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Real-Time Software-in-the-Loop EMT Models of Wind Turbine and Power Plant Controller: Applicability and Experiences

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Abstract

As the penetration of wind turbine generators (WTG) and other inverter-based resources increase in the system, offline electromagnetic transient simulations (EMT) using black-box user-defined controls are becoming widely available and used in the industry for stability and grid compliance studies. Nonetheless, there are certain challenges when using offline EMT models for tasks that involve large system simulation, testing of protection and control devices (i.e., protection relays), or interoperability analysis of different OEMs and other equipment such as HVDC, STATCOM, etc, mainly posed by simulation time. In this sense, real-time EMT simulations are emerging as important solutions for such challenges, where traditionally, hardware-in-the-loop (HiL) is used, incorporating control and protection hardware and, more recently, real-time software-in-the-loop (RTSiL). This paper gives an overview of RTSiL, illustrating different alternative development approaches of real-time SiL models. The paper starts by defining the domain of applicability of offline EMT models, real-time SiL, and HiL, highlighting the importance and differences between each method. It then proceeds to explain the different methodologies available for black-boxing controls and simulating SiL in different real-time simulators and the advantages and disadvantages of different methods. The paper shows results for the implementation of the real-source code of Type IV offshore wind turbines and power plant control (PPC) in both offline and online platforms, utilizing PSCAD and the SiL solutions from Real-Time Digital Simulator (RTDS) with GTSOC. The paper ends by discussing important differences between offline and online and the fact that RTSiL, as a new technology, still needs more maturation and verification.

1 Introduction

The penetration of large-scale wind power plants (WPPs) and other inverter-based resources (IBRs) is expected to grow significantly in the coming decades, leading to increased complexity in power system design and operation. In light of these challenges, Real-time Simulation (RTS), especially with the use of hardware-in-the-loop (HiL), has become increasingly important in recent decades. The need for thorough verification of control, protection, and communication features has grown across various power system sectors [1]. HiL testing has been popular for verifying the functionality of control systems, but software-in-the-loop (SiL) testing is emerging as a viable alternative. SiL testing involves embedding the control system's software in the loop with the real-time simulator instead of using the actual physical proprietary control hardware. While HiL testing has the advantage of testing the control system's hardware and software together, SiL testing has benefits in terms of requiring very little to no extra hardware apart from the real-time simulator itself. Therefore, developing and scaling up large-scale real-time simulation environments becomes simpler and more flexible, as the setups can be quickly adapted.

In this paper, the experiences and results of RTSiL development in RTDS are shown. The paper starts by clearly defining the region of applicability of real-time SiL models. It further addresses and highlights the importance of offline EMT models and why offline EMT models shall still be considered the primary source for studies in grid compliance and stability, especially for plant-level studies. It then proceeds to explain the different methodologies available for black-boxing controls in different real-time simulators. Results are also shown for the implementation of the real-source code of industrial large-scale Type IV WTGs and power plant control. The SiL solutions from Real-Time Digital Simulator (RTDS) with GTSOC are benchmarked in the paper with PSCAD.

The rest of the paper is divided as follows. An overview of different aspects of model validation is presented in Section 2. Section 3 presents the model development, the test cases used, and the code generation process for the different platforms. The benchmarking between the offline and online platforms is shown in Section 4. The main contributions of this paper are summarized as follows:

1. OEM perspective on the applicability and relevance of Real-Time SiL.
2. Definition of currently available methodologies for applying Real-Time SiL.
3. Benchmarking results between offline and online platforms, utilizing PSCAD and RTDS.

2 Overview of Simulation and Testing Strategies

In this section, an overview of simulation and testing strategies online is given. The focus is given to control HiL and SiL. Different types of SiL are further described, and finally, an OEM point of view on the applicability of this strategy is also given.

2.1 Types and Terminologies of Real-Time EMT Simulation Systems

Across different guidelines and standards, it is common to see various terminologies for testing in real-time systems. Different types of hardware and software can be coupled to a real-time simulator, and acronyms such as cHiL (control & protection HiL), mHiL (mechanical HiL), pHiL (power HiL), and more recently SiL (software-in-the-loop) are used to identify what is included in the system [2]. Different standards also deal with such terminologies in different contexts. For testing and certification of WTGs, the recently released "IEC DTS 61400-21-4: Wind turbine components and subsystems" [3] defines testing procedures and classifications for acceptance of different test benches. Moreover, on the WPP level, the upcoming standard "IEC TS 61400-21-5: Configuration, functional specification, and validation of hardware-in-the-loop test bench for wind power plants" [4] is intended to establish consistent specifications for control-hardware-in-the-loop test benches used to test the reliability and compatibility of large wind power plants connecting to AC or DC grids.

