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Fast and real-time EMT simulations for Hardware-in-the-Loop controller performance testing and for on-line transient stability analysis of large-scale low-inertia power systems

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SUMMARY

The increase in Inverter-Based Renewables (IBRs), Flexible AC Transmission System (FACTS), and High Voltage Direct Current (HVDC) systems, coupled with the retirement of synchronous generating plants, is significantly reducing inertia in large-scale power systems. Fast controllers of IBRs should stabilize these systems, but they are highly sensitive to fast transients, harmonics, and system imbalances. Research findings indicate that relying solely on simplified positive-sequence simulations is inadequate for evaluating the transient stability of extensive power grids equipped with a substantial number of IBR controllers. In this context, detailed Electromagnetic Transient (EMT) simulations are becoming essential for the seamless integration of renewable energy sources such as wind and solar. The capability to perform fast simulations in Software-In-The-Loop (SIL) mode with generic or real-code controllers is indeed useful to determine the worst contingencies in the shortest time to develop the equivalent circuit required for real-time Hardware-In-The-Loop (HIL) simulation to test and optimize control performance. Naturally, fast EMT simulation of large-scale power systems will also become essential for online transient stability assessment to aid system operators, planning, and IBR integration analysis.
However, EMT simulation of large-scale power systems with complex power electronic systems is computationally intensive. Moreover, it involves managing a significant amount of data and interfacing HVDC, FACTS, and IBR plant controller models, which are often delivered as black box codes without any interoperability standard, with grid simulation tools. This paper describes solutions to achieve real-time or near-real-time EMT simulation of large-scale power systems with high IBR penetration. The proposed techniques implement fast parallel simulation either based on in-house clusters of high-performance computers or cloud servers.

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The proposed solution further simplifies the design and testing of Wide Area Monitoring, Protection and Control Systems (WAMPAC) through near-real-time fully digital Software-In-The-Loop (SIL) tests with virtual wide area controllers or in real-time with the actual hardware controller equipment typically used in the control room. Most importantly, it will aid system owners and operators in performing online transient stability assessments at much higher speeds and with high-fidelity models, including OEM control emulators.
HIL cloud simulation and high-accuracy EMT digital twins will indeed become a reality and a critical necessity.

KEYWORDS

Real-Time Simulation, Inverter-Based Resources, Wide-Area EMT Simulation Analysis, Hardware-in-the-Loop (HIL), Faster-than-Real-Time Simulation, One-Line Simulation, Software-in-the-Loop (SIL), Transient Stability Assessment (TSA), Digital Twin, Cloud-based Simulation, Wide Areal Monitoring, Protection and Control Systems (WAMPAC)

1. INTRODUCTION

High penetration of inverter-based resources (IBRs), widespread installation of FACTS and HVDC interconnection systems, and the decommissioning of thermal and nuclear plants are significantly reducing inertia in large-scale power systems. The control and protection schemes of the power-electronics based generation act faster than those of conventional generation, and they are more sensitive to harmonics, transients, and system imbalances. It has been shown that simplified positive-sequence RMS simulations alone are insufficient for Transient Stability Assessment (TSA) of large-scale power grids with high penetration of IBRs [1]-[2]. Therefore, Transmission System Operators (TSO), Regional Transmission Organizations (RTO) and reliability coordinators such as North American Electric Reliability Corporation (NERC), as well as professional associations such as CIGRE and IEEE, have begun investigating detailed Electromagnetic Transient (EMT) simulation in that context [3]-[4].

However, detailed EMT simulation of large-scale power grids integrating several HVDC systems and IBRs is very computationally intense. Typically, scenarios with large disturbances with timeframes of 20 to 30 second need to be simulated and hundreds of contingencies must be evaluated to assess the grid stability properly, optimize controller settings and to find the worst cases. Such analysis could take several hours or days depending on system size, number of contingencies and simulation tool efficiency. Also, in the context of real-time HIL testing with controller replicas it is very important to identify the worst-case scenarios and optimized controller settings firsthand because HIL tests with physical controllers are time consuming and expensive.

