Cross-Platform Real-Time Simulation Models for Li-ion Batteries in Opal-RT and Typhoon-HIL

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***Abstract*—Today's power generation fleet is becoming more diversified, including both traditional energy sources and a variety of renewable energy sources. To help operate such a wide variety of energy sources reliably and in harmony, Energy Storage Systems (ESS) provide an alternative that offers a high degree of flexibility. To understand their behaviour and exploit their flexibility, modeling and simulation of ESSs is crucial in using the ESSs to solve the challenges introduced by the increased usage of photo-voltaic, wind, and other renewable energy sources. Most industrial energy storage systems use batteries as the primary energy storage device. This paper reports a simplified model for the Li-ion batteries, which can calculate the state-of-charge (SOC) and output terminal voltage, while still meeting real-time modeling constraints of different hardware platforms. To test the model's validity, its outputs for both charging and discharging modes were compared with those of an existing battery model. The accuracy and performance of the proposed model was analyzed in two different real-time hardware architectures- (i) OPAL-RT OP4520/5030 and (ii) Typhoon HIL 603.**

***Index Terms*—– Real-time Simulation, Battery Modeling, Opal-RT, Typhoon HIL, Power System Simulation,**

I. INTRODUCTION

A. Motivation

The proliferation of solar, wind, fuel-cell and other non-conventional energy sources has given rise to new challenges in power systems operation. Energy storage systems are emerging as a potential solution to such challenges. To understand their potential and limitations, it is crucial to model and simulate such energy storage systems with accuracy. In order to perform experiments to control the charging and discharging of energy storage systems a detailed and accurate mathematical model of energy storage systems (ESS) is necessary. It has been reported in [4] that the cost of ESS have decreased drastically, making their application economically viable, both in grid-tied and remote-systems. It is also observed that, Li-ion batteries are the most widely used energy storage devices across all such industrially available ESS. This highlights the need for fast and accurate modeling of Li-ion batteries, both for their charging and discharging modes. Therefore, this paper reports a simplified and efficient model for Li-ion batteries, suitable for real-time simulation.

To test the accuracy of the proposed model, the work in this paper was compared with the battery model available in the *Simulink Simpowersystems* library, both in charging and discharging modes. Because, power system operations are time-critical in nature, it is important to test the real-time compatibility of the proposed models, so that they can be used in the development, implementation and testing of different control schemes. In order to test the real-time performance of the proposed model, it was implemented on Opal-RT 4520/5030 real-time simulator, and its performance was compared with an existing model. In addition, to address the differences arising from the modeling environments of different real-time simulators, the proposed battery model has been tested on two real-time simulators in order to ensure its cross-platform compatibility. One of the critical features of the proposed model is that, it is absolutely reproducible across different hardware platforms.

B. Related Works

Authors in [1] developed models and calculation methods for extracting the parameters of an electrical battery. Then, authors of [2] implemented those equations and built a complex lithium-ion model containing five subsystems in Matlab/Simulink. [5] presents LiFePO4 dynamic battery modeling for a battery simulation. MathWorks also provides an accurate and detailed generic battery model [3], which can model four types of rechargeable batteries. This model is suitable for off-line simulations and was used as a benchmark the model in this paper. However, the existing battery models mentioned pose some difficulties when attempting to achieve real-time simulation. The authors of [6] described a real-time battery management model of a resistance-capacitance battery, however, this model is not generally compatible with the Li-ion batteries generally used in power systems. Furthermore, none of the above models have been verified for cross-platform real-time simulation. Thus, this paper reports a simplified cross-platform lithium-ion battery model that is suitable for real-time simulation. In [7], it was reported that the real-time simulation results can be made similar across two entirely different real time simulators (Opal RT-4520/5030 and Typhoon HIL) if meticulous care is taken in model implementation. However, minor but visible mismatches were still observed between the transient responses when the same model was simulated across two different real-time simulator hardware architectures. To make the model's response consistent in different environments, the proposed Li-ion battery model was implemented and simulated across the two different hardware architectures: **Opal RT 4520/5030 and Typhoon HIL 603**.