Particularly for grid compliance, stability, and interoperability testing purposes of WPPs in connection with large systems, cHiL or SiL are the main types used with real-time simulators. Figure (1) is a high-level representation of the different choices one can make for RTS when it comes to SiL and cHiL. In the first part, the entire system is represented, and CHiL is shown. Additionally, one can connect the power plant controller in real-time systems either in HiL or SiL. The "grid" modeling can comprise different electrical simulated parts as well as other hardware representing control & protection systems from HVDC, STATCOM, BESS, etc.

2.2 Types of SiL

In the context of SiL, the terminology can be applied to both offline (e.g., PSCAD, EMTP, etc.) and real-time systems. The meaning of the concept is that one or more pieces of software are running in the loop with the simulation tool, where each determined time-step the tool calls the software and executes the logic, regardless if offline or real-time. On this topic, guidelines from ENTSO-E for HVDC control interfaces

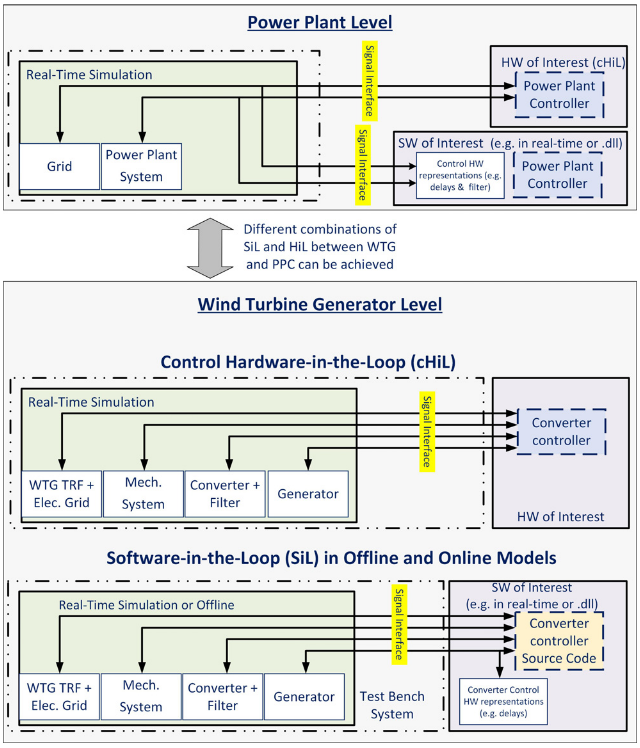

Fig. 1 Different Types of Software-/Hardware-in-the-loop Real-Time Simulation Test Benches. [2].

were presented back in 2020 [5], and some experiences were reported in 2022 [6].

For offline applications, the most common implementation of source code is the use of dynamic libraries. In the context of Windows-based operating systems, .dlls interface source code with simulation software such as PSCAD, EMTP, PowerFactory, etc. Recently approved CIGRE and IEEE JWG 1N° B4.82/IEEE working group on "Guidelines for Use of Real-Code in EMT Models for HVDC, FACTS and Inverter based generators in Power Systems Analysis" defined a standardized interface for dynamic libraries.

A .dll is a collection of small programs that larger programs can load when needed to complete specific tasks. The .dll file contains instructions that help the larger program handle what may not be a core function of the original program. However, due to the limitations of DLLs with Windows^{TM} proprietary software, other solutions may be required for real-time software integration.

In this context, three emerging ways of implementing source code and running it in real-time are currently implemented in the industry. The first is using external hardware (HW), which is not the actual control HW, where an example is the GTSOC by RTDS [7]. The second method is using an external computer with an operating system capable of running .dlls, where an example of that is the use of .dlls in the interval zero program [8]. Finally, another option is to implement real code directly in the RTS hardware. Several sub-options are currently available, ranging from compiling/running code directly from Matlab Simulink, compiling code in dynamic libraries for Linux, using static libraries (.a), etc. [9, 10].

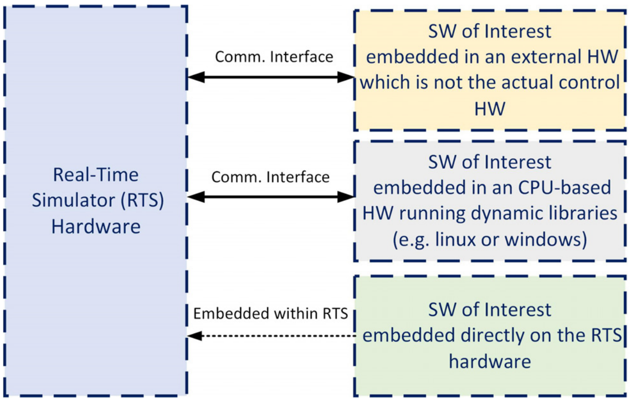

Fig. 2 Types of implementation of Real-Time Software-in-the-Loop.