Furthermore, plant controllers provided by Original Equipment Manufacturers (OEMs), are in the form of black-box pre-compiled dynamic-link libraries (DLL) for Windows or shared objects (.os) for Linux, which are often implemented for specific simulation tools, without any interoperability standard or unified interface. Interfacing black-box models with real-time simulators or other simulation tools is then complex and time consuming unless they have been implemented and tested by OEM for specific simulators or they are implemented following a standard interface facilitating the interoperability between simulation tools.

These detailed models are also particularly demanding on computation resources, making stability assessment of large-scale integration of IBRs and HVDC system very long to execute unless very large numbers of processors are used. The implementation of some black-box controllers is often not optimized or uses unnecessary detailed converter models requiring very small time steps. This slows down the complete simulation and prevents to reach real-time speed. Collaboration with OEMs are therefore often necessary to optimize the controller code implementation to reach real-time.

This paper describes solutions to achieve faster than or close to real-time simulation for grids with several thousands of buses and hundreds of HVDC converters, FACTS and IBRs with a 50-microsecond time-step to accelerate optimisation studies and reach real-time speed for HIL testing using the same model and tool chain but with physical controller replica. Solutions involve using parallel real-time simulator technology developed over the last 25 years on clusters of high-performance computers (HPCs). The detailed OEM controller models can be executed in parallel through a real-time co-simulation platform.

Alternatively, it is possible to perform the same type of fast EMT simulation for on-line stability analysis using cloud computing. Promising results of Wide-Area Monitoring, Protection and Control system (WAMPAC) design and tests in SIL and HIL using cloud-based simulation are demonstrated in this paper. In the use case, a modified IEEE 118-bus network with inverter-based generation simulated on the cloud communicates with a wide-area control algorithm implemented on an industrial controller in the lab to demonstrate real-time HIL simulation on the cloud. The proposed method can be scaled for very large grids using more computing resources as parallel EMT simulation implemented in HYPERSIM has been optimized over the last three decades. In fact, the largest HYPERSIM simulator, installed at China EPRI, uses more than 300 to 600 high-end processors to simulate the entire Chinese AC-DC transmission system at 50 µs time step [5].

2. THE NEED FOR FAST AND REAL-TIME EMT SIMULATION TO SUPPORT IBR INTEGRATION

Shifting dynamics from mostly electromechanical interactions of high-inertia machines to fast dynamics with HVDC, FACT, IBR controllers and their protection systems have increased the complexity of control and protection setting optimisation, TSA as well as real-time HIL testing. IBR and several HVDC and FACTS models in modern power grids are now provided as precompiled black-box models by OEMs, which complicates control optimisation and finding the root causes of control instabilities to implement countermeasures. This complexity increases when control instability involves power electronic systems supplied by several vendors who cannot share their respective controller details to protect their intellectual properties (IP).

It is noted that with increasing peneration of power electronics to the grid, several control and protection functions have time-constants and reaction time much faster than a few milliseconds, which is out-of-range of simplified positive-sequence RMS models. Three-phase RMS dynamic simulation capability overcomes some of the limitations of positive-sequence simulation tools. However, power electronic controls and protection functions may react to harmonic and fast transients only visible with EMT simulation. Consequently, the dynamic performance and TSA of power grids integrating several IBRs cannot be evaluated using phasor-domain simulations only. A simulation event in [6] illustrates that, contrary to the EMT model, the RMS model does not predict sustained commutation failure and subsequent disconnection of the HVDC link. Publication [3] recommends EMT models to be required for all newly connecting IBRs and in [4] it is clear that an increasing number of utilities are adopting EMT simulation for wide-area stability analysis, control design and testing.

In fact, numerous utilities planning and operating complex grids integrating several HVDC and FACTS are equipped with large-scale EMT HIL simulators since the last 25 years to analyse the interactions between power electronic controllers and protections. Such EMT simulation work will be even more critical with the addition of inverter-based renewable resources and HIL testing with control replicas should become a common industry practice.