C. Contributions

- A model to emulate the behaviour of a Li-ion battery system is proposed. The model was implemented in Simulink and the simulation results are compared with the benchmark battery model archived by the *Mathworks*. The proposed model can also compute the state-of-charge of the battery in real time
- Once the model was verified, it was prepared for real-time simulation on an Opal-RT target. Its performance was compared with the benchmark model, when run in real time. For this part, RT-LAB software was used.
- The proposed model was carefully migrated to Typhoon HIL family of real time simulators to ensure reproducibility and cross-platform compatibility. A sample test-case was implemented in Typhoon, where the battery operates as part of a microgrid. This implementation ensures the usability of the proposed battery model for simulating real-life applications.
- The models are made available as open source software in the GitHub repository : `github.com/alsetlab`

II. Theory

A. Review of the Real-time Hardware Platforms

The two Real Time simulator hardwares used for this analysis were (i) Opal-RT OP4520/5030 and (ii) Typhoon HIL 603.

The OP4520/5030 uses the OPAL-RT RT-LAB software and the Artemis real-time solver, along with the standard *Simulink* library. The Typhoon HIL platform uses a separate software package, *Typhoon HIL Control Center*, which has its own component libraries and can compile standard C programs to generate block level functionalities. A short summary of the two hardware platforms is given in Table I.

TABLE I
Real Time Hardwares: A Comparison of Features

RT Hardware	Opal RT 4520/5030	Typhoon HIL 603
Processor	Intel Xeon Quadcore 32 cores	ARM R 8x2 cores
FPGA	Xilinx Kintex 7	Xilinx Virtex 6
PCIe Connection	1-7 PCIe	8-Lane; 2 PCIe 4x

B. Description of the Proposed Model

As mentioned earlier, [2] reports an accurate and comprehensive model, which constructs a very detailed circuit to represent the behaviour of a battery. The model includes a capacitor $C_{capacity}$ and a discharge resistor $R_{self-discharge}$ in parallel with a current controlled current source. This part of the circuit effectively models the behaviour of the State-of-charge (battery lifetime), and the resultant voltage-parameter V_{SOC} is used to construct the remainder of the model. The remainder of the model contains an RC network that follows the same modeling rationale as the models reported before in [2], [5]. This RC network is parameterized based on the transient V-I response of the battery-system. The overall model is shown in Fig. 1. A voltage controlled voltage source which relates an equivalent *Thevenin Voltage* to the State-Of-Charge is connected in series with this RC network. However, it was observed that the contribution of this RC network is negligible for Li-ion [1], [2] batteries.

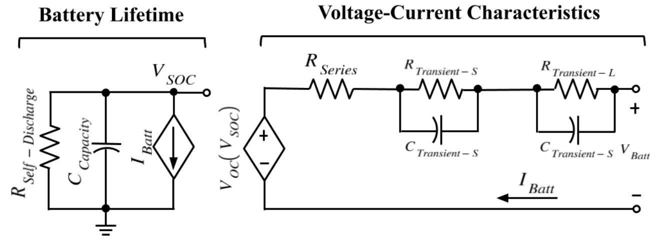


Fig. 1. The Existing Comprehensive Battery-Model

The observation above indicates that any potential transients due to the RC constant will be of ultra-fast nature, which would inherently limit the time-step for real-time simulation. Hence, assuming that their effect is minimal, the model proposed in this work replaces the RC components with a single series resistance R_{series}. This simplified model is shown in Fig. 2.

This model is expected to emulate three important dynamic characteristics of a battery system.

