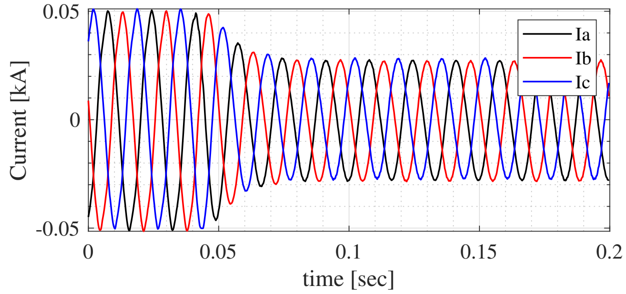


(d) Voltages at PV plant terminal

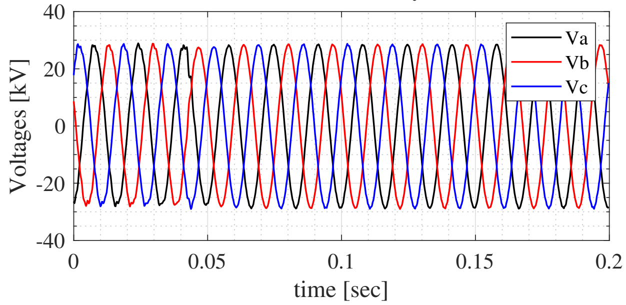


(e) Active power at PV plant terminal

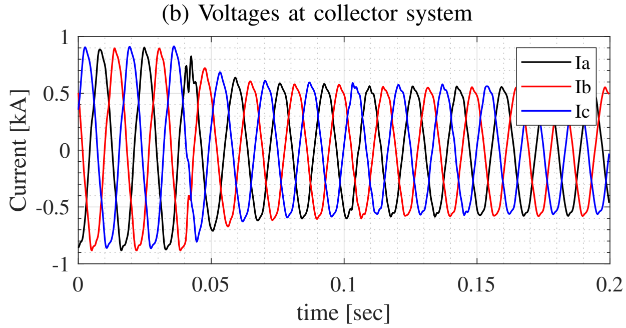
Fig. 6: Scenario 1 - States from the developed PV plant in RTDS under a steady state condition



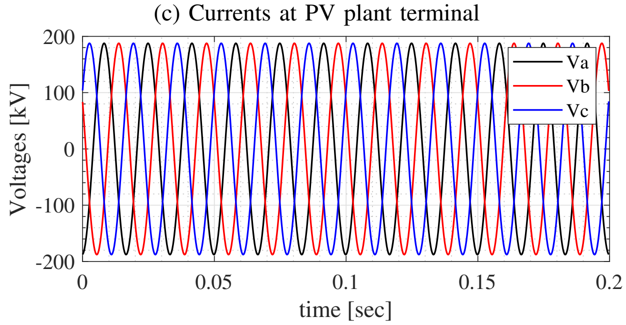

(a) Currents from a PV system



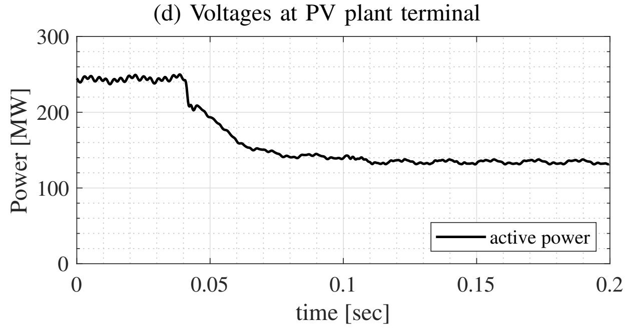

(b) Voltages at collector system




(c) Currents at PV plant terminal




(d) Voltages at PV plant terminal




(e) Active power at PV plant terminal

Fig. 7: Scenario 2 - States from the developed PV plant in RTDS for power step change by dc-link voltage reference in the PV inverter modules

it is evident that the proposed techniques effectively mitigate numerical stability issues when executing the hardware-based Electromagnetic Transients (EMT) simulation model of the large-scale PV plant. These techniques ensure stable operation of the hardware-based EMT simulation model on RTDS, preventing overflow errors and forced termination.

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