However, when the number of IBRs become too large, the use of control replica for all power electronic systems may become impraticable or too expensise. In such case, critical power electronic systems, or the new HVDC system and IBR being integrated in the grid, can be simulated with control replica in HIL mode together with the remaining system simulated using previously validated generic controller models or black-box controller emulators. In some cases, utilities may decide to perform control and protection system parameter optimisation and performance testing using only black-box controller and protection system emulators or a mix of black-box emulators and validated generic models. This is what is called Software-in-the-Loop (SIL) fully numerical simulation as explained in the next figure.

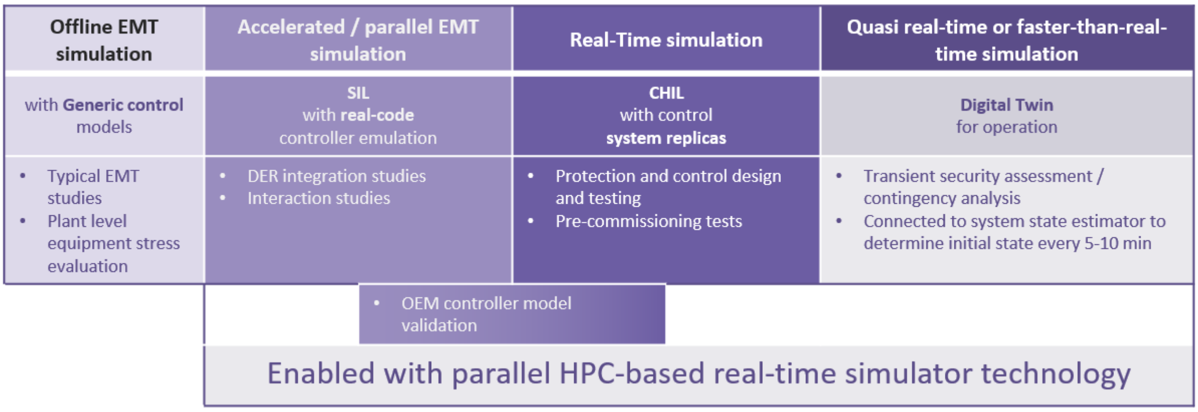

Figure 1. Study-simulation matrix with real-time simulator technology

Black-box controllers are normally validated using replica but with a small grid equivalent. In most cases, such tests are performed by OEM during factory acceptance tests using a rather small real-time simulator. However, the need to perform EMT simulation of large-scale power systems, normally performed by TSO, calls for fast and powerful computing capabilities, either close to real-time or HIL simulation mode, to quickly assess the system stability as well as controller and protection system performance under different operation conditions and multiple contingencies [7]. Fast fully numerical simulation can be executed in batch mode on cloud or in-house computer servers. Large series of tests to be performed with replica and HIL simulator can also be automated.

But in all cases, the simulation turnaround time should be fast enough to enable effective interaction with simulation specialists. They may need to intervene to modify the test sequence, validate results, or analyze abnormal phenomena detected in previous tests or while the simulation is running.

3. CLOSE TO REAL-TIME AND REAL-TIME SIMULATION

Real-time simulation, due to its strict time constraint, leads to the development of advanced fixed time-step solvers and computational techniques to maintain numerical stability and accuracy [8]-[9]. Usually, large systems are decoupled into smaller portions for parallel computation taking advantage of the natural propagation delay of the long transmission lines. The decoupling helps to reduce the size of individual sub-system matrices which accelerate computation as compared to solving a single large matrix for the complete systems. The HYPERSIM simulator [10] enables automatic distribution of the model across multiple processors and seamless management of inter-processor communication. This feature streamlines the simulation process, ensuring efficient utilization of resources and facilitating smooth cooperation between processors.

By utilizing compensation and interpolation methods to accurately simulate fast switching events in power electronic devices within a fixed time step, the simulation accuracy can be maintained even with a relatively higher time step as compared to very detailed power converter models.

Leveraging these fast simulation techniques and parallel processing, it becomes feasible to accelerate Electromagnetic Transients (EMT) simulations of large-scale power systems, achieving simulation speeds close to or faster than real-time, or in real-time when needed for HIL tests.