- Capacity: Usable capacity is the total extracted energy from the battery. It decreases with increasing discharge current, storage time and number of cycles under operation. It is also observed to increase when the ambient temperature decreases. The capacitor $C_{capacity}$ together with the resistors $R_{Self-discharge}$ and R_{series}. $C_{capacity}$ does not depend on current variations. However, the effective SOC depends on current variations, because a variation in current leads to a variation in the voltage drop across the R_{Series}. The $R_{Self-discharge}$ resistor, on the other hand, models the discharge of the battery when it is stored idly for a long time.
- Open Circuit Voltage: $V_{OC}(V_{SOC})$ is a function of V_{SOC} as it depends on the state-of-the-charge. Open-circuit voltage V_{OC} is the steady-state terminal voltage at a certain SOC value.
- Transient V-I Response: The circuit parameter that determines the transient response is R_{Series}. This assumes that

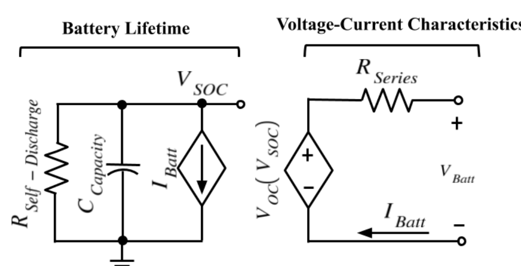
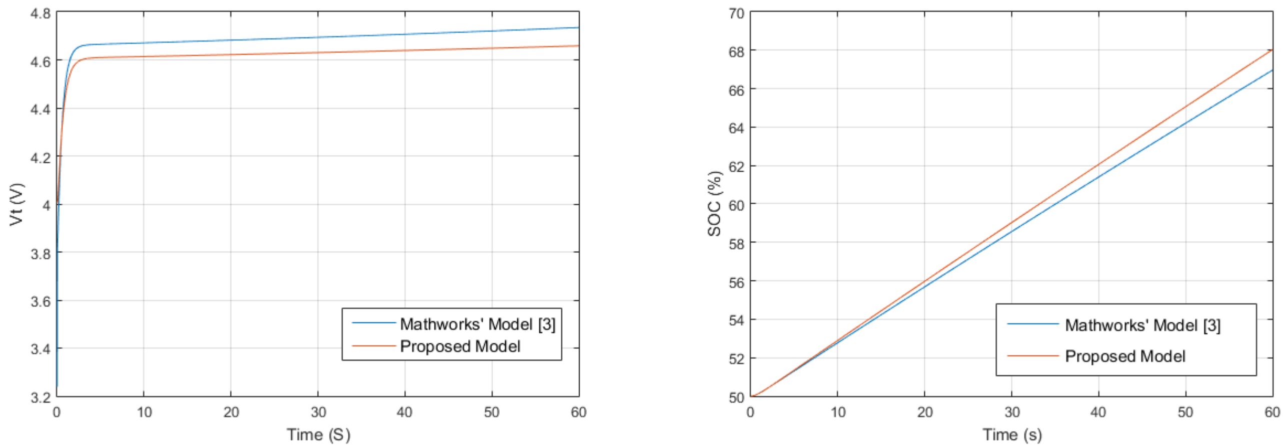
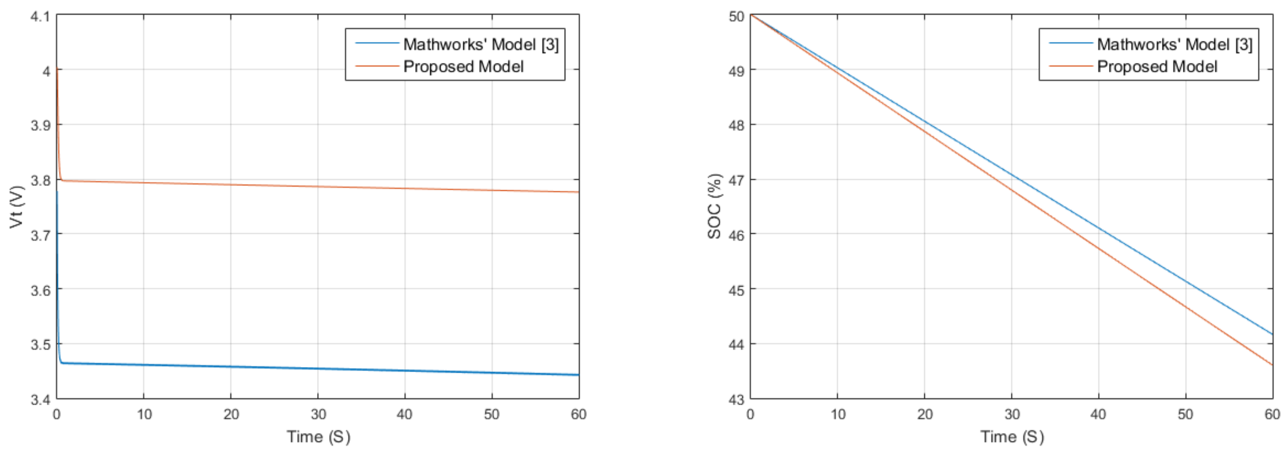


