Towards Grid Code Compliance Testing at Real-Time Speeds: A Workflow to Migrate OEM Black-Box Controller Models from Offline to Real-Time

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***Abstract*—The rapid integration of inverter-based resources (IBRs) is increasing the demand for grid code compliance with emerging standards such as IEEE 2800. However, many original equipment manufacturers (OEMs)-supplied IBR controller models remain limited to offline electromagnetic transient (EMT) simulation environments as black-box models, where slow runtimes make real-time applications such as controller hardware-in-the-loop testing impractical. This limits the ability of renewable developers and system operators to perform repeatable, standards-based validation. To address the issues, this paper presents a streamlined workflow for migrating black-box controllers to real-time simulation using a standardized interface architecture, based on the IEEE–CIGRÉ B4.82 joint working group's technical guidelines. This interface preserves OEM's intellectual property (IP) while supporting platform interoperability. The workflow also includes automated migration of the power circuits, preparation for execution of the models in real-time, and an automated IEEE 2800-based test suite to accelerate compliance efforts. Simulation results demonstrate strong alignment with offline models while achieving a 2× reduction in simulation time. Our approach enables full real-time execution of the IEEE 2800 test suite and supports scalable software- and controller-in-the-loop testing, ensuring grid code compliance validation for OEM controllers while maintaining fidelity comparable to offline EMT simulations. This method enables pre-installation hardware-in-the-loop testing of protective relays, grid support devices, and other hardware to identify performance issues, adverse interactions before deployment.**

***Index Terms*-- Inverter-based resources, EMT, real-time simulation, black-box controllers, IEEE 2800, compliance testing**

I. Introduction

As power grids increasingly integrate more inverter-based resources (IBRs), the available system inertia is reduced and fast control dynamics become more prominent. Consequently, high-fidelity electromagnetic transient (EMT) simulations are becoming essential for accurately analyzing large-scale power systems with high IBR penetration [1]-[2]. Additionally, the need for real-time simulation capabilities is growing as it becomes crucial to support advanced testing methods such as controller-hardware-in-the-loop (CHIL) for the sake of model validation and grid code compliance testing during the interconnection process [3]. Real-time EMT simulation facilitates dynamic testing by interfacing actual controller hardware or digital replicas, offering a closer representation of field behavior while enabling comprehensive compliance testing and model validation in a lab environment. This growing emphasis on real-time simulation becomes even more critical in the context of evolving regulatory standards. The implementation of newly introduced grid codes and performance standards, such as IEEE Std 2800-2022, imposes strict performance requirements on the IBR plants for their interconnection to the power grid. These requirements include capabilities, such as fault ride-through, active/reactive power control, and fault current contribution [4]. Consequently, original equipment manufacturers (OEMs) and developers are required to demonstrate compliance by simulating numerous test scenarios [5]. However, traditional offline EMT simulation environments are often too slow, making the compliance process time-consuming and inefficient. To overcome this limitation, there is growing interest in accelerating compliance testing through real-time or faster-than-real-time simulation, as well as in automating test workflows to better meet evolving regulatory demands [6]. A major challenge in this context lies in the black-boxed nature of OEM controller models, which are typically provided in compiled formats, such as dynamic-link library (DLL) for Windows-based platforms, without access to their source code. While this protects OEM intellectual property (IP), it typically restricts model interoperability, as the black-box is generally prepared for use only within a specific simulation platform [8]. To address this issue, the IEEE/CIGRÉ Joint Working Group B4.82 proposed a vendor-neutral standardized interface to encapsulate controller code allowing OEMs to maintain IP protection while enabling integration into multiple simulation environments with minimal modification, thus enhancing model interoperability [9].

This paper presents a workflow that enables real-time grid code compliance testing for OEM-supplied black-box IBR controllers. The process begins with the automated migration of models from an offline EMT simulation environment to a real-time platform (HYPERSIM) leveraging a unified modeling database for power circuits and non-proprietary control components [9], [10]. OEM black-box controllers are then integrated via the standardized interface methodology recommended by IEEE/CIGRÉ guideline [9]. Model accuracy is verified by benchmarking real-time results against offline simulations. Then, an automated test suite for grid code compliance such as the IEEE 2800 is deployed through a custom

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scripting framework, which applies disturbance scenarios, monitors system responses, and evaluates compliance against defined pass/fail criteria. Our test results confirm that the migrated black-box controller successfully executes the IEEE 2800 test suite in real-time, offering a repeatable, automated validation workflow that greatly reduces compliance testing time compared to offline simulation-based workflows.

