High-Performance Computing Based EMT Simulation of Large PV or Hybrid PV Plants

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***Abstract*—Faults in the transmission grid have led to reduced power generation from power electronics resources that are typically not connected to the faulted transmission line. In many of the cases, partial loss of power is observed within the power electronics resources like large photovoltaic (PV) power plants. This phenomena is not captured in existing simulation models and/or simulators. High-fidelity switched system electromagnetic transient (EMT) dynamic models of PV power plants can improve the fidelity of models available for accurate analysis of the impact on PV plants during simulation of faults. However, these models are extremely computationally expensive and take a long time to simulate. Long simulation times limit the ability to use these models as larger regions are studied in EMT simulations with more power electronics resources. In this paper, numerical simulation algorithms are combined with high-performance computing techniques and applied to the high-fidelity switched system EMT model of PV plants. Using these techniques, a speed-up of up to 58x is obtained, while preserving the accuracy of the simulation at greater than 98%.**

***Index Terms*—Renewable, EMT, PV, Hybrid PV plant, high-performance computing, HPC**

I. Introduction

The penetration of power electronics resources such as photovoltaic (PV) power plants, hybrid PV and energy storage system (ESS) plants, wind power plants, among others, are rapidly increasing in the power grid. The renewable energy penetration targets setup recently in United States is 100% by 2035 [1]. A significant portion of this generation is expected to come from PV, hybrids, and wind. Similarly, the presence of power electronics is also increasing in the loads like in electric vehicle chargers.

With the increased penetration of power electronics resources in power grids, electromagnetic transient (EMT) simulation is necessary in planning and operations. This necessity arises from the fast dynamics observed in power electronics resources that are captured only in EMT simulations. Recent events studied in California and Texas have highlighted the need for EMT simulations to accurately capture the dynamics of power electronics and power grids [2]–[6]. Additionally, high-fidelity switched system EMT dynamic models of renewable (PV, wind) and hybrid plants are necessary to capture the partial trips or momentary cessations that happen during disturbances. The high-fidelity switched system EMT dynamic model may represent the dynamics of all individual components in a plant like inverters, inverter controllers, filters, transformers, distribution cables/line, capacitor banks, power transformer, power plant controllers, among others. EMT simulation of high-fidelity switched system dynamic models and large regions of the power grid are extremely slow. There has been research focused on methods to improve speed of EMT simulation of power grids in general [7]–[9] as well as of large power electronics systems [10]–[14]. However, there has not been any high-performance computing (HPC)-based EMT simulation of large PV plants (or other power electronics resources).

In this paper, numerical simulation algorithms coupled with HPC algorithms are applied on the high-fidelity switched system EMT dynamic models of large PV plants. The application of these algorithms speeds up EMT simulations and can enable simulation of a large number of power electronics resources using high-fidelity switched system EMT dynamic models. The following sections explain the work in this paper: PV plant description, EMT numerical simulation algorithms applied to the high-fidelity switched system model of PV plant that are implemented in PSCAD/Fortran, PSCAD/Fortran to C/C++ conversion method, HPC techniques and optimizations performed on C/C++ codes for the PV plants, and simulation results from a HPC implementation of high-fidelity switched system model of a PV plant and validation/benchmark of these results.

II. PV Plant & High-Fidelity Model

A PV plant consists of a large number of components such as PV inverter modules, distribution transformers, distribution feeder (with overhead lines and underground cables), voltage compensation devices (like shunts), and power plant controller (PPC). A PV inverter module consists of a PV array connected to a dc-dc boost converter that are connected to a three-phase inverter and LCL filters. The dc-dc converter and the inverter in a PV inverter module have their own controllers.

Research sponsored by the Laboratory Directed Research and Development Program of Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U. S. Department of Energy.

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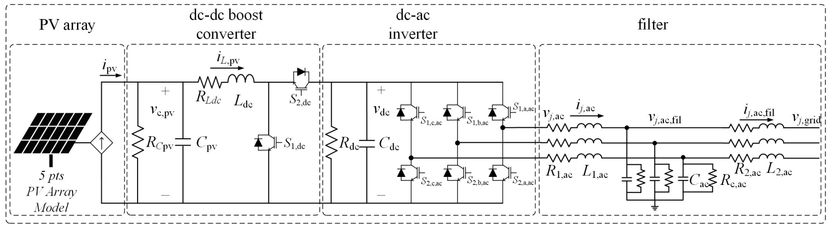


Fig. 1. PV inverer module consisting of PV array, dc-dc converter, dc-ac inverter, and LCL filter.