Fig. 2. Proposed Simplified Equivalent Circuit Model for a Battery



Charging Mode: Terminal Voltage and SOC variation for the proposed and benchmark models



Discharging Mode: Terminal Voltage and SOC variation for the proposed and benchmark models

Fig. 3. The Accuracy of the proposed model in charging and discharging modes, when compared to the benchmark model

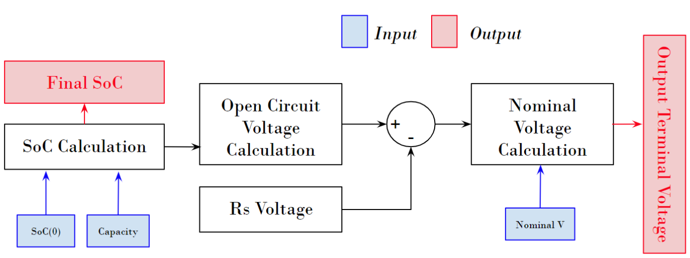


Fig. 4. Flowchart of the proposed model implementation

the impact of very short time constants on the response of the battery-system is negligible as per [2].

The battery model proposed in this paper was implemented in Matlab/Simulink consists of several parts, as shown in Fig. 4, the main ones being the State-Of-Charge (SOC) calculation and the output terminal voltage calculation. The three input parameters of the model are Initial SOC (SOC_0), Rated Capacity, and Nominal Voltage. The two outputs are Final SOC (SOC_n) and Terminal Voltage (V_t). The SOC calculation algorithm is based on the Matlab-Simulink model as reported in [3]. After updating the final state-of-charge from (SOC_0), the new value of SOC_n is used for computing the value of open-circuit voltage (V_{OC}). This computation is based on the following mathematical expression, first reported in [1]:

$$\begin{aligned}\mathrm{V}_{OC}(SOC) = -1.031e^{-35\times SOC} + 3.685 + 0.2156\times SOC \\ - 0.1178\times SOC^2 + 0.3201\times SOC^3\end{aligned}$$

The value of SOC is also used to estimate the value of the resistance R_{Series} using the following expression:

