Hybrid EMT-TS Simulation of High-IBR Penetration Power System: The ISO-NE Experience

Xingyu Zhao, Jason Ploof, Xinghao Fang, Bin Wang, and Junbo Zhao.

***Abstract*—The power industry is undergoing a paradigm shift, transitioning from a grid dominated by synchronous generators (SGs) to one increasingly powered by inverter-based resources (IBRs). Since the dynamics of IBRs span both electromechanical and electromagnetic timescales, phasor-domain transient stability (TS) simulation tools, such as `PSS®E`, may fall short to capture the fast electromagnetic transients (EMTs). However, current EMT simulation tools, such as `PSCAD`, are computationally intractable for large-scale grids. Combining detailed EMT models of IBRs in the study area with phasor-domain models of the external area, hybrid EMT-TS simulation technique provides a practical and accurate way to capture both fast and slow dynamic phenomena. This paper aims to share our experiences of building a realistic large-scale hybrid simulation case with high penetration of IBRs using `PSCAD`, `PSS®E` and `E-Tran`. Comparative results between hybrid and conventional phasor-domain `PSS®E` simulation are also shown. This paper provides engineering insights to the industry and contributes to a better understanding of the need for EMT simulation for operation studies.**

***Index Terms*—High IBR penetration, hybrid EMT-TS simulation, realistic large-scale power system.**

I. Introduction

A. Motivations

The growing integration of IBRs presents novel challenges for dynamic stability analysis. Currently, all independent system operators (ISOs) in the United States utilize only phasor-domain simulations for their operation studies except for ISO New England (ISO-NE). ISO-NE has taken a leading role in adopting EMT and hybrid EMT-TS simulation techniques due to the high penetration of IBRs and the presence of weak grid conditions in certain areas. To accelerate the acceptance, storage and update of IBRs' EMT model, ISO-NE has maintained an internal EMT model repository and developed automation tools for model acceptance and integration testing. Since there is no existing standard format of IBR EMT model, ISO-NE has standardized the model packaging process internally for planing and operation. Additionally, an EMT model validation tool [1] based on field data has been developed. These efforts have established a solid technical foundation for the application of EMT and hybrid EMT-TS simulation.

When compared to the phasor-domain models, EMT models offer clear advantages when studying the dynamic behavior of IBRs by capturing fast electromagnetic transients, detailed control dynamics, and unbalanced fault conditions, which are essential for analyzing protection schemes, fault ride-through behavior, and stability in weak or low-inertia grid conditions. While EMT modeling offers clear advantages, constructing a complete EMT representation of an ISO-level power system is currently unrealistic because of the significant computational demands. Therefore, the hybrid EMT-TS simulation scheme is applied, where the area containing the IBRs of interest, referred to as the study area, is modeled using EMT simulation tools for detailed dynamic analysis. The remainder of the power system, referred to as the external area, is modeled using TS simulation tools to improve computational efficiency. Given that multiple IBRs may be present in the study area, the EMT simulation is parallelized so that each IBR is computed on a separate CPU. This paper aims to implement these concepts to model an ISO-scale power system (including the entire Eastern Interconnection, which is significantly larger than the New England grid) and evaluate simulation performance in terms of computational cost and accuracy relative to operational study requirements.

B. Literature Review

1) Theoretical Foundation: The concept of hybrid simulation was firstly proposed in [2] for modeling the HVAC-HVDC system. Recent achievements on advancing hybrid simulation to large-scale power system mainly focus on:

- *Equivalent of external system in EMT simulator:* methods such as frequency dependent network equivalent (FDNE) [3] and multi-port Norton equivalent [4] were proposed to cover a wider range of frequency variations.
- *Equivalent of study area in TS simulator:* methods based on Fourier transform [5] or least squares [6] are proposed for extracting phasors from waveform instantaneously.
- *Boundary location:* Sufficient electrical distance between the boundary buses and the unbalanced/harmonic sources is needed to avoid numerical instability in TS [7], [8].
- *Simulation protocol:* The iterations of the EMT and TS simulators can be executed in parallel on different CPUs, thereby enhancing the overall simulation efficiency [9].