The next figure demonstrates the capability of HYPERSIM to simulate the 1666-buss Hydro-Québec system including all HVDC systems and SVCs with less than 60 processors at 40 µs in real-time [11]-[12]. One can see the very high efficiency of parallel processing for this case as the simulation time for a 15-second event decreases from 2565 s with one CPU to 15 s with 56 CPUs as compared to the theoretical value of 46 s (the time for one CPU divided by the number of CPU used in the simulation). The efficiency is improved to be more than 300% due to an efficient management of the processor cache memory and the use of more powerful processors and LINUX operating systems for the real-time benchmark.

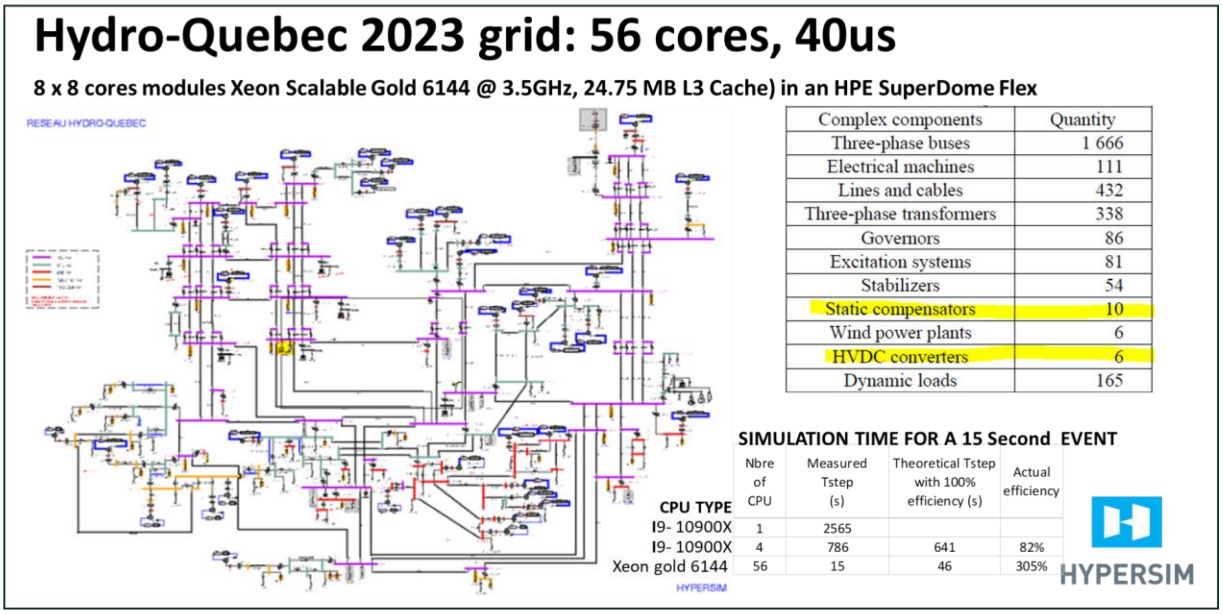

Figure 2. HIL benchmark of Hydro-Québec 1666-bus system

It is important to highlight that the EMT simulation acceleration techniques mentioned above, implemented in HYPERSIM, are now being adopted by most offline simulation tools, including EMTP and PSCAD. This widespread implementation benefits all stakeholders involved in power system analysis and simulation.

Based on these real-time simulation techniques, two solutions 1) based on simulator clusters and 2) on cloud servers to perform on-line transient stability analysis of large-scale low-inertia power systems and Hardware-in-the-Loop controller performance testing are presented in the next sections.

4. LARGE-SCALE EMT SIMULATION OF IBRS WITH OEM CONTROLLERS

This section presents a solution involving HYPERSIM parallel simulation technology to provide real-time or faster-than-real-time simulation for large-scale networks with many HVDC systems and IBRs. The approach utilizes clusters of high-performance computers and an optimized co-simulation platform designed to achieve the highest performance possible. The same technology is being implemented on cloud computing to eliminate the need to maintain in-house servers and to increase computational power as needed accessibility to many users.