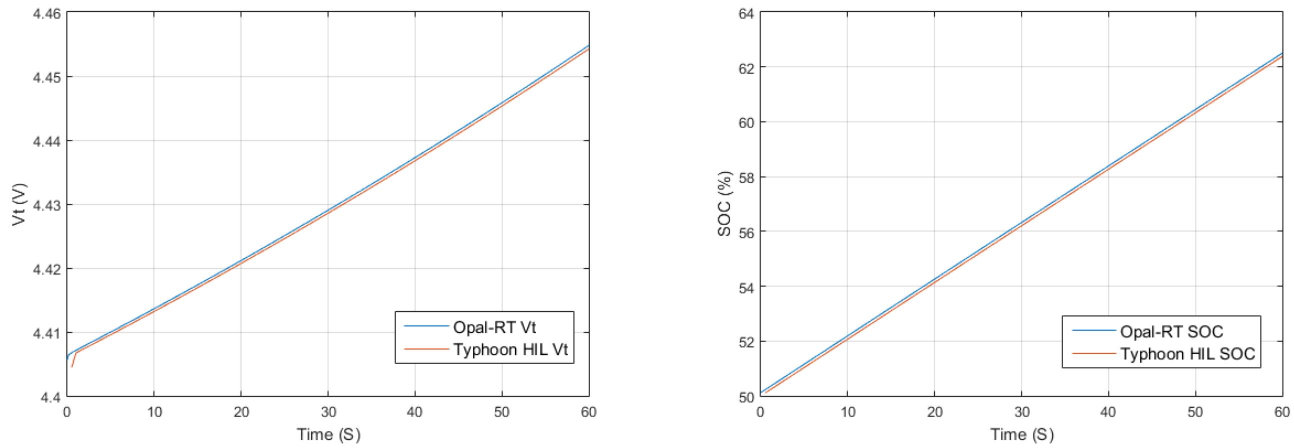
$$R_{Series}(SOC) = 0.1562\times e^{-24.37\times SOC} + 0.07446$$

Finally,the terminal voltage $V_t = V_{OC} - R_{Series}\times I_{Battery}$, as seen from the circuit in Fig. 2.

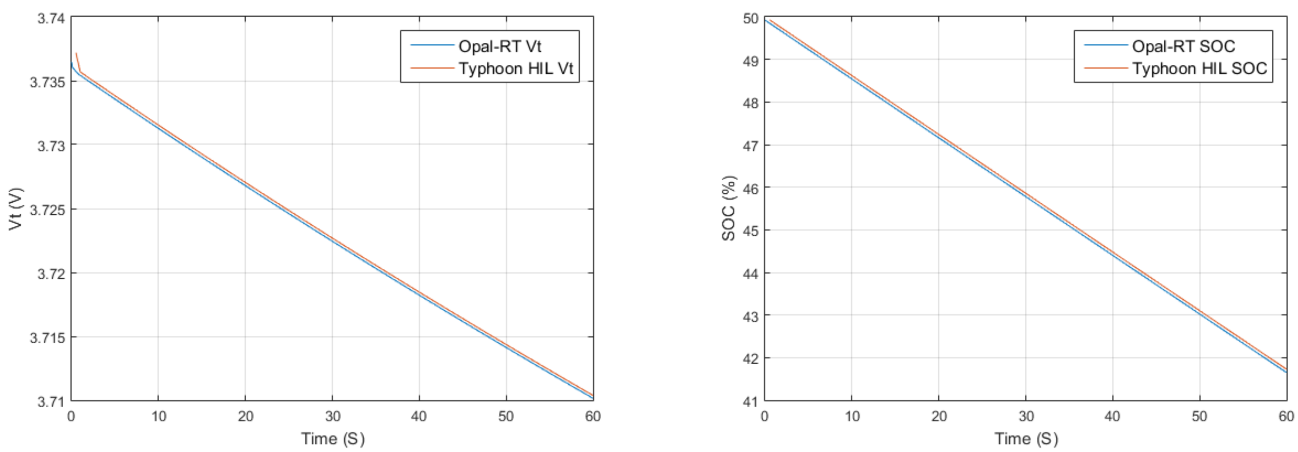
III. Results

A. Model Verification and Characterization

It has already been discussed that, in order to validate the proposed model, it must be shown that:



Charging Mode: Terminal Voltage and SOC variation for the proposed model in Opal RT and Typhoon HIL



Discharging Mode: Terminal Voltage and SOC variation for the proposed model in Opal RT and Typhoon HIL

Fig. 5. Comparison of Real Time Simulation results in different Real Time Simulators

- The proposed battery model performs satisfactorily both under charging and discharging scenarios.
- Both the responses of the terminal voltage V_t and the state of charge SOC are accurate.