2.3 Applications of Real-Time SiL

Besides the types and implementation options for Real-Time Software-in-the-Loop (RTSiL), it is also crucial to define its possible applications. When comparing SiL, it is important to define the two sides that SiL comprises. On the one hand, real-time SiL is similar to offline tools such as PSCAD, as it only uses the software. In this paper, the exact same software is utilized in the offline EMT tool PSCAD. On the other hand, unlike offline software tools, it is a solution that can run in real-time and be interfaced with hardware from other equipment. Therefore, real-time SiL can offer new applications to the industry, such as:

- **Interoperability with several devices for stability and grid compliance analysis**: One of the primary areas of application for RTSiL is to assess interoperability between different equipment in a scenario where control interactions are expected to occur. Since HVDC systems are primarily tested in large HiL setups [11], it is envisioned that SiL for wind turbines can be a good complementary solution for carrying out studies on such systems. An example of that is the European Union (EU) Horizon Europe project InterOPERA [12], which is focused on facilitating interoperability of multi-vendor, multi-terminal HVDC grids that link large-scale offshore wind power plants to the DC grid.
- **Evaluation of Protection Relays with Integration of Wind Power Plants and other IBRs:** The protection challenges for systems with high penetration of wind and other inverter-based resources are an emerging topic. Traditionally, protection relays are tested in real-time environments where the protection HWs are connected in the loop with the simulator. In such systems, including RTSiL solutions from WTGs and other IBRs would enrich and ensure more accurate testing and parametrization of such devices.
- **Large-Scale EMT Simulation of Large-Systems:** This use case is emerging in some grids as a potential way to simulate large systems in real-time or quasi-real-time [13]. In this sense, RTSiL can be incorporated into the simulation for more accurate responses from WPPs.
- **Speeding up simulation:** RTSiL can speed up verification in the early studies of a new WPP, contrasting with offline EMT models. Particularly for studies with power plant controllers (PPCs) where long simulation times are necessary (on a scale of tens of seconds), real-time simulation can facilitate testing and debugging.
- **Operational training:** is becoming more and more essential for complex systems with high shares of converters. Certain transmission system operators (TSOs) and plant operators are investing in real-time simulation tools not only for performing studies but also for aiding in the training of operators, often using the same interface of the real control room. In this context, RTSiL of WTGs and PPCs can be incorporated into such real-time simulators and can offer more flexibility while keeping a reduced size footprint.
- **Lifetime Assessment and Continuous Model Validation**: These test benches can enhance grid compliance assessments throughout the plant's lifetime. Simulations can be performed faster, accounting for updates in the software version and parameters. Additionally, these test benches allow for the use of Digital Twin technologies. Offline EMT models, as shown by [14], can accurately replicate real events on WPPs. Real-time simulation and data feeding to actual hardware and high-fidelity EMT models enable systems for real-time model validation, opening avenues for new applications like real-time stability evaluation, prediction of possible failures, and optimization of operation, among many other use cases.
- **Evaluation Plant Controllers and other Energy Management System HW:** Often, the HW of energy management systems (EMS) and other higher-level plant controllers are tested in real-time to ensure proper HW design. In this context, SiL of WTG and PPC controllers can aid the development of such HW as the responses will be more accurate than using generic models.

Nonetheless, with all the applications mentioned below, it is also important to highlight that RTSiL is not a one-to-one match with HiL. Apart from using, in most cases, the actual source control source code, SiL presents differences. When considering HW dependencies such as delays, sampling, and filtering, among others, assumptions are often incorporated in SiL, which may yield minor differences in the response. It is important to, therefore, understand such differences and, most importantly, understand the region of applicability of SiL and HiL.

2.4 Differences between cHiL, RTSiL, and offline tools

As EMT models and real-time simulations are increasingly used in the industry, questions constantly arise about the applicability of these different tools. On one side, there are offline EMT models that do not run in real-time but contain the actual source code in the form of .dlls. On the other side, there are cHiL simulations where the actual hardware (such as control and/or protection) is simulated in the loop, providing high fidelity in terms of converter control and its hardware dependencies, including filtering, delay, etc. Nonetheless, throughout the last decade, the wind industry has developed quite a large experience with offline EMT model validation against full-scale field prototype WTGs [14, 15]. Therefore for most applications, offline models are accurate representations of the actual behavior.

RTSiL shall not be directly compared to any of these two tools. It should be treated as a tool for serving slightly different needs and is comparable to the equivalent offline model, except that it operates in real-time. This may result in minor differences in how the model operates due to real-time constraints. Since offline tools do not run in real-time, RTSiL may be an interesting solution, especially when studying interoperability between a wide range of equipment, including other IBR vendors and protection & control equipment. Furthermore, RTSiL is not the same as a cHiL simulation setup because it does not include the actual control hardware. Setups with cHiL are generally robust and applicable for most applications, but using hardware may present limitations in terms of scalability and flexibility when implementing solutions for larger systems with multiple wind turbines and different vendors. Therefore, a new avenue for RTSiL opens up where new use cases can be explored. However, it is essential to understand the limitations and qualities of a simulation tool/test bench so that the choice can be made accordingly.