Typical IBR plant model structure

Figure 3 shows a typical IBR model architecture with OEM controller models in HYPERSIM as an example. The model represents an inverter-based wind turbine generator. The model consists of the electrical circuit and the controllers. Local and point-of-common-coupling measurements are sampled and sent to the controllers. The plant controller determines the power setpoints and the converter controller implements the primary control functions. The converter duty cycles, or gating pulses are fed back to the electric circuit depending on whether an average or detailed converter model is selected. A switching function [13] converter model is recommended to be used since it presents a good compromise between the real-time performance of an average model and the accuracy of using detailed switches.

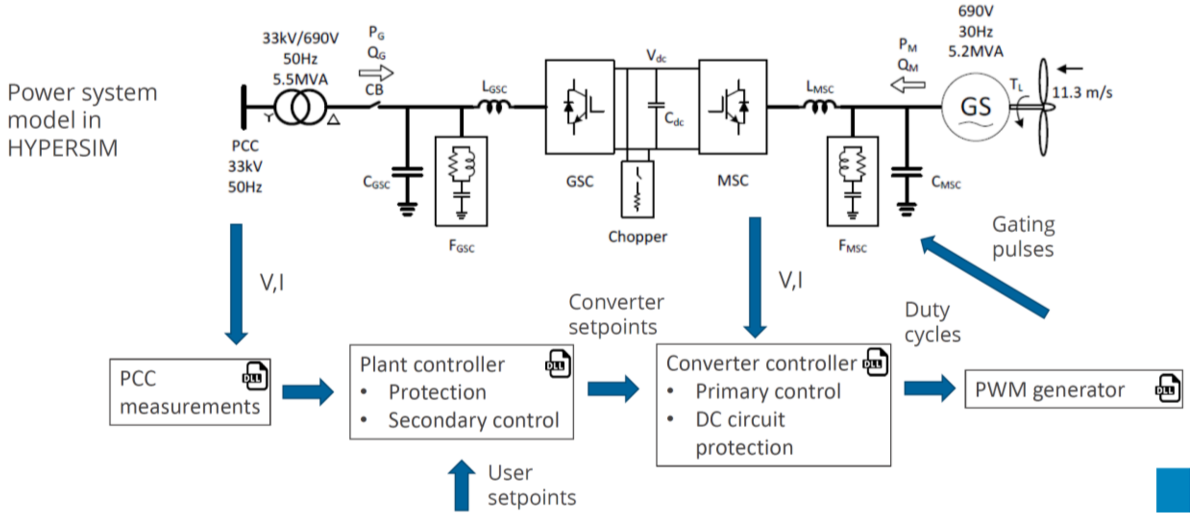

Figure 3. Typical IBR model architecture with OEM controller models

Interfacing Manufacturer Controller Code with HYPERSIM

In some rare cases, the OEM controllers are simple functions and can be replaced automatically directly by HYPERSIM components to improve simulation speed and documentation. However, in most cases, the controller is a pre-compiled black-box code. The controller code communicates with the electric system model simulated in HYPERSIM at its own time step and a co-simulation scheme orchestrates the data transmission and the execution of the controller and the model.

Due to a lack of standardized interface, it requires a significant effort or about 10 engineer-days to adapt the controller code using a semi-automatic translation tool and execute it with HYPERSIM or and other real-time or off-line simulation tools. In this section, two methods are proposed to automatically import the controller code to work with HYPERSIM. Both methods allow to execute as many as hundreds of controllers on a single standard simulator.

Method 1: Automatic import of OEM controller code from PSCAD to HYPERSIM

In the case where the OEM controller code is pre-compiled for PSCAD as a dynamic link library (DLL), an automatic import function is developed to add an interface wrapper around the DLL. The generated HYPERSIM controller block has the same I/Os and parameters as in PSCAD. An automatic open loop validation is performed using the recorded signals during the import process.

Method 2: Automatic import of OEM controller code – CIGRE standards/industry guidelines

If the OEM controller code is following the standards/industry guidelines (IEEE TASS-TF [14] and CIGRE WG B4.82 [15]), a dedicated interface is provided to easily integrate OEM controller codes in HYPERSIM. The controller codes can be executed in close to real-time under Windows operating system and distributed on parallel processors on the same or on a separate simulator.