These studies laid the theoretical groundwork for the industrial application of hybrid EMT-TS simulation.

2) Simulation Tools: A range of tools for hybrid simulation have been developed over the past few years. For instance, an open-source tool, `OpenHybridSim` [10], has been created to interface the TS simulator `InterPSS` with the EMT simulator `PSCAD`. In [11], the TS simulator `OpenDSS` is interfaced with EMT simulator `Matlab SimPowerSystem` to enable

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hybrid simulation. In [12], an open source tool `HELICS` is utilized for data exchange between the TS simulator `GridPack` and the EMT simulator `ParaEMT`. Although these tools have largely enriched academic research, the industrial application of hybrid simulation requires standardization and compatibility with commercial software. At ISO New England, `E-Tran`, a commercial tool for network equivalencing, and its extension `E-Tran Plus` for data exchange [13], are utilized to co-simulate `PSCAD` and `PSS®E`. Within this framework, a hybrid test case featuring only one wind power plant modeled in EMT domain is presented in [14]. When multiple IBRs are included in the EMT study area, the computational cost can become very challenging for operational studies. In addition, requirements such as time step size or software version may be incompatible across different IBR models. Thus, a distributed, plug-and-play and standardized approach for hybrid simulation is required. This paper aims to address this gap in industrial practice.

C. Contributions

In this paper, we want to share the industrial experience of ISO-NE in developing an ISO-level hybrid EMT-TS case that preserves a large-area system with multiple IBRs represented by EMT models and simulated in parallel.

The main contributions of this paper are threefold:

1) *Parallel substitution library:* The detailed IBR models in `PSCAD` are packaged into a substitution library, enabling free-lunch translation through `E-Tran`. Guidelines for selecting parallelization ports are also provided.
2) *Initialization:* While `PSS®E` automatically initializes dynamic models based on the power flow, `PSCAD` requires additional time steps to reach steady state and may exhibit steady-state mismatches compared with the power flow results. A practical method to mitigate this issue is proposed.
3) *Comparative Analysis:* The hybrid EMT-TS simulation are compared against the TS simulation currently used in ISO-NE's operation studies. This highlights the advantages of the hybrid approach in capturing fast inverter dynamics and control interactions. Moreover, the required computational time is reported.

D. Paper Organization

The reminder of this paper is organized as follows: Section II presents the bottom-up workflow for setting up hybrid EMT-TS simulation in parallel. Section III-C showcases the numerical results of hybrid and TS-only simulation of the Downeast area, a realistic part of the ISO-NE power system. Finally, section IV concludes this paper and points out future directions.

II. Hybrid Simulation Workflow

A. Model Preparation

Upon receiving the EMT models of IBRs from the vendors or manufacturers, ISO-NE preprocesses and adapts the models to ensure consistency in format and reduce computational cost with the following procedures:

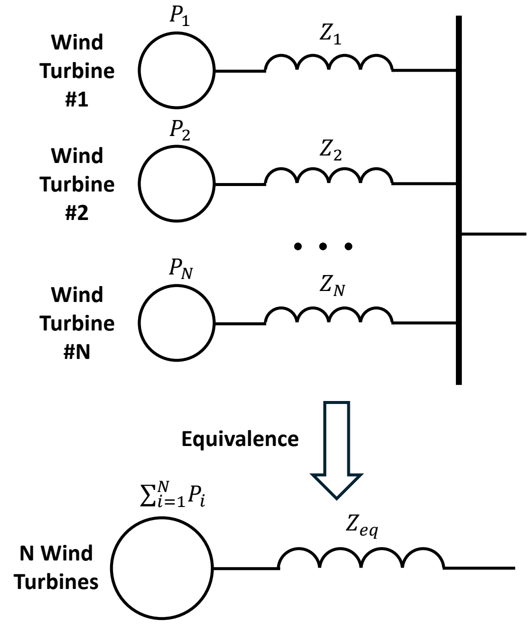

Fig. 1. The aggregation of parallel wind turbines

1) Model Aggregation: When there are multiple homogeneous IBRs connected to the point of interconnection (POI), aggregating them into a single IBR is preferred as the external dynamic behaviors instead of their interplays are of interest for interconnection study. An illustration graph for this procedure is shown in Fig. 1. The aggregated impedance Z_{eq} is calculated using the method proposed in [15] as follows:

$$Z_{eq} = \frac{\sum_i^N P_i^2 Z_i}{\left(\sum_{i=1}^N P_i\right)^2} \tag{1}$$

where P_i and Z_i denote the rated power and series impedance of the i^{th} wind turbine, respectively.

