Real-Time Simulation Models for Photovoltaic Cells and Arrays in Opal-RT and Typhoon-HIL

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Abstract—**The increase of solar power generation in the last decade makes reliance on this energy source of great importance, and highlights the need of studying photo-voltaic (PV) cells and modelling their behaviours. Consequently, efficient and accurate mathematical modeling and simulation of PV cells have become very important for different studies, e.g. their use in microgrids and as distributed energy resources in the grid. This paper reports a custom, homogeneous, cross-platform, real-time simulation model for PV cells, modules & arrays; and characterizes their performances when compared to other existing models. Once the model was successfully verified, its performance was analyzed in two different real-time hardware architectures: (i) OPAL RT OP5030 Simulator with OP4520 Expansion unit and (ii) Typhoon HIL 603 Simulator.**

Index Terms—**Real-time Simulation, PV Cell, PV Cell Modelling, Opal-RT, Typhoon HIL, Power System Simulation.**

I. Introduction

A. Motivation

Solar power generation is gaining relevance every year as one of the fastest growing sources of renewable energy. Solar (photo-voltaic) power generation is environment friendly, cost-efficient and ideal for distributed generation technologies. Photo-voltaic (PV) power generation is dependent on PV cells, which convert the radiant energy received from sunlight into electrical energy. However, an individual PV cell is too small for practical applications, which leads to the concept of PV modules and PV arrays. Multiple PV cells are connected in series or parallel connections to create a PV module, which meets required output voltage and current specifications. Multiple PV modules are then combined in parallel or series to make a PV array. The behavior of PV arrays or PV modules are highly non-linear in nature, and require analysis in order to derive a viable mathematical model which can be used for simulations. These mathematical models are also useful to design, manufacture and test power-converters which will be used to convert the DC power obtained from PV arrays into AC power. From the utility stand point, modelling of PV arrays are of paramount importance because they are used to study and assess power system planning and operating impacts in any system containing PV generation.

The time-critical nature of electrical power systems, calls for simulation models which are not only accurate but also efficient for real-time simulation. Real-time simulations and Hardware-in-the-Loop simulations are critically important when testing control and protection systems related to PV systems. However, a major challenge arises when dealing with different real-time simulators that have different hardware architectures and different modeling libraries. Hence, any proposed model for PV arrays, needs to be tested on different real-time simulators to ensure its cross-platform compatibility and result homogeneity.

B. Related Works

Authors of [1] introduced and discussed the single-diode equivalent circuit model to represent a PV cell. That model has been modified and enhanced in [2]-[5]. Authors in [2],[3],[5] reported an accurate methodology to determine the parameters of the single-diode equivalent circuit of a PV cell. In [4], the single-diode model was extended to be used to represent PV panels made with amorphous silicon technology. While other, more complicated models, have been proposed by different authors, the simple representation of the single-diode model is still appealing and sufficiently accurate as reported in [6].

The simplicity of the single-diode representation makes it suitable for real-time simulation. Authors in [7] incorporated the single-diode PV model coupled with a fully functional inverter and controller into a real-time power-system model, along with detailed results for EMT-like real-time simulations using the Opal-RT hardware. In addition MathWorks has a very detailed PV model [8] that uses an improved version of single-diode representation of PV cells. This model is suitable for off-line simulations and was used as a benchmark for the work in this paper. Note that, this benchmark model cannot be modified, it is a "black-box" with limited documentation and limited access. The proposed model in this paper aims to address this limitation, so to facilitate real-time simulation.

Because, reproducibility of results is a critical issue in power systems research, it was important to extend this study to other real-time simulation hardwares apart from Opal-RT. In this work, the Typhoon HIL platform provided an excellent opportunity for this study. It was reported in [9], that even though the hardware architectures of these two real-time simulators are significantly different, their simulation results can be made similar if adequate care is taken during model implementation. Hence, to test that hypothesis further,

the proposed PV model in this paper was implemented in both Opal RT (OP 5030/4520) and Typhoon HIL (HIL 603) real-time simulators separately and their performances were analyzed.

C. Contributions

- A simple model is proposed to represent a PV system in real-time simulation environments. The accuracy and performance of this model (in Opal-RT real-time simulator) is compared with the PV model from the MathWorks.
- The proposed model was re-implemented and migrated to Typhoon HIL 603 hardware-infrastructure. The real-time simulation results in this new platform are compared with those obtained using the Opal-RT real-time simulators.
- Comparisons between the proposed model and the existing model from the MathWorks [10] in terms of hardware usage and efficiency are presented.
- The models are made available as open source software in the GitHub repository : `github.com/alsetlab/pvmodel2020`

II. THEORY

A. Review of the Real-time Hardware Platforms

The *Opal-RT 5030 Real Time Simulator (with OP4520 Expansion Unit)* was used to simulate the proposed PV system in real-time. The hardware consists of 32 cores Intel Xeon quad-core series processors and a 7 series Kintex FPGA which provides I/O capabilities. The high speed optical fibre cables are able to support upto a speed of 5 MBit/sec. The standard Simulink (along with some additional libraries provided by Opal-RT) environment were used to design the proposed PV system model.