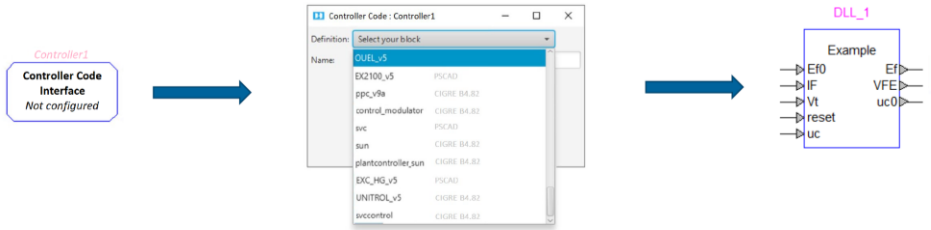

Figure 4. Automatic import of OEM controller code following standards

The same method can be applied to interface the PSCAD DLL with HYPERSIM for real-time HIL simulation when other HVDC or IBR controllers are simulated with replica. In such a case a special tool is under development to execute Windows DLLs on top of OPAL-RT real-time LINUX environment as required HIL tests.

Hardware configuration

Once the OEM controller codes are imported, the complete simulation is performed by distributing the simulation process on parallel processors. Figure 5 presents the hardware setup of the proposed solution. The electrical circuit of each IBR plant is run on different cores of an HYPERSIM simulator while the OEM controllers are run in parallel on a cluster of high-performance simulators. Fast communication links are deployed between the simulators. Automatic task mapping optimizes the assignment of different processes to achieve the fastest simulation speed. Such co-simulation architecture is very scalable since processors can be added as needed to maintain the simulation speed close to real-time as the number of IBR plants increases.

Case Study and results for a 4000-bus EMT Benchmark

A 4000-bus EMT network based on the synthetic Australian electricity network [16] is used as a benchmark. The number of components is listed in Table 1. The computation time for a 30-second simulation is 90 s wall clock time on a 500-core Windows server (1 High Performance 128-core Windows Computer and 22 High-Performance 4-GHz 18-core Computers). About 100 cores are used for the 4000-bus system while 300 cores are used for the controller codes. The simulation time step used in the simulation is 50 µs for the main grid and 10 µs or 16.66666667 µs for manufacturer controller codes. While aiming for real time in the near future, this milestone of three times slower than real-time simulation speed already makes it feasible to perform a large number of contingency studies in one-hour time, which greatly accelerates the stability and control performance analysis of large-scale power systems. A simulation time of 90s for a 30s phenomenon would also enable to implement on-line EMT TSA tools for grid operator requiring simulation results at each 15-minute interval. Near real-time simulation can also expedite the development and validation of a reduced model for executing EMT simulations in real-time with replicas and/or DLLs. This can be particularly useful when there are limitations in the real-time simulator facility and fewer processors are available.

It must be noted that real-time could normally be achieved but the simulation speed was limited by several black-box controllers which take too much time to simulate. Collaboration with OEMs would be required to optimize the implementation of the code for real-time execution. Critical cases can then be run in HIL using control replicas.

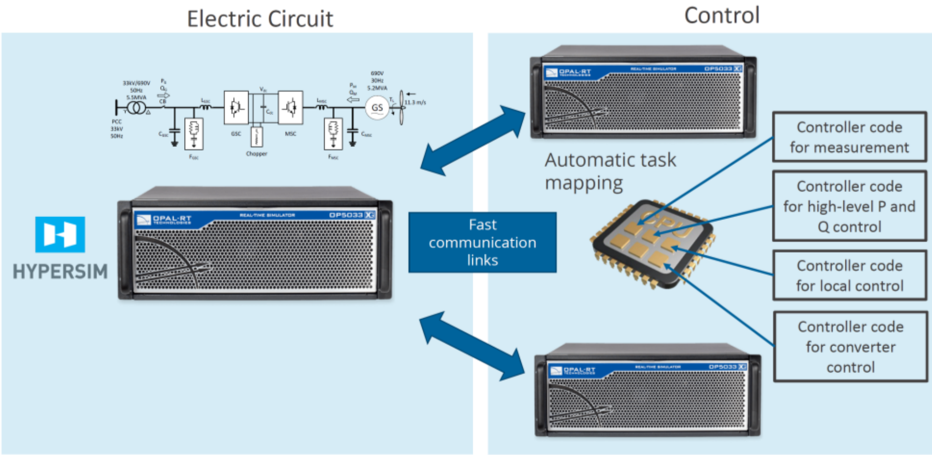

Figure 5. System configuration

Table 1. Summary of 4000-bus EMT model benchmark.