Essentially, our contribution provides a workflow that combines the use of an interoperable approach for black-box model integration, migration of offline models into real-time, and an automated test suite for model validation and grid code compliance into a single framework. The rest of this paper is organized as follows: Section II reviews related work; Section III outlines the model migration process; Section IV describes the application case study of an OEM-specific IBR model and shows simulation results; Section V presents the automated IEEE 2800 test suite; and Section VI concludes with key findings and future directions. This work aligns with recent industry efforts toward model interoperability and faster grid code compliance testing.

II. Background and Related Work

A. Real-Time EMT Simulation

Recent advancements in real-time EMT simulation technologies have enabled the accurate modeling of complex power systems, including those with detailed switching converters [3]. Real-time simulation tools have demonstrated the capability to simulate large-scale networks with numerous IBRs by distributing computational loads across multiple processor cores [11]. However, meeting real-time constraints remains challenging as the computations for each time-step (e.g., 50 µs) must complete within their actual time duration to maintain synchronization for real-time. This constraint becomes especially difficult when integrating black-box controller models not optimized for real-time use, as they can significantly slow down execution, sometimes by a factor of three, until optimization is applied to improve performance [11]. To overcome these issues, careful migration strategies, model simplification, and computational offloading are often necessary to meet performance requirements while preserving simulation fidelity.

B. Black-Box Controller Models and Interface Standards

In the power industry, it is common for vendors to deliver control models for HVDC systems, STATCOM/FACTS devices, wind turbines, and solar plants as encrypted or compiled black-box components for EMT simulation tools. However, the absence of a universal interface standard has led to significant interoperability issues resulting in models developed for one platform often requiring extensive rework to be used with another [7]. To overcome this challenge, the IEEE/CIGRÉ B4.82 Joint Working Group published a technical brochure that provided guidelines for integrating proprietary controller models into EMT simulation platforms in a standardized manner [8]. This brochure defined a consistent functional interface, including input/output signals and initialization routines, enabling cross-platform interoperability. Effectively, it proposed the encapsulation of the OEM proprietary logic within a standardized "container," allowing seamless data exchange between the simulator and the control model at each time step.

C. IEEE 2800 and Grid Code Compliance Testing

IEEE Std 2800-2022 defines comprehensive performance requirements for large IBR plants, especially at the transmission level to ensure grid reliability. Key mandates include voltage and frequency ride-through capabilities, requiring IBRs to remain connected during disturbances and perform on par with conventional generators [4]. Real-time simulation is essential for verifying compliance quickly and efficiently. When combined with HIL, it enables automated, repeatable tests that closely replicate real-world grid conditions, supporting efficient lab-based certification for standards such as IEEE 2800 and UL 1741 [7], [12]. Even without physical hardware, real-time simulations significantly accelerate validation across diverse test scenarios involving ride-through behaviors.

III. Model Migration from Offline to Real-time

Migrating an EMT model from an offline platform to a real-time environment involves two parallel efforts: (1) translating the power circuit and non-proprietary control logic, and (2) embedding the OEM-supplied black-box controller into the new simulation framework. In the presented workflow, the first task is accomplished using a unified data exchange and conversion tool, while the second is addressed through a custom interface wrapper developed in accordance with the standardization principles outlined earlier.

A. Automated Power Circuit Conversion

In our case, the electrical system of the IBR model, including power components and standard control blocks, is imported from an offline tool (PSCAD) into HYPERSIM for real-time simulation. The migration process is streamlined using a Unified Database (UDB), which automates the conversion of supported third-party platforms into the real-time environment, as shown in Fig. 1. This significantly reduces manual reconstruction effort, minimizes human errors, and accelerates the workflow.