Multiple PV inverter modules connecting to a single distribution transformer forms a PV system. The components and structure of the PV plant in this paper is based on an actual PV plant installed in California as well as an power electronics resources in IEEE 2800 [15].

A. PV Inverter Module

A PV inverter module is shown in Fig. 1. The high-fidelity switched system EMT dynamic model of the PV inverter module is detailed in [11]. The control system in the PV inverter module employs a dc-dc control module to control dc-dc boost converter, dc-ac control module to control dc-ac three-phase voltage source inverter. Multi-rate control algorithms are utilized in the dc-dc and dc-ac control modules to incorporate control time-step, switching signal generation, and measurement delays within the models of the control systems. The hardware of the PV inverter module is simulated at the order of a μs and dc-dc and dc-ac control modules are simulated on an order of 50-100 μs.

B. PV System

In this paper, a PV system consists of 5 PV inverter modules connecting to a single distribution transformer. The distribution transformer connects to the distribution feeder at the medium-voltage side. The distribution transformer's EMT dynamic model is explained in [11].

C. Distribution Grid

There is a distribution grid with multiple feeders that connect to PV systems in a PV plant. Typically, multiple radial feeders are connected in parallel with a collector bus within a PV plant. In this paper, the radial feeder can have up to 5 distribution transformers and the collector bus has 5 radial feeders. The modular nature of the development of the high-fidelity EMT dynamic model makes it easy to expand to higher number of feeders and/or distribution transformers. Thus, the PV plant studied in this paper includes a total 25 PV systems (and a total 125 PV inverters) and 5 radial feeders. The high-fidelity EMT dynamic model of distribution lines and cables are modeled based on the equations shown in [11].

III. EMT Simulation Algorithms

Multiple numerical EMT simulation algorithms are applied to the high-fidelity switched system EMT dynamic model of each component within the PV plant model. The algorithms include numerical stiffness-based hybrid discretization, differential algebraic equations (DAEs) clustering and aggregation, multi-order integration methods, and Kron reduction technique [11].

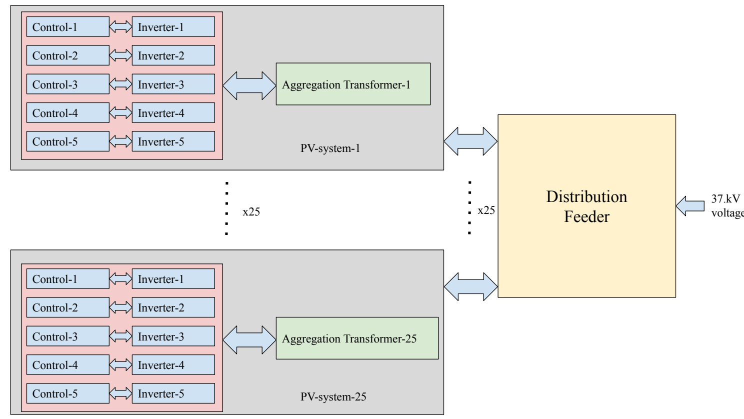


Fig. 2. Overview of the high-fidelity switched system EMT dynamic model of a PV plant with numerical EMT simulation algorithms applied.

Numerical stiffness-based hybrid discretization and first-order integration are applied to the PV inverter module's high-fidelity switched system EMT dynamic model. The model is segregated based on numerical stiffness characteristics of their associated DAEs. Since inductor current of the dc-dc converter, inverter currents, filter voltages, and filter currents exhibit stiffness characteristic, the DAEs of the states are discretized by backward Euler method. The DAEs of capacitor voltages in dc-dc converter are discretized by forward Euler method due to their non-stiffness characteristics. By this way, the simulation time of the PV inverter module's high-fidelity switched EMT dynamic model is largely reduced.

DAEs clustering and aggregation as well as first-order integration are applied to the PV system's high-fidelity switched system EMT dynamic model. The DAEs of all the PV inverters can be clustered by aggregating their similar dynamics. In this way, large matrix operations in EMT simulation of the high-fidelity switched system dynamic model of the PV system can be reduced, resulting in simulation speedup.