Hardware setup	Component	Approximate number of components	Component	Approximate number of components
	Buses (3-phase)	4000	IBR plants (Solar, Wind)	150
	Lines, loads, switched shunt reactors	6700	OEM Controllers (precompiled DLLs)	300
	Transformers and synchronous machines	2000	FACTS and HVDC converters	70
	Protection relay models	100		

5. CLOUD-BASED EMT SIMULATION FOR WIDE AREA CONTROL HIL TESTS

This section highlights HYPERSIM's capability to harness cloud infrastructure for conducting Electromagnetic Transients (EMT) simulations of large-scale power systems, and to execute Hardware-in-the-Loop (HIL) tests for control schemes implemented on computer hardware identical to what's used in actual control rooms. Preliminary tests suggest that this method yields satisfactory results despite the C37.118 Ethernet communication between the cloud and the controller under test being slower than actual real-life communication architectures that employ dedicated channels. This is because the C37.118 protocol uses time-stamped data. This feature greatly enhances flexibility for testing wide-area control and Special Protection Systems (SPS). HYPERSIM On Demand [10] is a solution that enables parallel execution of simulation tests on multiple cloud simulators based on Microsoft Azure. The implementation on Amazone AWS cloud is under development.

The computation resource is scalable depending on the need. Since the cloud server is based on Windows, the system is not optimized for hard-real-time computation. A LINUX version is under implementation to increase computational performance. However, for hardware controllers or virtual controllers which do not feature a fast response, TCP/IP based communication protocols such as IEEE C37.118 protocol, Modbus, DNP3, etc. can be used to interface the grid simulation on the cloud. With the communication latency stays well within pre-defined boundaries, the proposed solution facilitates planning and stability studies to design and test wide area special protection and control system for large power systems and makes it possible to interface external hardware and software to perform HIL tests.

Hardware configuration for a cloud-based EMT simulation

Figure 6 shows the hardware setup of a Cloud – HIL test proof-of-concept. A modified IEEE-118 bus network with IBR generation plants is simulated on the Cloud server. Virtual phasor measurement units (PMUs) are placed in the network to report phasor measurements to a Wide Area Control (WAC) system through the IEEE C37.118 protocol. The WAC algorithm, which executes in RT-LAB in real-time on a local industrial SEL 3365 computer, monitors the states in the system and acts when stability concerns are raised.