Hence, the responses of the proposed model for V_t and SOC under both charging and discharging modes were compared with the respective responses of the MathWorks' benchmark model. These results are illustrated in Fig. 3.

Observe that the terminal voltage suffers the largest discrepancy, which is due to a high value of R_{Series}, this would need to be calibrated to better match the benchmark's results. Meanwhile other responses expose similar behaviour with minor deviations from the benchmark.

Having determined that the proposed model has sufficient accuracy, its efficiency (in terms of hardware consumption and speed) needs to be assessed. For this, its hardware consumption for real time implementation (on Opal RT) is compared to that of the MathWorks' model. This comparison is summarized in Table II. It can be seen that the proposed model consumes a small additional amount of hardware resources and its speed is slower than the MathWorks' model. However, it needs to be noted that the proposed model does not use any closed and/or proprietary library-specific functions and depends only on simple mathematical operations. This makes this model suitable for migration to a different platform, as shown next for case of the Typhoon HIL-603 simulator.

TABLE II
PERFORMANCE CHARACTERIZATION OF THE PROPOSED BATTERY MODEL IN OPAL-RT PLATFORM

	MathWorks' Benchmark Model	Proposed Model	Change
Charging Mode			
SSN: State Space Operation Count	63	71	+12.6%
SSN: Memory Usage	0.00202 Mb	0.00228 Mb	+12.8%
Computation Time	0.7096 us	0.9496 us	+33.8%
Discharging Mode			
SSN: State Space Operation Count	45	51	+13.3%
SSN: Memory Usage	0.001448 Mb	0.00164 Mb	+13.1%
Computation Time	0.6609 us	0.9565 us	+44.7%