The *Typhoon HIL 603 Real Time Simulator* has Xilinx's Virtex 6 series FPGAs and ARM R-class Processors. The communication links used are standard Ethernet, and this hardware is capable of reliable simulations upto a minimum time-step of 1us. Typhoon has its own HIL Schematic mdoel design environment which was used to design the PV system shown in Fig. 3.
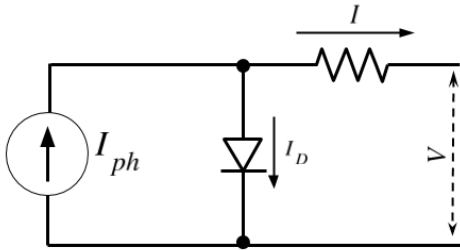

Fig. 1. Single Diode model to represent a PV cell

B. Description of the Proposed Model

The PV array model is constructed by series-parallel connection of multiple PV modules and each of these PV modules contains the same number of PV cells. A single PV cell is represented by the single-diode model shown in the Fig. 1.

In this model, I_{ph} is the photoelectric current, I_D is the diode current and I_0 is the dark current. Additionally, the series resistance R_s is used to model the losses due to poor conductivity in the solar cell, and V_t represents the thermal voltage. Using the method described in [7], if a short circuit is applied, then the resultant photoelectric current I_{ph}, is defined as the short circuit current I_{sc}.

If an input voltage V is applied to the PV cell, the output current I is given by

$$I = I_{ph} - I_D = I_{ph} - I_0 \times e^{\frac{V+IR_s}{V_t}} \tag{1}$$

Hence, the parameters of interest are I_{sc}, I_0, V, V_t and R_s. While these variables are known, it is possible to compute the output current of a single PV cell, and together with with the knowledge of the series parallel configuration of the PV array, they can be used to compute the output current of the system, as shown in (1).

Once, the output current of the PV cell is computed, and based on the series-parallel configuration the PV system, the output current of the entire PV array can be calculated. The detailed calculation methods for each of these quantities are described below and illustrated in Fig. 3.

1) Thermal Voltage (V_t) computation: To compute the magnitude of thermal voltage V_t of the PV array, the first step is to calculate the magnitude of the thermal voltage of a single PV cell. The mathematical expression to derive the thermal voltage of a single PV cell is given by:

$$V_{t_{cell}} = \frac{AkT}{q} \tag{2}$$

where, A is the diode quality factor, k is the Boltzmanns constant, q is the charge of an electron and T is the temperature in Kelvin. For simplicity, the diode quality factor is often assumed to be 1. Additionally, it is assumed that there are N_{cell} of PV cells in each PV module. The output thermal voltage V_t of PV array is given by:

$$V_t = V_{t_{module}} \times N_s = V_{t_{cell}} \times N_{cell} \times N_s \tag{3}$$

where N_s is number of series-connected PV module in each string.

2) Series Resistance (R_s) computation: The series resistance for individual PV modules can be mathematically formulated as:

$$R_{s_{module}} = \frac{V_{t_{module}} \ln(1 - \frac{I_{mpp}}{I_{sc_{STC}}}) + V_{OC_{STC}} - V_{mpp}}{I_{mpp}} \tag{4}$$

where $I_{sc_{STC}}$ and $V_{oc_{STC}}$ are the short circuit current and open circuit voltage under standard time condition (STC), I_{mpp} and V_{mpp} are the current and voltage at maximum power point, respectively. The series resistance of the PV array is further computed from here, according to the following relationship where N_p is the number of parallel connected PV module strings:

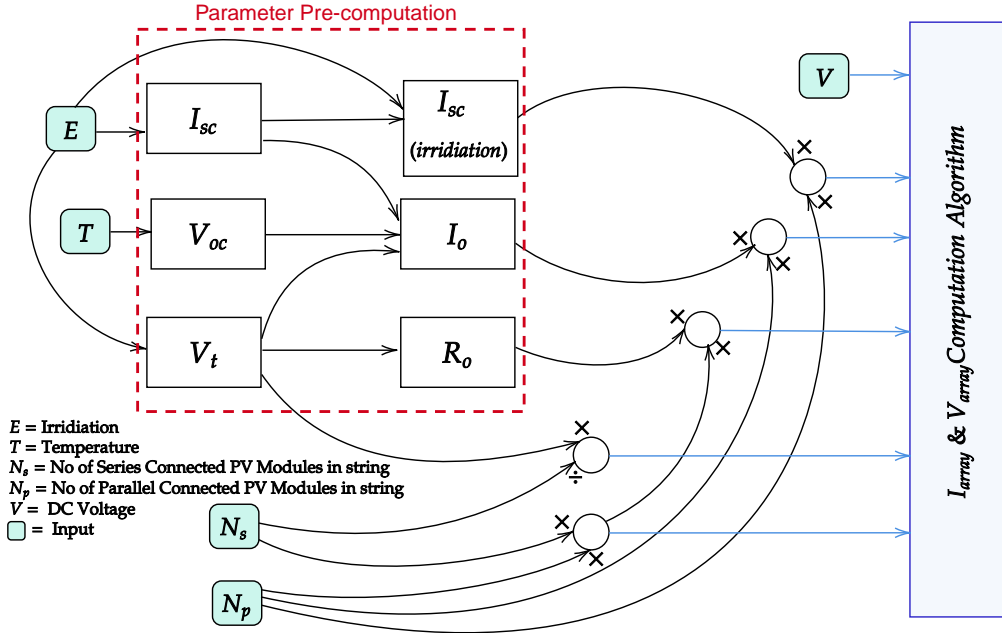$$R_s = R_{s_{module}} \times \frac{N_s}{N_p} \tag{5}$$

Fig. 2. Block-diagram containing different units of the model for the PV cell

3) Open-circuit Voltage (V_{oc}) computation: This subsystem computes the effect of temperature on the open circuit voltage of the PV module. The procedure is described in [8]. It estimates the open circuit voltage V_{oc} at temperature T when the open circuit voltage at STC ($V_{OC_{STC}}$) is known. The mathematical relationship that estimates the opne circuit voltage is given by

$$V_{oc_T} = V_{oc_{STC}} + V_{oc_{STC}} \times \beta_{V_{oc}}(T - 25) \quad (6)$$

where T is the input operating temperature for the PV array.

4) Short-circuit Current (I_{sc}) computation: This subsystem computes the effect of temperature on the short circuit current of the PV module. The procedure is described in [8]. It estimates the open circuit voltage I_{sc} at temperature T when the open circuit voltage at STC ($I_{SC_{STC}}$) is known. The mathematical relationship that estimates the open circuit voltage is given by

$$I_{sc_T} = I_{sc_{STC}} + I_{oc_{STC}} \times \alpha_{I_{sc}}(T - 25) \quad (7)$$

I_{sc_T} is further modified to take into account the effect of irriadiation to compute the actual short circuit current of the PV module $I_{sc_{module}}$, as follows:

$$I_{sc_{module}} = I_{sc_T} \times \frac{E}{1000} \quad (8)$$

Finally, the short circuit current of the PV array is finally estimated as

$$I_{sc} = I_{sc_{module}} \times N_p \quad (9)$$

5) Dark Current (I_o) computation: The Dark Current computation as reported in [7] and is represented by the following mathematical relationship:

$$I_o = N_p \times \frac{I_{sc_{module}}}{e^{\frac{Voc_{STC}}{Vt_{module}}}} \quad (10)$$

With all the computations above completed, I_{sc}, I_o, V_t and R_s are fed to a Newton-Raphson algorithm to solve eqn (1) , which gives the values of V_{array} and I_{array}. In the Opal-RT platform it was implemented using a MATLAB script, where as in Typhoon-HIL platform the implementation was based on Typhoon's advanced C functionality support.

III. RESULTS

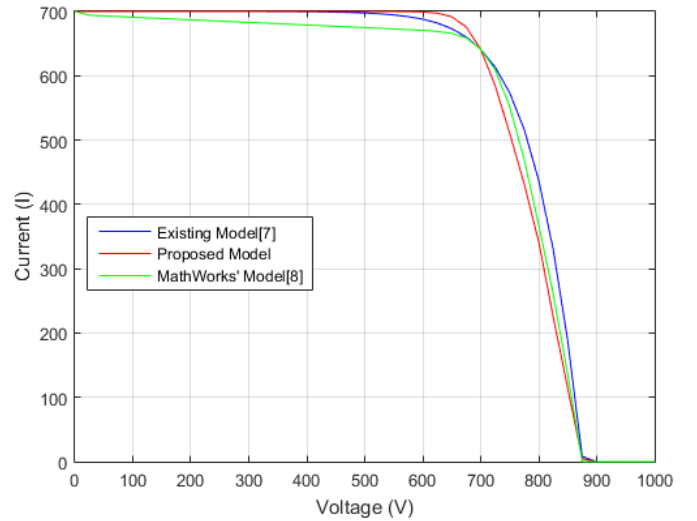### A. *Verification of the Proposed Model in Opal RT*