Kron reduction technique and second-order integration are applied to the high-fidelity EMT dynamic model of the distribution grid. Unlike the PV systems in the PV plant, the DAEs of the high-fidelity EMT dynamic model of distribution grid can be discretized by second-order integration such as trapezoidal integration, enabling higher simulation time-step. The smaller time-step in the high-fidelity EMT dynamic model of the PV system is necessary due to the switching characteristics of the power electronic switches. After applying the discretization, a large sparse matrix is generated. This large sparse matrix must be operated upon in every simulation time-step, which can be computationally burdensome. Therefore, Kron reduction technique is applied to reduce the size of operated matrix during simulation. In this way, the simulation speed-up can be further increased while maintaining accurate dynamics in the distribution feeders.

The overall interaction of the high-fidelity switched system EMT dynamic model based on application of numerical EMT simulation algorithms is shown in Fig. 2. The inverter and control blocks shown in the figure represent the PV inverter module. The DAE clustering and aggregation algorithm applied to a PV system is showcased through the aggregation transformer in the figure. The distribution grid is shown by the distribution feeder.

IV. HPC-Compatible Simulation of PV Plant

The numerical EMT simulation algorithms applied to the high-fidelity switched system EMT dynamic model of the PV plant has been performed in PSCAD/Fortran environment [10]–[12], [14]. To develop the HPC-compatible numerical EMT simulation algorithms and apply them to the high-fidelity switched system EMT dynamic model of PV plant and/or other components in the power grid, the models developed in PSCAD/Fortran need to be converted to C++. Thereafter, the converted code is modularized using object-oriented programming. Finally, the HPC techniques are coupled with the numerical EMT simulation algorithms in the HPC-compatible simulation codes developed. The latter part is discussed in the next section.

A. Automated PSCAD/Fortran-to-C

While there is a standard F2C conversion utility [?] converts standard Fortran code to C or C++ codes, this can not be directly applied to the PSCAD/Fortran code. The F2C conversion can not be directly applied as the syntax in PSCAD/Fortran is different from the standard Fortran code. For example, the variables that are inputs and outputs of the PSCAD/Fortran code in PSCAD utilize a $ (token) in front of the variable. Similarly, there are differences in line continuation and spacing between PSCAD/Fortran and standard Fortran code. To convert the PSCAD/Fortran code to C code, a pscadf2c utility is developed that works along with the F2C conversion utility. The pscadf2c utility developed converts PSCAD/Fortran codes into C codes. The pscadf2c utility is a simple transpiler: it converts a specific dialect of Fortran used within PSCAD into standard C. Transpilation occurs in two steps: first, PSCAD/Fortran code is converted into standard Fortran 77 code. This is a simple ASCII transformation that includes removing tokens from variables, generating a header from collected tokenized variables, and enforcing Fortran 77 line continuation and spacing conventions. The second step is to run the F2C conversion utility with appropriate options to convert the standard Fortran into equivalent C code.

B. Object-Oriented Programming

An objected-oriented approach is taken to develop the C++ codes of the PV plant to ensure a modular development that is easily modified. The ease of modification helps with implementation of different PV plant configurations.

The object oriented approach is taken to implement various modules of the high-fidelity switched system EMT dynamic model of the PV plant shown in the Fig. 2 and their functionalities. The C++ classes $pv\_hardware$, $pv\_dcdc\_control$, $pv\_dcac\_control$, $pv\_inverter$, $pv\_agg\_transformer$, pv_system, $pv\_distribution\_feeder$, and pv_plant were implemented in the modular approach. A common structure of all these C++ classes is shown below (refer listing 1). All the input variables, output variables, and constants are declared as private members of the respective class. The public members of each of these classes contain constructor that initializes the variables of the class at the initial time-step. The $get()$ and $set()$ methods define functions to get and set values of a particular class variable, respectively, during each time-step. Depending on the interactions and dependencies between these various modules multiple $get()$ and $set()$ functions are defined. Finally, each class has it's own function called $core()$ which defines it's behaviour (or the evaluation of the corresponding high-fidelity switched system EMT dynamic model). The definition of this $core()$ function obtained using the PSCAD/Fortran-to-C conversion capability described in the earlier subsection.