3 Model Definitions

This section includes model definitions and detailed descriptions for code generation.

3.1 OEM Defined WTG and PPC models

The EMT models utilized in this paper are developed in PSCAD and RTDS. Both models are identical in terms of electrical equipment, control algorithm, and simulation time-step. To satisfy requirements for higher simulation time-step, the Type IV WTG converter system is developed as voltage source model without a PWM, where the modulation signals are directly connected to controlled voltage sources. In PSCAD, the different control blocks and the PPC are called separately as $.dlls$, while in RTDS, the same control blocks are embedded into GTSOC, which then communicates with RTDS at a specific desired cycle time. The models presented in this paper all run at 20 us of simulation time step and are processed to show RMS and sequence component quantities.

3.2 Code Generation

For generating the code and embedding it in the offline and online platforms, the high-level procedure is shown in Figure (3). The different blocks of source code described are compiled in C++, which are then used to generate the code in a specific format for the desired platform. In the case of offline platforms, the steps are relatively similar, irrespective of the software utilized, where *.dlls* are generated. On the other hand, for the online tool, it will depend on how the online tool manufacturer embeds code into its hardware. In this case, the C++ code gets compiled into a ".a" file using an ARM compiler for static libraries. Sequentially, the ".a" file is used to generate the firmware for the GTSOC, by means of a proprietary builder and a wrapper, defining the interface. The steps described here are for the RTDS platform and may differ from other real-time OEMs.

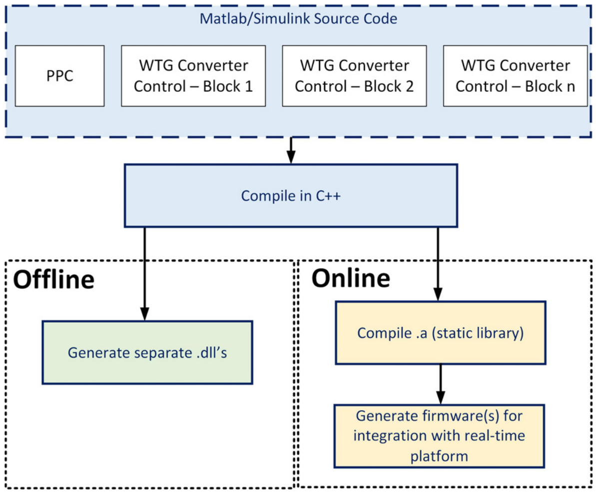

Fig. 3 Code Generation Steps for Offline and Online platforms.

3.3 Model Architecture for Benchmarking

The test system of a Single Machine Infinite Bus (SMIB) is described in Figure (4). The PSCAD model has been validated as shown in [14]. The wind turbine model is connected to a simplified grid represented by a voltage source behind a Thévenin impedance (Z_{th}). The Thévenin impedance used in the simulation can be calculated based on (1). The resistance and reactance between the turbine's high voltage terminals and the fault, as well as the ones between the voltage source and the fault, are calculated based on (2). In these equations, four important values are used: the short circuit ratio (SCR), reactance over resistance ratio (X/R), fault location (F_{loc}), and retained voltage (V_{retain}). F_{loc} is defined by the distance in % of Z_{th} between the turbine HV terminals and the fault point. If $F_{loc} = 0\%$, the fault happens in front of the HV terminals of the turbine transformer, and if $F_{loc} = 100\%$, the fault is located in front of the voltage source.

$$
\begin{aligned}
Z_{th} &= \frac{V_{base}^2}{S_{base} \cdot SCR} \\
X_{th} = \frac{Z_{th}}{\sqrt{\frac{1}{X/R}^2 + 1}} \;&\&\; R_{th} = \frac{X_{th}}{X/R}
\end{aligned}
\tag{1}
$$

$$
\begin{aligned}
R_{wt} = R_{th} \cdot F_{loc} \;,\;\; R_{sc} = R_{th} \cdot (1 - F_{loc}/100) \\
X_{wt} = X_{th} \cdot F_{loc} \;,\;\; X_{sc} = X_{th} \cdot (1 - F_{loc}/100)
\end{aligned}
\tag{2}
$$

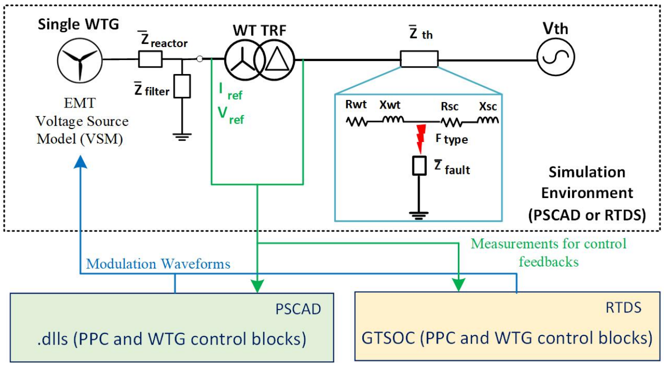

Fig. 4. SMIB system for model benchmarking.