Fig. 3. V-I Characteristics of all the PV models

The model reported in [8] was taken as the benchmark model, and the proposed model in this paper makes the enhancements discussed next. The following enhancements to

the model proposed in [7] are proposed in this work to make its behavior similar to that that of [8]:

- The computation of the thermal voltage V_t is improved by introducing the N_{cell} variable as described in Section II.A. A change in thermal voltage results in a change in the dark current I_o computation as well.
- The computation of open circuit voltage V_{oc} is improved by introducing the $\beta_{V_{oc}}$ parameter.
- The computation of short circuit current I_{sc} is improved by introducing the $\alpha_{I_{sc}}$ parameter.

Figure 3 shows the V-I characteristics of the model in [7], the benchmark model in [8] and the modified model proposed in this paper on the same plot. It can be seen that in terms of accuracy, the proposed model is closer to the benchmark than the model in [7] for the range of [700-900]V. It is important to note that, the proposed model is simple and contains only simple mathematical functions along with a Newton-Raphson solver, making it more hardware resource efficient than the benchmark model itself, which uses closed source library functions and blocks. This claim is justified by further observations, presented in Table I. It can be seen that, in terms of hardware resource consumption, the proposed PV model is more economical than the benchmark model.

However, the proposed model is also, a little slower than the benchmark model from MathWorks (it takes about 15.5% more computation time), due to the use of the iterative solver. However, the increase in computation time is insignificant when considering time-steps of 5us or higher. For the simulator to produce accurate results it is important that the entire **computation executes within a single time-step**. When the time-step under consideration is 5us or higher, and the computation time is of the order of 1us, at 15.5% increase in computation time **will not affect** the quality or reliability of the simulation results. If, hypothetically the simulation step is reduced to the order of 1us, the computation (in each time-step) will not be finished within each time step, and a run-time over-run error is expected.

B. Implementation in the Typhoon HIL Platform

The proposed model was re-implemented (see Fig. 3) for the Typhoon HIL-603 real-time simulation hardware to provide re-producibility of the results across different hardware platforms. The *Newton-Raphson* V_{array} and I_{array} calculation-block was replaced with the *Advanced-C-function* functionality (Algorithm 1) available in *Typhoon HIL schematic* environment. It can be seen in Table II, that the memory consumption during simulating the PV model is well within reasonable limit for microgrid applications.

Studies were performed to compare the model's response in the two different real-time hardware architectures. Figure 4

[1] The Benchmark Model (Model A) is proprietary model within Opal/Simulink library which was available as a **blackbox**, and the internal circuitry/model was not visible from the user-end. This proprietary model is extensively tested by National Renewable Energy Laboratory (NREL) for accuracy and reliability as reported in [10]. Thus, in this work, while proposing the new custom model for PV systems, it was compared against a benchmark model which is already validated extensively.

Algorithm 1 Calculation of I_{array} and V_{array}

Require: I_{sc}, V_t, N_s, R_s, I_o, V_{DC}
Require: Define:
$\quad f(I_n) = I_n - I_{sc} + I_o \times ((exp(V_{DC}/N_s + I_n \times R_s)/V_t) - 1)$
Ensure: $I_{start} = 0$, $e = 10^{-3}$, $L = 0$
$\quad$ **while** $L \neq 1$ **do**
$\quad\quad$ **if** $n = 0$ **then**
$\quad\quad\quad I_n = I_{start}$
$\quad\quad$ **else**
$\quad\quad\quad n++$
$\quad\quad\quad I_n = I_{n-1} - f(I_{n-1})/f'(I_{n-1})$
$\quad\quad\quad e_n = I_n - I_{n-1}$
$\quad\quad\quad$ **if** $\mid e_n \mid \leq e$ **then**
$\quad\quad\quad\quad I_{array} \leftarrow I_n$
$\quad\quad\quad\quad L = 1$
$\quad\quad\quad$ **end if**
$\quad\quad$ **end if**
$\quad\quad V_{array} \leftarrow V_{DC}/N_s$
$\quad$ **end while**

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shows that the results in these two platforms are identical. This observation confirms that the proposed model can be successfully implemented in different real time hardware platforms and the results are reproducible if meticulous attention is paid to their implementations. A simulation time-step of 20us was used for both the simulation platforms.