2) Model Formation: The IBRs' EMT models are packaged into substitution libraries, which provide a standardized model format that can be recognized by `E-Tran` and automatically utilized when transforming a case from `PSS®E` into `PSCAD`. Compared to manual copy-and-paste, the substitution library automates the process and enables seamless updating of power flow results from `PSS®E` to adjust the IBR controller setpoints in `PSCAD`. While `E-TRAN` provides standardized substitution libraries for commonly used components such as synchronous generators (including condensers) and transmission lines with fault logic, IBRs typically rely on customized black-box models, and therefore require redefinition. A designation system that specifies the component type (e.g., transformer, transmission line, IBR) and index (e.g., bus number) is required by `E-Tran` to systematically rename each component.

3) Model Parallelization: In the serial simulation case, the substitution library contains the dynamic model of each component. In contrast, in the parallel simulation case, the components in the substitution library are replaced with dummy models, leaving only communication ports. This dummy substitution library is referred to as `PSub`. The actual EMT

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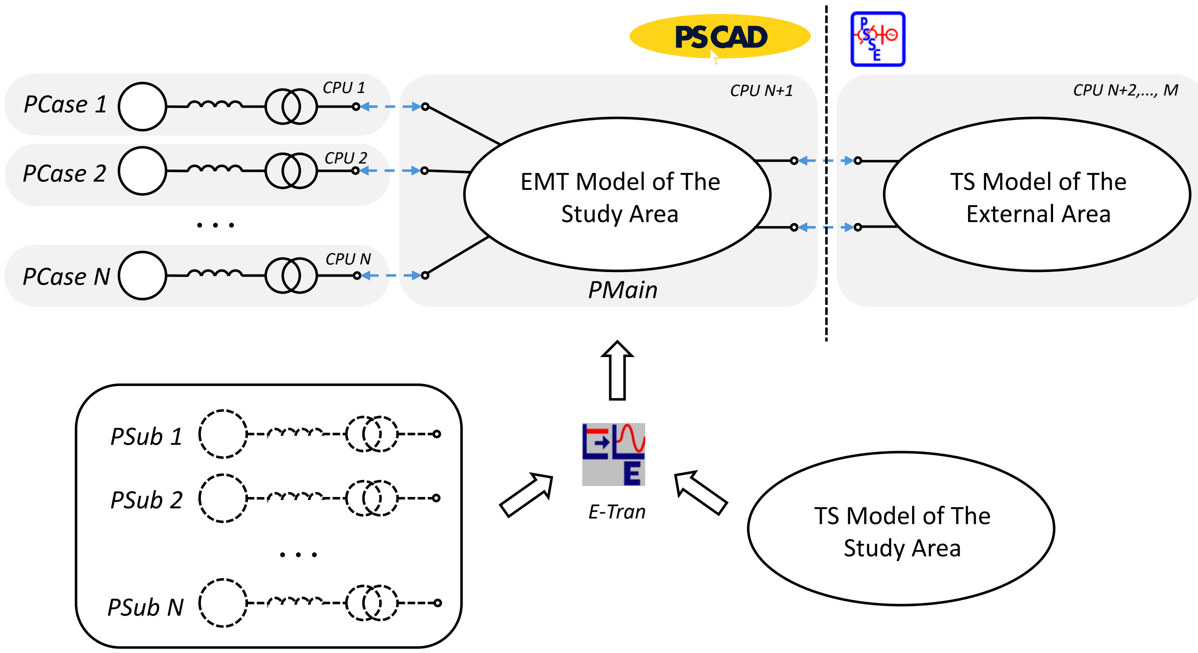

Fig. 2. The case preparation and parallelization scheme of the hybrid EMT-TS simulation