Where S_{base} represents the nominal power of the WTG and V_{base} represents the nominal voltage at the HV terminals of the transformer. To calculate the retained voltage (V_{retain}) at the fault point, a reverse calculation is carried out to determine the correct fault impedance, as per the following equation.

$$Z_{fault} = \frac{Z_{th} \cdot V_{retain} \cdot (1 - F_{loc})}{V_{base} - V_{retain}}$$
$$R_{fault} = \sqrt{\frac{Z_{fault}^2}{1 + X/R^2}}, \quad X_{fault} = \sqrt{Z_{fault}^2 - R_{fault}^2} \tag{3}$$

4 Benchmarking Results

In this section, the benchmarking results between the two solutions are shown. Initially, a time-domain simulation of PPC setpoint changes was performed both in RTDS and PSCAD for initial benchmarking. Next, fault ride-through (FRT) simulations were performed. The results present five quantities in total, namely Positive Sequence Voltage, Active Power, and Reactive Current (i.e. V_p, P_p, and I_{rp}) and Negative Sequence Voltage and Reactive Current (i.e. V_n and I_{rn}).

The FRT simulation test cases are based on the following eight parameters, namely voltage and power reference to the WTG (V_{ref} and P_{ref}), the magnitude of the infinite bus voltage source (V_{sys}), the short circuit ratio (SCR) and X/R ratio of the equivalent grid impedance, the voltage retained (V_{r}) at the fault location, fault location (f_{loc}), and fault type. The first 6 cases simulated are described in Table 1.

Case	V_{ref}	P_{ref}	V_{sys}	SCR	$\frac{X}{R}$	V_r	f_{loc}	Ftype
1	1	1	1	5	7	0.05	0	3ph
2	1	1	1	5	7	0.05	0	2ph
3	1	1	1	2.5	7	0.05	0.7	3ph
4	1	1	1	2.5	7	0.05	0.7	2ph
5	1	1	1	10	7	0.85	0.7	3ph

Table 1. Test cases for Benchmarking Online and Offline

4.1 *Comparison for Setpoint Changes*

Initially, as described above, the complete model with the converter control, additional blocks, and PPC was tested. Figure (5) shows the results for the test where a grid impedance relative to SCR of 5 and X/R of 7 was used. At time $t \approx 12s$ and $t \approx 27s$, the voltage reference is changed from 1 p.u. to 1.05 and then to 0.95 p.u. Sequentially, at $t \approx 42s$ and $t \approx 57s$ the active power reference is changed from 1 p.u. to approximately 0.5 and 0.225 p.u.

4.2 *Results for Fault-Ride Through*

Figures (6) and (7) show the results for Cases 1 and 2, where 3ph and 2ph faults are applied in front of the MV side of the WTG. It is possible to see that the models match very well

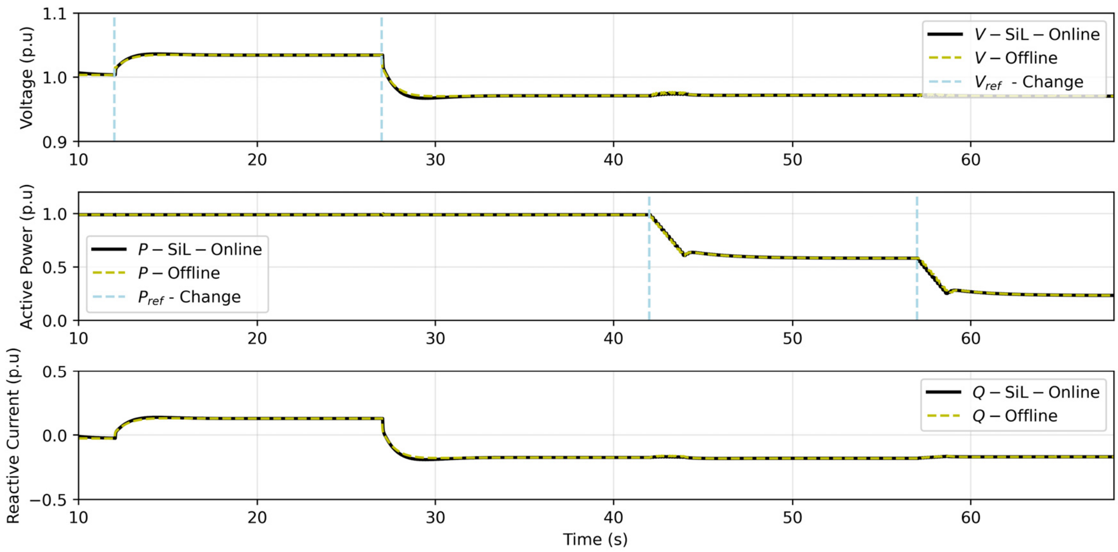

Fig. 5. Comparison of Complete Model with PPC.