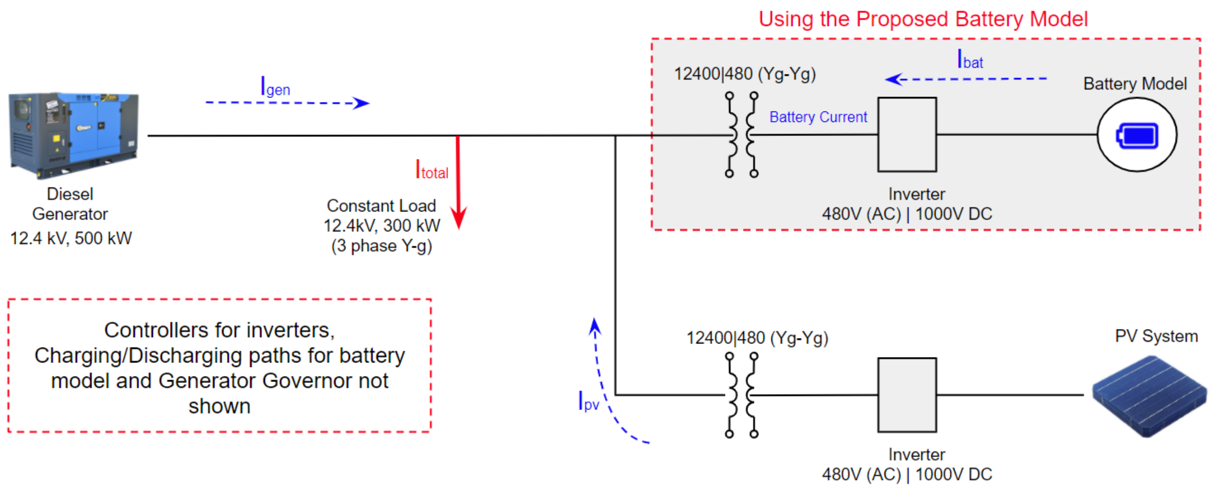


Fig. 6. Microgrid Implementation to validate the battery model

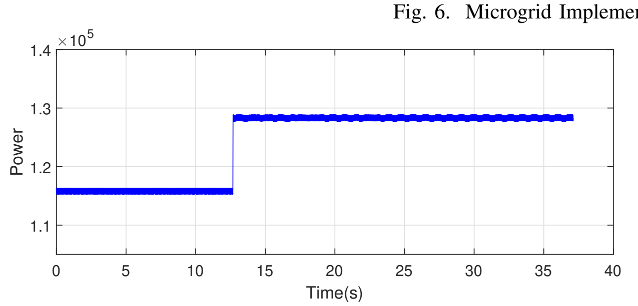


Fig. 7. Step Increase in the Reference Active Power for the Battery Unit

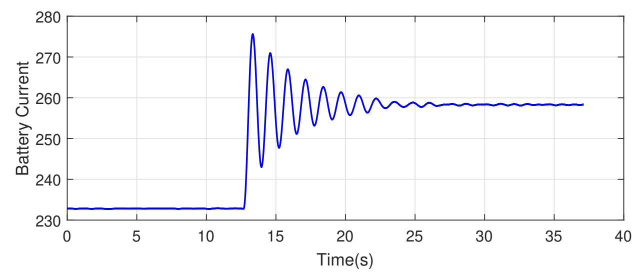


Fig. 8. Output Current from the Battery Unit

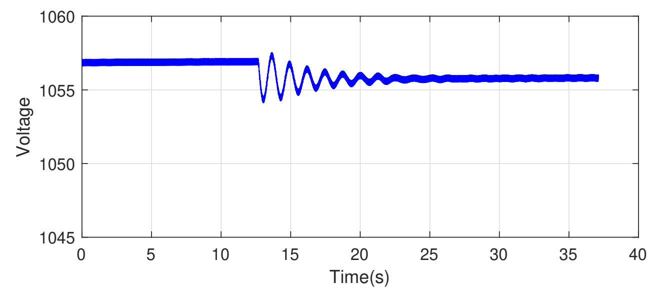


Fig. 9. Terminal Voltage of the Battery

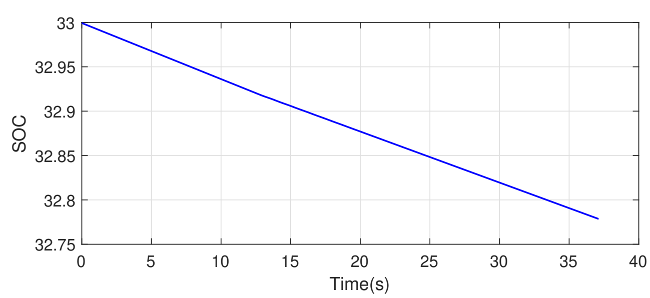


Fig. 10. Response of the Battery-SoC

B. Simulation in Typhoon HIL Platform

In order to test the cross-platform compatibility of the proposed model, it was re-implemented in the Typhoon HIL real time simulator hardware. Details of this implementation including a detailed flow chart is provided in the `github.com/alsetlab` repository.

In this case, a Typhoon HIL 603 real-time simulator was used. Because only fundamental mathematical functions and numerical operations were used to construct the model, it was completely independent of specialized MATLAB/Simulink library functions. Thus, it was expected that the Typhoon HIL real-time simulation results would be identical to those observed in the Opal-RT platform. The responses that are summarized in Fig. 5 affirm this hypothesis. It can also be concluded that for both in the charging and discharging modes, the proposed model is consistent in both platforms, i.e. compatible between Opal-RT and Typhoon. During compilation and execution on the Typhoon platform, the memory consumption by this model that are summarized in Table III.