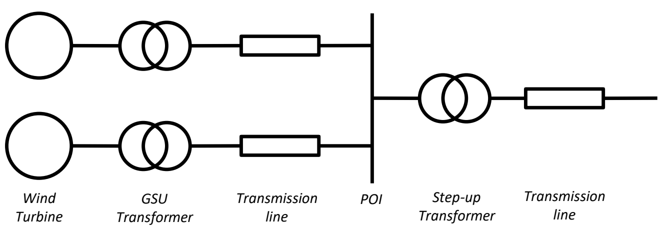

Fig. 3. A typical topology of the wind power plant

model of the IBR is stored in a separated case file with communication ports, referred to as `PCase`. When `PSub` and the `PSS`®`E` files, including both steady-state and dynamic data, are available, the main case, called `PMain`, which contains the EMT network with the communication ports of IBRs, can be generated using `E-Tran`. By including `PMain` and `PCase` into a simulation set in `PSCAD`, the hybrid simulation can be set up in parallel. An illustration graph for this parallelization scheme is shown in Fig. 2. The boundary between the study and external area must be predefined before generating the `PMain`. Up to now, there are no absolute criteria for selecting the boundary buses. A straightforward approach is to include all IBRs within the EMT area and maintain sufficient electrical distance from the fault locations to avoid numerical instability. In `E-Tran`, only two types of models can be chosen as parallelization ports: Bergen transmission lines and transformers. This can make the selection of parallelization ports quite challenging. Here, an illustration figure of a wind power plant is given in the Fig. 3. In many cases, the transmission line connecting the step-up transformer to the rest of the grid may not be long enough to be represented as a Bergen line under a practical simulation timestep, and the generator step-up (GSU) transformer may be integrated into the black-box model of IBR. In this scenario, the step-up transformer at the point of interconnection (POI) is commonly chosen as the parallelization port. However, if a three-winding transformer connecting a synchronous condenser is used at the POI, the GSU transformer may become the only viable choice for the parallelization port, at the cost of playing back a large number of control signals through the port.

4) Model Initialization: In `PSS`®`E`, the dynamical states are initialized based on the power flow results. Therefore, the TS simulation remains flat prior to the fault. However, In `PSCAD`, the dynamical states are initialized from zero. Thus, sufficient initialization time is required for the dynamic states to settle to their steady-state values before applying the fault. In ISO-NE's practice, matching the steady-state voltage, active power, and reactive power at the IBR terminals between the EMT and TS simulations can be very challenging. A common cause of this mismatch is that when a power plant controller (PPC) is implemented for the IBRs, it may introduce setpoint deviations that are not reflected in the power flow results. When the PPC is known, it is possible to derive analytical compensation to mitigate this mismatch. However, most industrial EMT models are black boxes, requiring a model-free compensation method. To address this challenge, a proportional–integral (PI) controller is used to calculate and compensate for the steady-state mismatch. An illustration graph of this method is given in Fig. 4. Here, t_0 is the time for initializing the IBRs, and t_1 is the time for settling down the PI controller. When $t > t_0$, the PI controller is activated to mitigate the mismatch between the `PSS`®`E` load-flow results and the actual IBR outputs by adding a compensation term to the PPC output. When $t > t_1$, ($t_0 < t_1$), the PI controller settles, and its output is frozen while the controller is deactivated. This approach eliminates