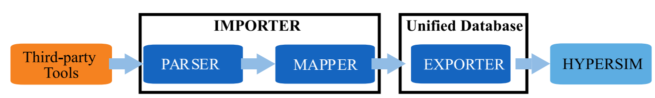

Fig. 1. Unified Database Migration Workflow of a model into HYPERSIM

During migration, the Importer module parses the source model into structured objects, identifying relevant power and control components and their parameters. These are mapped to final real-time model format's (HYPERSIM) library components using the Mapper, and the Exporter generates an equivalent model, preserving the original parameters, layout, and connections. However, in cases where certain components lack specific equivalents, due to custom or unsupported blocks, those elements require manual review and adjustment. After the import, small-scale unit tests are performed to manually verify model accuracy and parameter mapping. This ensures each component, including those modified manually, behaves consistently with its original version, enabling reliable migration of large-scale offline models to real-time simulation.

B. Integration of OEM Black-Box Controller

A key challenge in the workflow is the integration of an OEM-supplied controller, typically delivered as a DLL using a Fortran wrapper, into the real-time simulation environment. To

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streamline integration, the controller is reformatted using the standardized IEEE/CIGRÉ black-box interface methodology, enabling plug-and-play functionality via a built-in CIGRÉ interface block. This interface supports threaded and non-threaded execution modes, offering flexibility for real-time deployment. In threaded mode, the controller operates on a dedicated CPU core, introducing a fixed one-time-step delay that decouples the electrical and control domains, an approach well-suited for multi-rate simulation architectures. In non-threaded mode, the controller code executes synchronously within the main simulation loop. Users can select the execution mode based on performance requirements and available hardware resources.

In the integration process, the controller block is validated on the real-time simulation platform through open-loop testing. In this step, input waveforms recorded from the reference simulation in PSCAD are replayed into the standalone controller within HYPERSIM, and the outputs are monitored to ensure consistency with the original reference. It is to be noted that for real-time execution, the OEM must also supply a Linux-compiled binary (e.g., .so files) compatible with the real-time simulator system. After successful validation, the controller can be reconnected to the EMT circuit for full real-time operation.

IV. Case Study and Simulation Results

To demonstrate the proposed workflow, a representative utility-scale IBR available in PSCAD (offline platform) was migrated to HYPERSIM (real-time environment) and evaluated through comparative studies focused on accuracy and simulation performance. Simulation results show that the real-time implementation closely replicates the original offline behavior while significantly reducing simulation time.

A. Test System Description

The IBR model benchmark schematic system employs a two-level voltage-source converter (VSC) controlled by an OEM-supplied IBR controller. As shown in Fig. 2, the converter DC link, rated at 1.3 kV, is connected to a constant DC source through pre-charge and main DC contactors that regulate inrush current and isolation. On the AC side, the inverter output passes through an R-L-C filter, AC breaker, charging branch, and step-up transformer (0.6/20 kV, 3 MVA) before interfacing with the 20 kV equivalent grid at point of interconnection (POI). The converter controller was provided by the vendor as a black-box in both .dll and .so binary formats. This model contained actual field firmware with hidden internal logic, exposing only predefined I/O ports for user interaction. Within the EMT simulation environment, the black-box controller interfaces directly with measured plant signals and operates at a 166.67 µs time step, while the EMT network runs at 33.33 µs, using trapezoidal integration with periodic signal exchange between the control and power circuits. The controller receives terminal voltages, currents, DC bus voltage, and power references, and outputs converter modulation and gating signals.

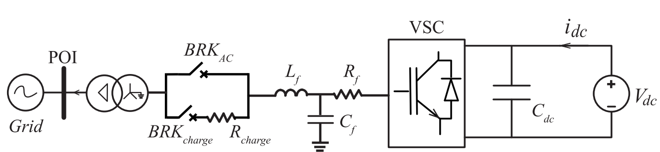

Fig. 2. Schematic of the utility-scale IBR model

B. Accuracy Validation

To evaluate the accuracy of the migrated model, the IBR system is tested under a three-phase-to-ground (3LG) fault. Real-time results using threaded mode (HYP-TH) are compared with offline results from non-threaded mode (HYP-NTH), both validated against the original offline reference (REF). Fig. 3 and Fig. 4 illustrate the transient response to the fault applied at 12 s, highlighting the trade-offs between execution modes.