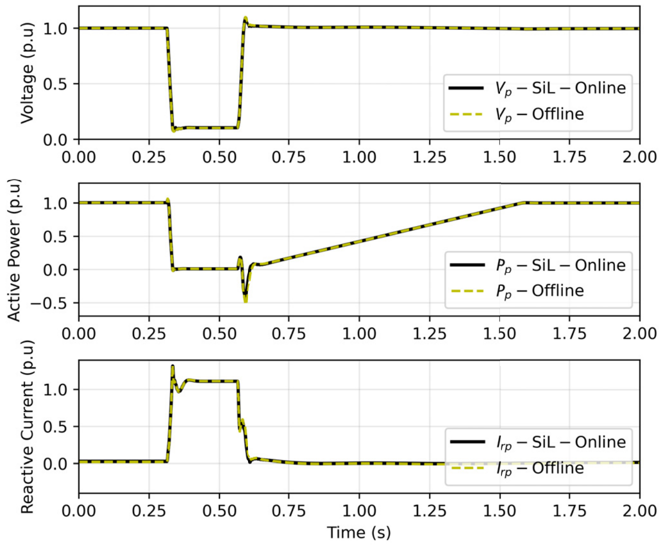

Fig. 6. Case 1 - 3ph Fault in front of the WTG.

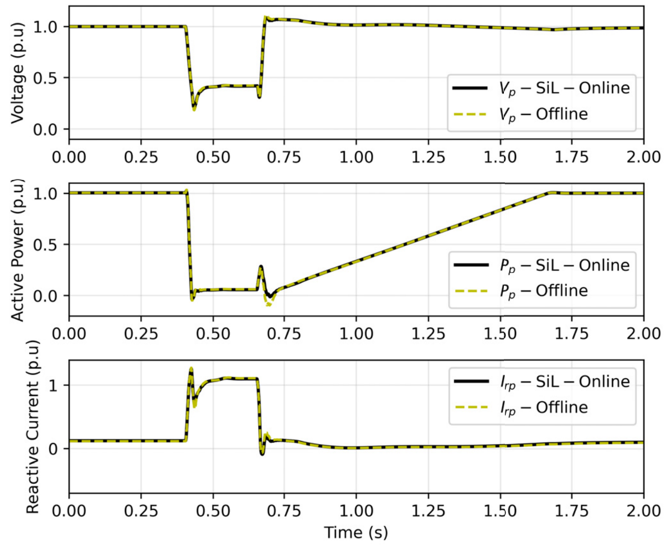

Fig. 8. Case 3 - Distant 3ph Fault at low SCR.

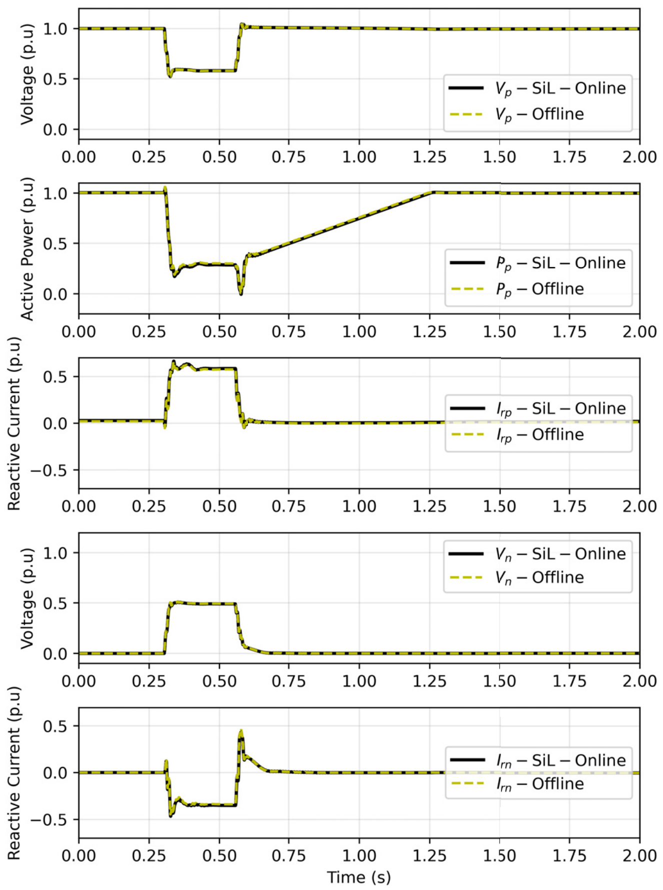

Fig. 7. Case 2 - 2ph Fault in front of the WTG.