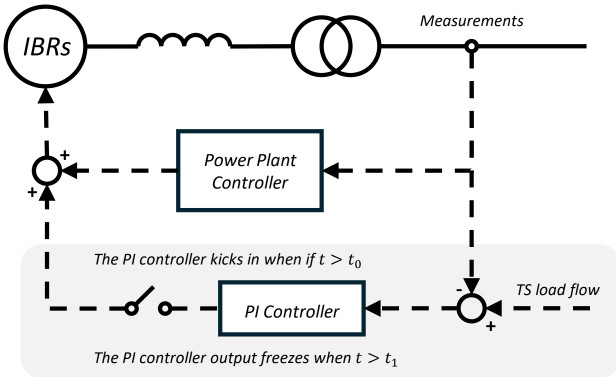

Fig. 4. The proposed PI controller-based initialization scheme

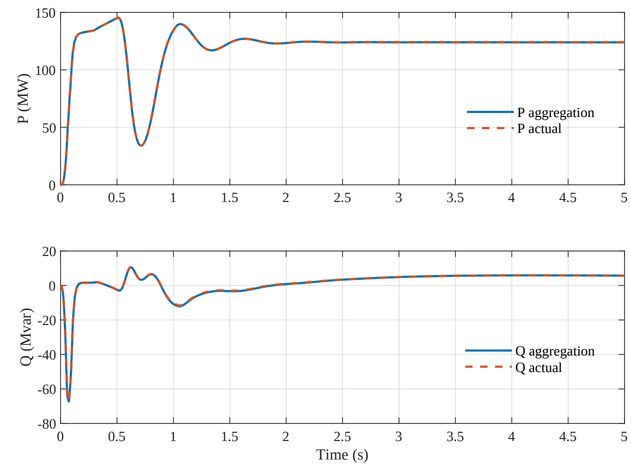

Fig. 5. The comparison between the actual model and the aggregated model

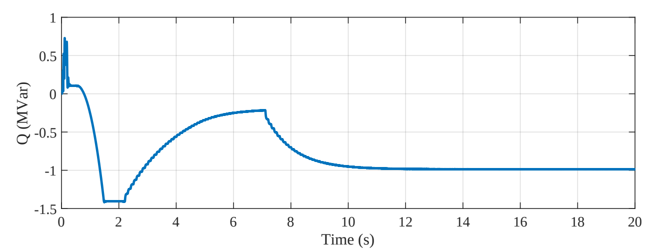

Fig. 6. A numerical example of the proposed PI controller-based initialization

the steady-state error without introducing additional dynamics. In addition, the PI control loop is easy to implement in PSCAD, making it an acceptable solution for industry applications.

III. The Downeast Case Study

In this section, the numerical results of the hybrid simulation for the Downeast area are presented. This area includes seven inverter-based resources (IBRs), consisting of six wind power plants and one STATCOM. The study area consists of more than 90 buses in total. Moreover, two synchronous condensers are included in the study area as well. The external system is the remainder of the entire Eastern Interconnection, consisting of more than 20000 buses.

A. Wind Turbine Aggregation

A comparative plot of active and reactive power between the actual and aggregated models, constructed using the aggregation method introduced in Section II-A1, for a wind-power plant in the Downeast region is shown in Fig. 5. It is observed that during the initialization process, the aggregated model closely matches the dynamic behavior of the actual model. Moreover, the steady-state values of both models are identical, indicating that the aggregation introduces no drift or offset in steady-state behavior. As all individual wind-turbine models are industrial-standard high-fidelity EMT models, this comparison further validates the feasibility of the aggregation method for realistic system scenarios.

B. PI Controller-Based Initialization

To demonstrate how the PI controller aligns the IBR initialization with the power-flow solution, Fig. 6 illustrates the reactive-power initialization of a wind farm in the Downeast Area. In this case, the power-flow solution specifies a reactive-power setpoint of $-1\,\mathrm{MVar}$. During the first $7\,\mathrm{s}$ of initialization, however, the reactive power converges to a value between -0.5 and $0\,\mathrm{MVar}$, which would result in a steady-state offset if uncorrected. At $t = t_0 = 7\,\mathrm{s}$, the PI controller is activated, using the load-flow reactive-power value of $-1\,\mathrm{MVar}$ as its reference. It then drives the system toward the correct steady-state operating point. Once the system reaches the new steady state at $t = t_1 = 12\,\mathrm{s}$, the output of the PI controller is frozen and the PI action is deactivated. Therefore, if a fault is applied after t_1, the PI controller will not influence the subsequent transient-stability response.