C. Test Case: Application of the Battery Model

A sample case where the proposed battery model was utilized in a microgrid application is presented here. This microgrid contains a diesel generator (which is part of Typhoon's proprietary library [8]) and a PV system utilizing the model reported in [9] alongside the battery model presented in this paper. The simulation was carried out in the Typhoon HIL 603 real-time simulator. The proposed battery model was linked to an inverter designed for connecting Li-Ion battery units

TABLE III
MEMORY UTILIZATION TO SIMULATE THE MODEL IN TYPHOON HIL 603

Memory Type	Used Memory	Available Memory (kb)	Utilization
Internal Memory	48	256	19.04%
Code Segment Size	38	256	14.94%
Data Segment Size	10	256	4.10%

to AC-grids. The details of this inverter is reported in [10]. The block-level representation of this microgrid is shown in fig. 6. However, a discussion on the detailed modeling of the individual components of this microgrid is beyond the scope of this paper.

While simulating the microgrid, the battery was subjected to a load increase of 12.5 kW as shown in Fig. 7. The battery responds to this step-change by increasing the output current as shown in Fig. 8. It needs to be noted that, further studies of the *transient response* of the battery output current during this step-change, as observed in Fig. 8, is beyond the scope of current work. As demonstrated in Fig. 9, the voltage output of the battery remains relatively constant through the entire duration of this simulation. Since the battery is providing power to the microgrid, it is expected that the SOC of the battery would decline steadily, which is confirmed by the simulation results demonstrated in Fig. 10.

IV. DISCUSSIONS AND FUTURE WORKS

It is desirable to ensure cross-platform compatibility and model response consistency in order to minimize the uncertainty in the simulations across different hardware acrhitectures. In other domains of science and engineering, modern interoperability standards such as Modelica and theFMI (Functional Mock-up Interfaces) are already in place. However, these standards are only adopted in very few power system tools[7]. The work in this paper helps to motivate further the need for model portability using the Modelica and FMI standards for power system simulation.

It is reported in [7] that the library coverage for Simulink and Opal-RT is larger than that of other simulation platforms e.g. Typhoon HIL. It was also observed in [7] that the existing library models for similar components across these two different infrastructures can give different results. Thus, in order to obtain compatible simulation models for batteries, it is necessary to build them from the scratch. It is also highly recommended that, only simple mathematical and numerical functions are to be used to construct new models, so to limit platform dependencies.

The current work establishes that simplified simulation models for Li-ion batteries are portable across different real-time simulation platforms if proper implementation is made. Fig. 5 exhibits that the proposed model was able to generate identical simulation results across the two different platforms. To ensure this, the charging and discharging circuits used for experimentation was kept simple and minimal. This enabled a identical testing environment for the proposed model, across the two hardwares. It is expected that when the charging/discharging paths get more complicated, the proposed model's cross-platform performance may deteriorate.

A preliminary demonstration of the usage of this battery model is shown in the context of a simple microgrid model. However, this part of the work needs a lot of further analysis and studies to understand how the battery model responds to changes applied to different blocks of the microgrid. This analysis is crucial for the validation of the proposed battery model.

V. CONCLUSIONS

This paper reported a simplified cross-platform compatible real-time simulation model for Li-ion batteries. The model, when implemented on Opal RT real-time simulator, is competitive in terms of accuracy and efficiency, while compared to a closed-source proprietary battery model. The proposed model was then migrated to the Typhoon HIL real time simulator. The real-time simulation results for this model on Typhoon and Opal RT were found to be identical thanks to the implementation approach adopted in this work. The preliminary testing of this model was successfully carried out by connecting it to a microgrid system.

ACKNOWLEDGEMENTS

This work was funded in part by Dominion Energy, in part by the New York State Energy Research and Development Agency (NYSERDA) through the Electric Power Transmission and Distribution (EPTD) High Performing Grid Program under agreement number 137948, the Engineering Research Center Program of the National Science Foundation and the Department of Energy under Award EEC-1041877, in part by the CURENT Industry Partnership Program, and in part by the ECSE Department at RPI.

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