C. Hardware Selection

The computational performances were also identical between HIL 603 and HIL 604 as they have very similar hardware architecture and specifications. Since, the proposed model does not have any library dependence and utilizes simple mathematical functions only- it is fair to say that the model can run successfully in any Typhoon HIL hardware above and including HIL 603, and the computational performance will be better for simulators with better specifications. For comparatively lower-end models, it is still expected to perform successfully, but a hardware-in-the-loop testing is necessary. For Typhoon hardwares the model was simulated with 20us and 10us (minimum), successfully. In Opal-RT real-time simulator OP5030/4520, the proposed model was run successfully with a minimum step-size of 20 us. Because, the model has no library-dependency, it can be concluded that the

TABLE I
PERFORMANCE CHARACTERIZATION OF THE PROPOSED PV MODEL IN OPAL-RT PLATFORM

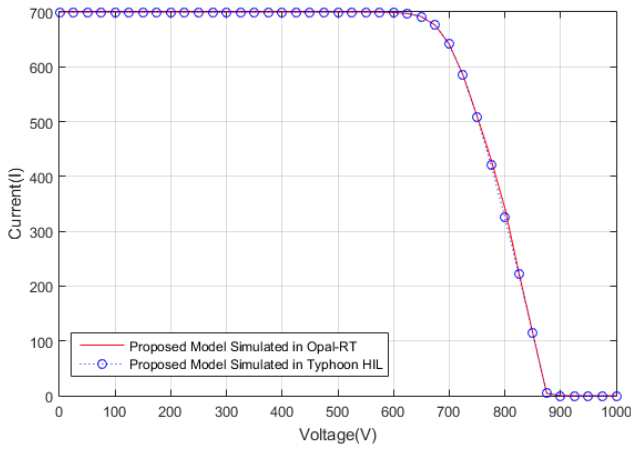|	MathWorks' Benchmark PV Model(A)	Proposed PV Model (B)	Change	Benchmark Model on Typhoon
SSN: State Space Operation Count	110	80	-27.27% -	Model A is not[1] reproducible in other platforms
SSN: Memory Usage	0.003528	0.002568	-21.21%	
Network Info	7	6	-14.28%	
Computation Time	1.098 us	1.268 us	+15.48%	

Fig. 4. Comparison of the PV model response between Typhoon HIL and Opal-RT

TABLE II
MEMORY UTILIZATION FOR SIMULATING THE PV MODEL IN TYPHOON HIL 603 IN REAL-TIME

Memory Type	Used Memory	Available Memory (kb)	Utilization
Internal Memory	60	256	23.57%
Code Segment Size	41	256	16.33%
Data Segment Size	18	256	7.24%

model will (at the very least) run successfully at 20 us time-step in any Opal-RT hardware starting from OP5030, OP5031 and beyond. For lower models, it is still expected to run, but a proper hardware-in-the-loop verification is preferable before concluding.

IV. CONCLUSIONS

This paper reported a simplified PV model, improved upon previously reported single-diode models. With the simplification of the PV model, the hardware resource requirements for simulating it in real time (Opal-RT platform) were reduced. It was also investigated whether the accuracy of performance deteriorates by the proposed simplification of the model. The accuracy of the reported model is determined in comparison with the benchmark PV model from MathWorks. Once, the results were found to be satisfactory, the same model was implemented and simulated in Typhoon HIL platform. The results in Typhoon HIL were compared with those obtained in Opal RT. It was concluded that, the real-time simulation results for the proposed model was reproducible across the two different hardware architectures, thanks to the care taken to make nearly identical implementations.

V. DISCUSSIONS AND FUTURE WORKS

Ensuring the consistency of model response is crucial in order to reduce the uncertainty while simulating a model across simulators of different hardware architectures. Modern model exchange interportability standards such as Modelica and the FMI (Functional Mock-up Interfaces) are already being used in some other domains of engineering and sciences.

However, very few research in that regard is done in the domain of power system.

Authors in [9] reported that the existing library models for similar components across these two different simulators can give different results. Hence, to obtain compatible simulation models for PV cells and arrays, it was necessary to build them from the scratch. Only simple operators, mathematical functions, and numerical programs (Newton-Raphson) were used. This practice is encouraged and recommended for further implementations of more complex systems across different hardware architectures, until modern model exchange standards are adopted in the power systems domain. The current work successfully proposes a simplified model for PV cells and arrays. It is also established that, if proper care is taken, those models can be ported across two different simulator hardwares.

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