C. Comparison With TS-Only Simulation

To show the necessity and superiority of hybrid phasor–EMT simulation in operational studies, a comparative case study is conducted. The results for a wind-power plant in the Downeast region from a hybrid PSCAD–PSS®E simulation and a TS-only PSS®E simulation are shown in Fig. 7. The initialization process of the hybrid simulation is omitted for clarity. A three-phase fault is applied to a bus in the study area at $t = 0.2\,\mathrm{s}$ and cleared after five cycles ($0.08333\,\mathrm{s}$), as indicated by the shaded red region in Fig. 7. It is observed that at the fault initiation and clearing instants, the TS-only simulation produces spurious spikes that are not physically realistic (e.g., an overvoltage approaching 2 $\mathrm{p.u.}$, and a Q spike exceeding 60 MVar). The spiky behavior observed in the PSS®E (TS-only) is characteristic of phasor-domain modeling limitations for IBRs. These spikes are numerical and modeling artifacts rather than physical dynamics. They arise from simplified control blocks, discrete current-limit logic, and larger solver time steps, which force abrupt changes in power and voltage states during fault and recovery. Moreover, a pronounced reactive-power oscillation is observed in Fig.7, which is also largely an artifact from phasor-domain modeling. By contrast, the hybrid EMT curves remain smooth because PSCAD resolves fast inner-loop inverter controls and switching

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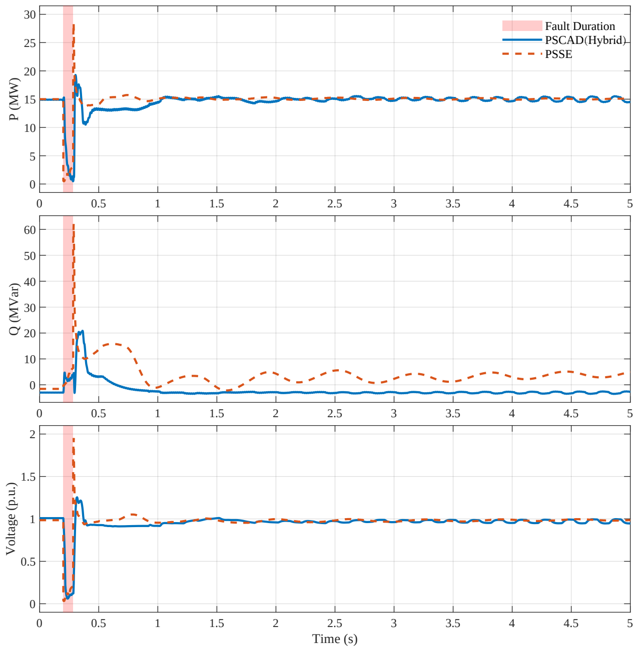

Fig. 7. Comparative result of a wind farm using hybrid and TS-only model

behavior continuously at EMT time resolution. These discrepancies demonstrate that TS-only models wrongly estimate IBR disturbance impacts and can misjudge system stability margins and protection timing. Therefore, hybrid simulation is essential for accurate operational studies in high-IBR grids, particularly for fault ride-through validation, dynamic control interaction assessment, and maximum transfer limit calculation. It is also noted that the hybrid simulation is computationally practical when executed in parallel. For a 30-second simulation window, including both model initialization and fault analysis, the study can be completed in 15 to 20 minutes on an engineering workstation at ISO New England. This demonstrates that hybrid simulation is feasible for practical operational studies.

IV. Conclusions

This work demonstrated ISO-NE's practical implementation of a large-scale hybrid EMT–TS simulation framework for high-IBR grids. A standardized model-packaging workflow, parallel EMT execution, and a PI-based initialization scheme were developed to enable efficient and accurate hybrid studies. The Downeast case results show that EMT-resolved inverter dynamics eliminate spurious spikes and oscillations observed in phasor-only simulations, yielding physically consistent fault responses while maintaining operationally feasible run times. These findings confirm the necessity and practicality of hybrid EMT–TS simulation for reliable operational studies in high-IBR systems.

For future work, ISO New England will continue to standardize the model-packaging process using the CIGRE/IEEE DLL methodology [16] and further automate hybrid EMT–TS case setup. In particular, scripting and software tools will be developed to streamline model preparation, and enable plug-and-play management of existing vendor EMT models. These efforts aim to reduce engineering overhead, improve model update efficiency, and expand the use of hybrid simulation in routine operational studies across the ISO-wide system.

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