Listing 1. Structure of C++ classes defined in this work.

```
class pv_x{
   private:
      //input variables
      //output variables
      //constants
   public:
      pv_x(); //constructor
      get(); // to access class variables
      set(); // to set value of a particular
          variable/s

      void core(); // defining the behavior
          of the module
};
```

The $pv\_inverter$ class encompass the objects of $pv\_hardware$ (dc-dc converter and inverter hardware switched system model), $pv\_dcdc\_control$ (dc-dc converter control), and $pv\_dcac\_control$ (inverter control). As shown in the Fig. 2, one aggregation transformer (that represents the clustered and aggregated PV system) is connected with five such PV inverters to form a PV system. In the class definitions, the class pv_system contains an array of five objects of $pv\_inverter$ class and an object of $pv\_agg\_transformer$ class. Finally, the pv_plant class contains an object of the distribution grid class, i.e. $pv\_distribution\_feeder$, and an array of 25 objects of pv_system class.

C. HPC Techniques and Optimization

OpenMP-based parallelism is exploited to simulate multiple instances of the HPC-compatible PV plant model in C++. This helps with task level parallelism across multiple central processing units (CPUs).

V. Simulation Results

The parameters of the PV plant considered in this paper are based on the one shown in [11]. The comparison of the simulation results from PSCAD/Fortran and C++ based implementation of the PV plant is performed in this section. Thereafter, the time taken to simulate PV plants using HPC-based implementation and single-core C++ based implementation are compared. The single-core C++ based implementation of the PV plant does not include the HPC techniques and optimization discussed in Section IV-C. The HPC-based implementation does include them. The computing hardware configurations are provided below:
Single-Core Tests: CPU: Intel Xeon W-2125 CPU @ 4.00GHz, RAM: 64 GB DDR4 2666MHz, OS: Windows 10 Enterprise 21H2 for PSCAD (v4.6) model.
HPC Tests: Intel Core i7-9850H CPU @ 2.60GHz, RAM: 16 GB DDR4 2667MHz.

A. Comparison of C++ vs. PSCAD/Fortran: Simulation of PV Plant

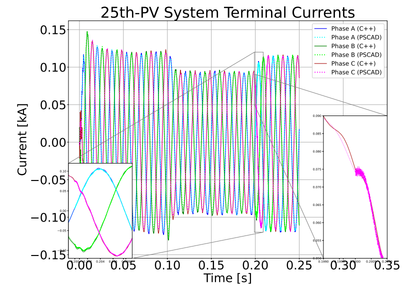
The simulation of single-core C++-based implementation of the high-fidelity switched system EMT dynamic model of the PV plant is compared with the corresponding simulation of the PV plant in PSCAD/Fortran implementation for steady state and dynamic use cases (step change in PV input power at 0.1 s and 0.2 s). The simulation results within a PV system are shown in Fig. 3. The PV system currents, PV inverter ac-side currents, and the PV inverter dc-link voltages are very close in both the simulations, as may be observed in the figure.

The simulation results within the distribution grid of the PV plant are shown in Fig. 4. The PV plant currents, one of the feeder currents, and the feeder voltages are very close in both the simulations, as may be observed in the figure.

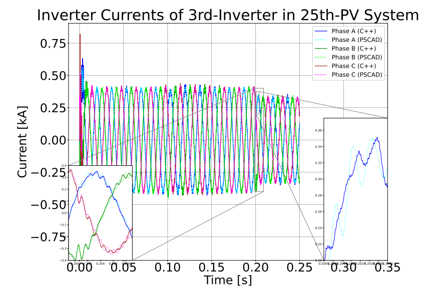
The time taken to simulate the PV plant in PSCAD using library components [11], PSCAD/Fortran, and C++ is shown in Table I. The times taken show that there is a speed-up in C++ based implementation of 11.67x with respect to PSCAD/Fortran. Both instantaneous and time-averaged normalized errors were less than 2% when comparing the C++-based implementation to PSCAD/Fortran. The implementation in C++ is HPC-compatible with easy integration of OpenMP. It is recommended to utilize C++ based hardware models of large power electronics resources (and not just the control).