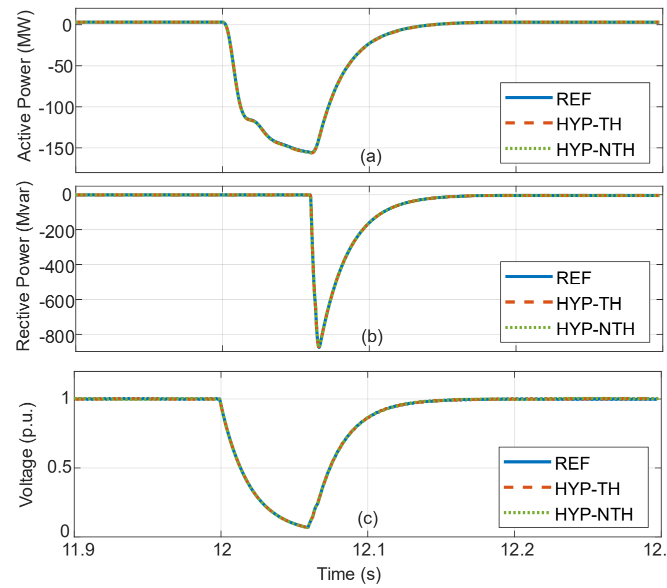

Fig. 3. Validation of real-time results against offline reference at POI for a 3LG fault event: (a) active power, (b) reactive power, and (c) RMS voltage.

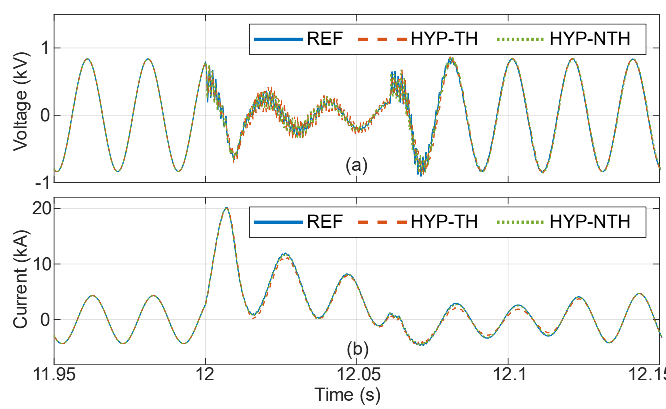

Fig. 4. Instantaneous waveforms during a 3LG fault event: (a) line-to-line voltage and (b) phase-A current.

In HYP-NTHmode, the controller operates synchronously within the main loop, closely matching the REF and confirming model fidelity. However, this configuration does not satisfy real-time constraints. In contrast, the HYP-TH mode runs the multi-rate controller on a dedicated core, enabling real-time performance but introducing a one-time-step delay between controller and electrical circuit. While this leads to minor deviations during fast transients (see Fig. 4), a high degree of accuracy is still maintained overall. Thus, the threaded configuration is utilized for real-time execution with minimal compromise to model precision.

Similarly, controller-level outputs are also compared. The black-box controller generated nearly identical control actions when considering converter reference signals, and breaker commands while operating in both real-time and offline environments as seen in Fig. 5. The zoomed in view highlights time-step delay introduced by the threaded mode in Fig. 5c.