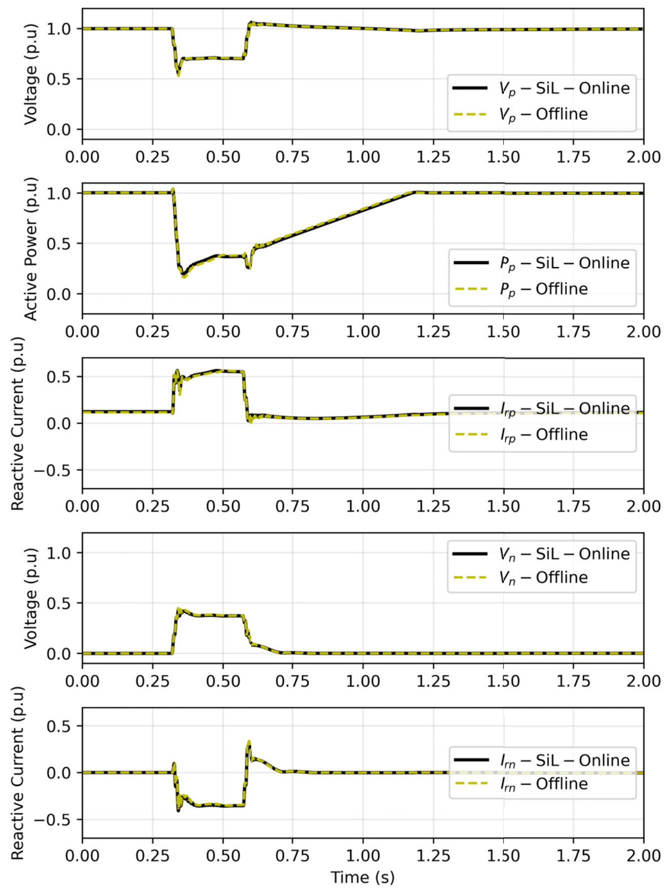

Fig. 9. Case 4 - Distant 2ph Fault at low SCR.

for all the stages. A minor mismatch in the 3ph fault clearing, especially for power, can be observed. Cases 3 and 4, shown in Figures (8) and (9), present results for far away faults applied at low SCR conditions. Again, the results match well between the different tools, with a minor mismatch on active power during fault clearing for Case 3. Finally, Case 5 in Figure (10) shows a longer fault applied for 850 milliseconds, and once more, a good match can be observed.

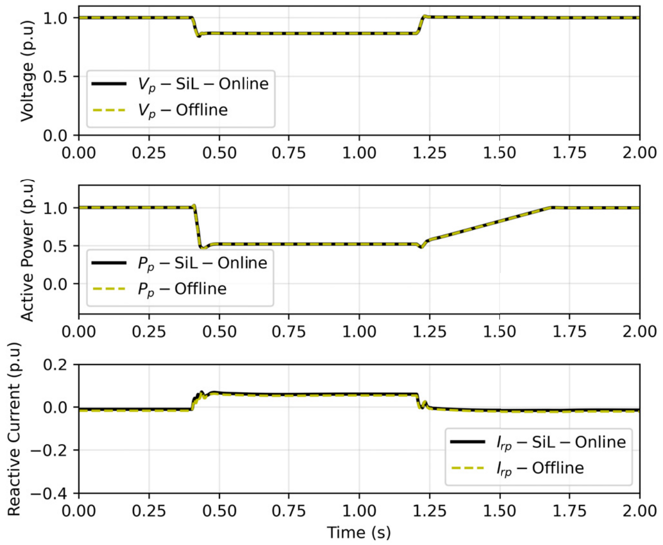

Fig. 10. Case 5 - Distant 3ph Fault for longer time.

5 Conclusion

In conclusion, this paper has provided an overview of Real-Time SiL, illustrating different alternative development approaches of real-time SiL models. The domain of applicability of offline EMT models, real-time SiL, and cHiL has been defined, highlighting the importance and differences between each method. Additionally, the paper has explained the different methodologies available for implementing SiL in different real-time simulators. Finally, results for the implementation of the real-source code of Type IV offshore wind turbines and power plant control in both offline and online platforms have been presented, utilizing PSCAD and the SiL solutions from Real-Time Digital Simulator (RTDS) with GTSOC.

Besides the events presented, many other scenarios were applied, and the conclusion is that the models match well with a wide variation of faults. However, the list of cases presented and tested in this paper is non-exhaustive, and it is important to reinforce that the two tools are not expected to show an exact match in every situation. As discussed extensively in the industry, there are intrinsic differences between running EMT models in offline and online tools and between different tools in general. It is, therefore, important to continue gaining maturity in running RTSiL of WTG and PPC controls in real-time to identify potential differences and limitations.