B. Comparison of HPC-based vs. C++: Simulation of PV Plants

A total of 12 PV plants are simulated in the HPC-based implementation and compared with the same implementation



(a)



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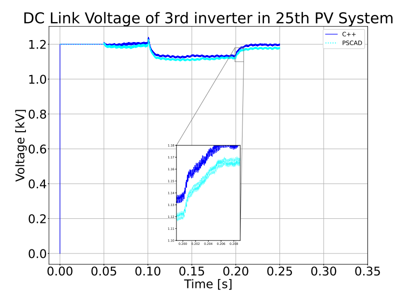


(c)

Fig. 3. Comparison of PSCAD/Fortran and C++ simulation results in PV systems: (a) PV system currents, (b) PV inverter ac-side currents, and (c) PV inverter dc-link voltage.

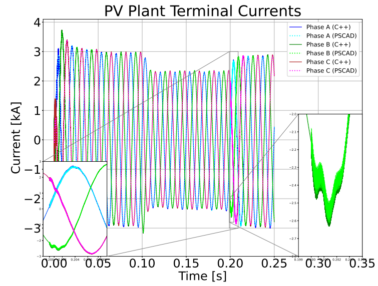
in the single-core C++-based implementation. The comparison of the time taken to simulate is shown in Fig. 5. From the figure, it is observable that with 12 cores, up to 5x speed-up is observable as compared to 3x speed-up with 6 cores and 1.5x speed-up with 3 cores. An approximately linear relationship in speed-up with the increase in cores is observable. This observation is key to highlight the need for HPC-based EMT simulations to simulate a very large number of PV plants or hybrid PV-BESS plants in the future power grid. Based on this observation, HPC-compatible PV plant models can exploit task-level parallelism for speed-up.

VI. Conclusion

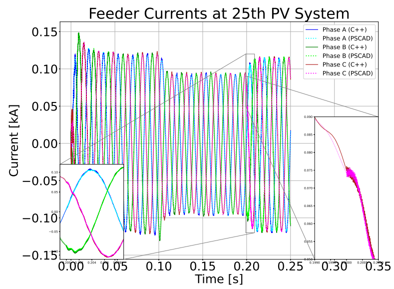
In this paper, coupling of HPC techniques and optimization with numerical EMT simulation algorithms is proposed for simulation of PV plant(s). To convert prior art in PSCAD/-Fortran (that incorporated only numerical EMT simulation algorithms for implementation in a single core) to C++, a PSCAD/Fortran-to-C automation method is proposed. Using

TABLE I
COMPARISON OF TIME TAKEN FOR EMT SIMULATION OF PV PLANT

	PSCAD Library (baseline)	PSCAD/Fortran	C++
0.25s simulation	58 hours	875 seconds	75 seconds
Speed-up	1.0x	238.6x	2784.0x



(a)



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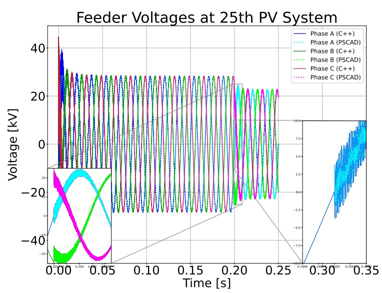

(c)

Fig. 4. Comparison of PSCAD/Fortran and C++ simulation results in PV plant: (a) PV plant currents, (b) feeder currents, and (c) feeder voltage.

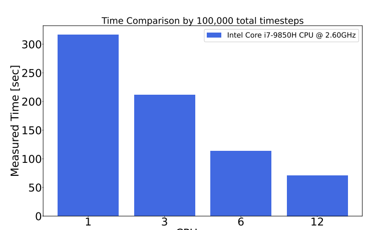

Fig. 5. Comparison of HPC-based and C++-based implementation in terms of time taken to simulate.

the same, C model of PV plant is generated automatically that can be implemented in a single core implementation, which is upgraded using object-oriented programming to develop to the C++ model. Thereafter, HPC techniques and optimizations are applied to generate HPC-based implementation of PV plants. Comparing the simulation results from C++ model of PV plant with PSCAD/Fortran has revealed an accuracy of greater than 98% and a speed-up of up to 11.67x. Additionally, comparison of HPC-based implementation of PV plants as compared to the C++ model showcased a speed-up of up to 5x, resulting in a total speed-up of up to 58x with respect to PSCAD/Fortran. Based on these observations, renewable plant owners and operators are recommended to develop C++ based implementation of hardware as well in the plant (and not just the control system).

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