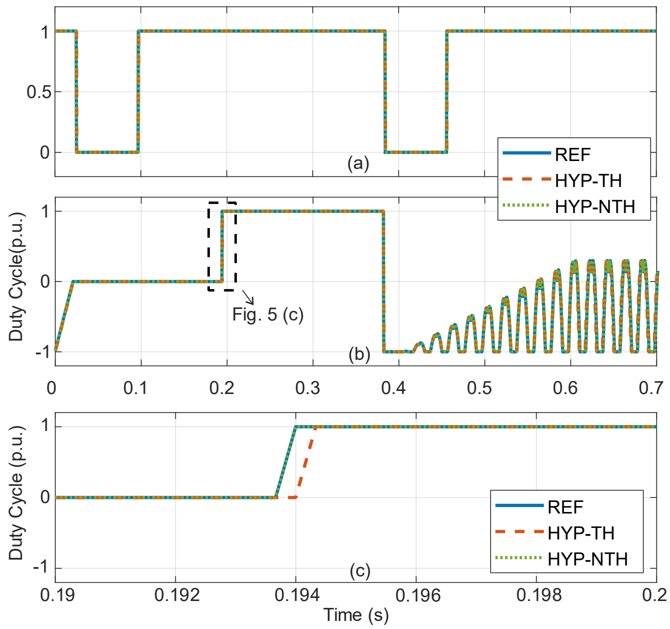

Fig. 5. Black-box controller outputs during black start: (a) AC energizing breaker command, (b) converter duty cycle, and (c) zoomed-in of duty cycle.

In addition, a quantitative comparison is performed using an RMS relative error metric as defined in (1).

$$E_{RMS}(\%) = \frac{\left(\sqrt{\left(\frac{1}{N}\right)\Sigma_{i=1}^{N}(x_{HYP,i} - x_{REF,i})^2}\right)}{\left(\sqrt{\left(\frac{1}{N}\right)\Sigma_{i=1}^{N}(x_{REF,i})^2}\right)} \times 100\% \qquad (1)$$

This metric evaluates the overall deviation between HYP-TH and HYP-NTH against REF across different stages of the simulation. Table 1 summarizes the computed errors for active power, reactive power, and RMS voltage at POI. It is noted that the higher errors observed in HYP-TH, especially during start-up and fault transients, are attributed to the introduced one-step delay. Nevertheless, the overall deviations remain below 1%, confirming the high accuracy of the real-time model.

TABLE 1. RMS RELATIVE ERROR RESULTS AT POI: HYP COMPARED TO REF

Signal	Start-up E_{RMS} (0-2s)		Steady-State E_{RMS} (2-10s)		Fault E_{RMS} (10-15s)	
	HYP-NTH	*HYP-TH*	*HYP-NTH*	*HYP-TH*	*HYP-NTH*	*HYP-TH*
P_{POI}	0.06 %	0.26 %	0.00 %	0.00 %	0.38 %	0.48 %
Q_{POI}	0.19 %	0.74 %	0.03 %	0.02 %	0.03 %	0.05 %
V_{rms}	0.03 %	0.03 %	0.03 %	0.03 %	0.06 %	0.06 %

C. Runtime Performance

Simulation runtimes are evaluated for real-time HYP-TH and offline REF. The offline platform exhibited longer execution times due to the computational demands of the EMT solver and its single-threaded architecture. For instance, a 60-second simulation takes 120 seconds of wall-clock time to complete on the offline platform. In contrast, the real-time platform leverages a threaded mode that executes the controller on a separate core, enabling real-time performance. Consequently, a 60-second simulation executed in 60 seconds of wall-clock time, corresponding to a speedup factor of up to 2× for HYP-TH. While this performance gain seems minimal on a plant level simulation, it will significantly increase when larger power system models are to be simulated along with the IBR plant. Real-time execution also facilitates HIL testing and extensive scenario sweeps that would be impractical using offline tools.

V. AUTOMATED IEEE 2800 TESTS FRAMEWORK

With a validated real-time IBR model, an automated test framework is developed to evaluate compliance with IEEE 2800 requirements. The framework is implemented using Python-based API functions, enabling scripted execution of multiple test scenarios in a sequential and repeatable fashion. Each test follows a standard workflow as illustrated in Fig. 6: loading the simulation case, initializing conditions, applying the disturbance or command, running the simulation, logging outputs, and recording and analyzing results.

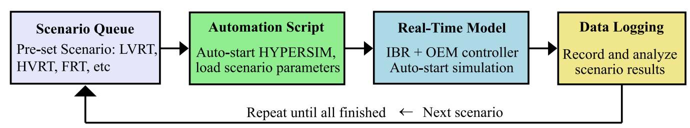

Fig. 6. Automated IEEE 2800 Compliance Test Workflow

Each test result is compared against acceptance thresholds derived from the IEEE 2800 standard. For example, LVRT compliance requires no tripping; HVRT requires no disconnection within over-voltage tolerances; and frequency ride-through requires the unit to stay online down to the specified frequency. A summary of tests included is provided in Table 2.