Moving forward, RTSiL solutions for WTG and PPC, when accurately represented in real-time, can be an useful tool to carry out simulations in real-time for interoperability and other types of study. Nonetheless, this is a new emerging technology, and several points on the overall limitations of the method still need to be thoroughly verified. For future work, the SiL models will be further enhanced with additional control blocks and the limitations will be further explored.

Legal Disclaimer

Figures and values presented in this paper should not be used to judge the performance of Siemens Gamesa Renewable Energy (SGRE) technology as they are solely presented for demonstration purpose. Any opinions or analysis contained in this paper are the opinions of the authors and not necessarily the same as those of SGRE.

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References

[1] F. Mihalič, M. Truntič, and A. Hren, "Hardware-in-the-Loop Simulations: A Historical Overview of Engineering Challenges," *Electronics*, vol. 11, no. 15, 2022. [Online]. Available: https://www.mdpi.com/2079-9292/11/15/2462

[2] G. M. Gomes Guerreiro, F. Martin, T. Dreyer, G. Yang, and B. Andresen, "Advancements on Grid Compliance in Wind Power: Component Subsystem Testing, Software-/Hardware-in-the-Loop, and Digital Twins," *IEEE Access*, vol. 12, pp. 25 949–25 966, 2024.

[3] IEC, "IEC DTS 61400-21 wind energy generation systems - Part 21-4: Wind turbine components and subsystems," 2024.

[4] ——, "IEC TS 61400-21 Wind energy generation systems - Part 21-5: Configuration, functional specification, and validation of hardware-in-the-loop test bench for wind power plants ," Ongoing.

[5] ENTSO-E, "ENTSO-E Standardized control interface for HVDC SIL/HIL conformity tests," Jul,2020.

[6] C. Heising, R. Bartelt, L. Osterkamp, V. Staudt, D. Vahle, V. Yellisetti, P. Wienkamp, R. Dimitrovski, C. Petino-Wagner, and W. Winter, "Contributions to the validation of the ENTSO-E standardized control interface for HVDC SIL/HIL conformity tests within the framework of the demands project," in *21st Wind Solar Integration Workshop (WIW 2022)*, vol. 2022, 2022, pp. 279–285.

[7] RTDS, "GTSOC V2: Multi-Function Auxiliary Simulation Hardware," [Online], Accessed: 2024-09-29.

[8] "Development of a Digital Twin Simulation Wind Turbine and Power Plant Controller Model in RSCAD, Based on Microsoft Windows Dynamic-Link Library Code Integration by Using IntervalZero," shorturl.at/HMX38, accessed: 2022-06-30.

[9] H. T. Nguyen, G. Yang, A. H. Nielsen, and P. H. Jensen, "Hardware- and Software-in-the-Loop Simulation for Parameterizing the Model and Control of Synchronous Condensers," *IEEE Transactions on Sustainable Energy*, vol. 10, no. 3, pp. 1593–1602, 2019.

[10] "Massively Accelerate PSCAD Models, including Manufacturer Real Code Controllers, with HYPERSIM," https://www.opal-rt.com/resource-center/document/?resource=Mkt_0027418, accessed: 2022-06-30.

[11] S. Dennetière, P. Rault, K. Sharifabadi, N. Krajisnik, T. Priebe, and P. Hjalmarsson, "De-Risking the First Multivendor HVDC Project using Real-Time Hardware-in-the-Loop Simulation: Electromagnetic Transient and Real-Time Simulations are Crucial," *IEEE Power and Energy Magazine*, vol. 22, no. 5, pp. 73–86, 2024.

[12] "Successful kick-off of InterOPERA Horizon Europe offshore electricity grids project," Accessed: 2023-04-12.

[13] M. Abdelmalak, H. Hooshyar, E. Farantatos, G. Stefopoulos, R. Kadavil, and M. Benidris, "Real-Time EMT-Phasor Co-Simulation Modeling for Large-Scale Power Grids: Challenges and Solutions," in *2022 IEEE Power Energy Society General Meeting (PESGM)*, 2022, pp. 1–5.

[14] G. M. Gomes Guerreiro, R. Sharma, F. Martin, and G. Yang, "EMT Model Validation of an Offshore Wind Power Plant with SGRE DD Wind Turbines Under Real Power System Events," in *22nd Wind and Solar Integration Workshop (WIW 2023)*, vol. 2023, 2023, pp. 44–49.

[15] P. Ghimire, I. Szczesny, R. Sharma, F. Martin, and P. Mahat, "Use of Full-order Electro-magnetic Transient Models for Grid Compliance Assessment of Wind Turbine: Part 1," *17th Wind Integration Workshop, Stockholm, Sweden*, 2018.