TABLE 2. SUMMARY OF AUTOMATED IEEE 2800 COMPLIANCE TESTS

Test Scenario	Disturbance Applied	Disturbance Duration
1. Low-Voltage Ride-Through (LVRT)	Voltage dip to 0.8, 0.6, 0.4, 0.25 p.u.	4 s; 3 s; 2 s; 3 s
2. High-Voltage Ride-Through (HVRT)	Voltage rise to 1.15 p.u.	3 s
3. Low-Frequency Ride-Through	Frequency drop to 49 Hz, 47.5 Hz	3 s each
4. High-Frequency Ride-Through	Frequency rise to 51 Hz, 52.5 Hz	3 s each
5. Grid Strength test	SCR reduced from 8 to 5; 3; 2; 1.5	4 s each

Fig. 7 presents the RMS voltage and reactive power responses at the POI during the automated IEEE 2800 ride-through tests (scenarios 1 and 2). Initially, voltage goes through

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the HVRT test in the first 3s, and the voltage level is restored to nominal voltage. Subsequent stepwise voltage reductions represent a sequence of LVRT events defined by the standard. As the voltage decreases, the inverter controller responds by rapidly increasing reactive power injection to support grid voltage recovery. However, once the voltage falls below approximately 0.4 p.u., the controller reaches its reactive current limit and causes reactive power saturation. When the voltage drops near 0.2 p.u., protection logic is activated, and the IBR model disconnects, potentially resulting in a failed compliance case. The automated framework flags this violation, records relevant waveforms, and allows engineers to analyze and modify control parameters before re-running the test to confirm corrective actions. This iterative process streamlines IEEE 2800 validation and supports regression testing after code updates.

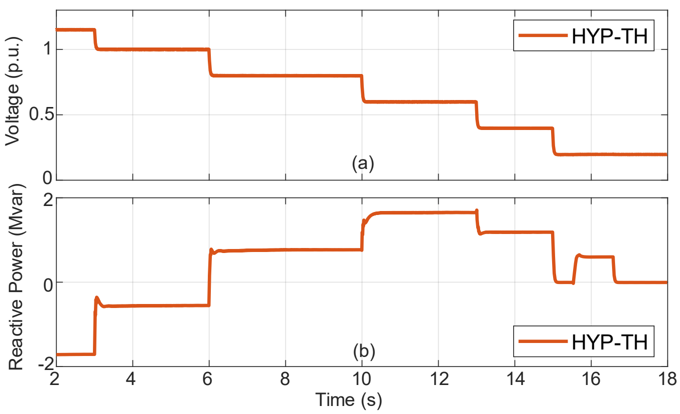

Fig. 7. Automated IEEE 2800 LVRT test results at the POI: (a) RMS voltage profile and (b) reactive power response

VI. Conclusion and Future Work

This paper presented a generalized workflow for migrating an IBR model with an OEM-supplied black-box controller from offline to a real-time simulation platform. Adopting the standardized IEEE/CIGRÉ black-box interface ensured the interoperability of the model to be executed in real-time while preserving OEM's intellectual property. Test results showed that the migrated real-time IBR model closely matches the offline reference, with less than 1% deviation across start-up, steady state and fault transients. While the migrated IBR model achieves a limited speedup factor (2x) in a plant level model, it has the potential for much greater speedup when larger network segments are to be simulated along with the IBR model to study control interactions or oscillations. Furthermore, enabling real-time performance makes the model amenable to CHIL testing at pre-commissioning stage to iron out practical interoperability issues. In addition, an automated IEEE 2800 compliance test suite developed using a Python API was presented to execute sequential test scenarios and perform objective pass/fail assessments. This test suite can be used to effectively identify failure cases and support rapid parameter tuning, re-testing, and iterative validation.

Future work will extend this framework to multi-vendor controller benchmarking, closed-loop CHIL verification, and controller integration with other standardized interfaces such as the Functional Mock-up Unit, further enhancing model interoperability across EMT simulation platforms.

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