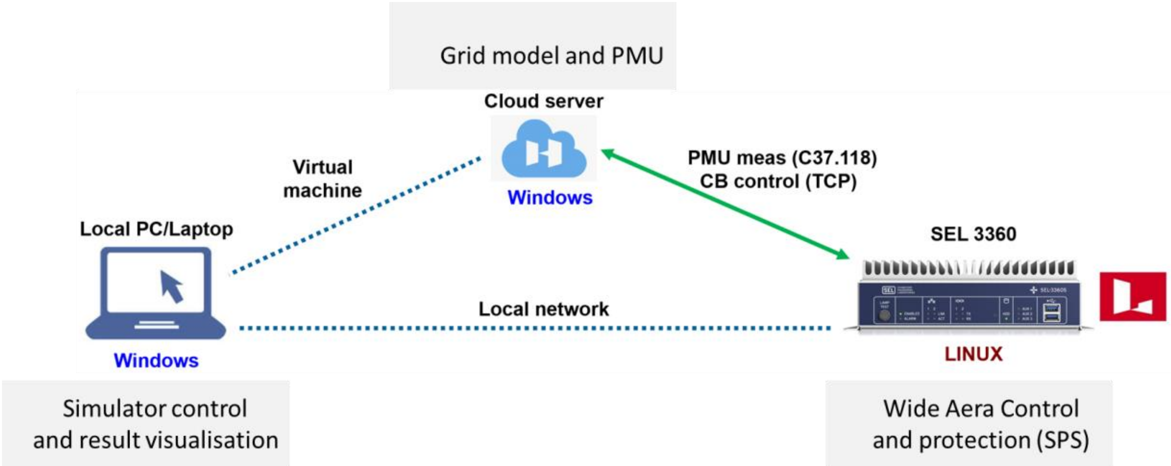

Figure 6. Hardware configuration for a cloud based EMT simulation.

IEEE 118-bus benchmark network

Figure 7 shows a simplified single-line diagram of the modified IEEE 118-bus transmission network tested in this section. Four IBRs have been included to the network, two type 3 wind turbine generation systems (WTGS1 at bus 32 and WTGS2 at bus 76) and two photovoltaic generation systems (PVGS1 at bus 107 and PVGS2 at bus 40). Two switched capacitor banks are also added to the network at buses close to the IBRs (Bank 1 at bus 27 and Bank 2 at bus 42) intended to support the voltage regulation at the Point of Connection (PoC) of each plant. The WAC algorithm determines the undervoltage event and sends a command signal back to the HYPERSIM model to activate the corresponding capacitor bank via Modbus TCP signals.

Simulation results

To analyse the dynamic response and the interaction between the generation units, the Wide Area Control (WAC) and the network shown in Figure 7 during a perturbation, two scenarios are tested, see Table 2.

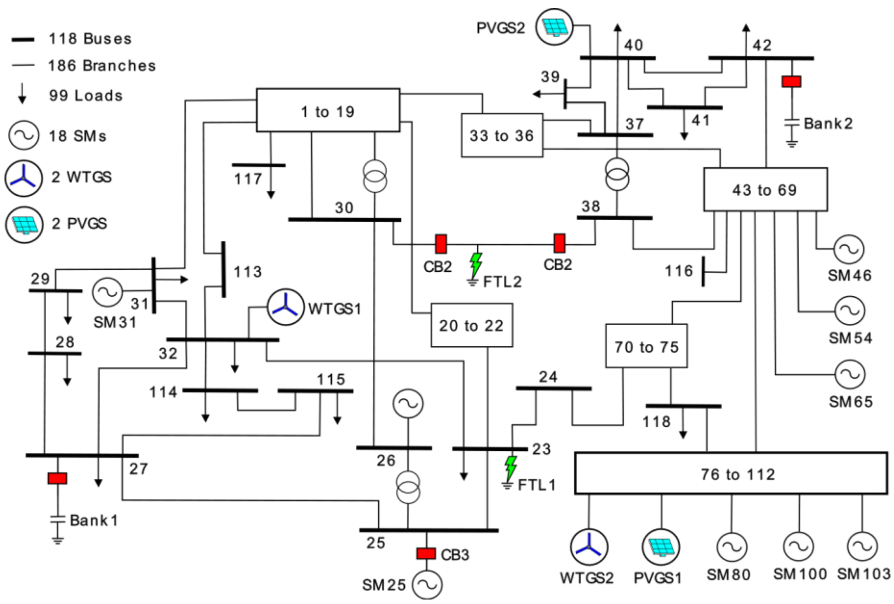

Figure 7. IEEE-118 network configuration

Table 2. Summary of the scenarios tested on the IEEE118 network.

Scenario	Description
1	A 3LG fault occurs at bus 23 and the protection fails to pick up.
2	A 3LG fault occurs at the end of the transmission line between bus 30 and bus 38 and is cleared after 0.3 s by disconnecting the line.

Figure 8 shows the RMS voltage measured at the PoC of WTGS1 and the control signal from the controller observed during the tests described in Table 2. In scenario 1, the fault creates an undervoltage at the POC of WTGS1 (bus 32) of about 0.62 pu, see Figure 8. To compensate for the voltage drop, the WAC controller sends the switch-on signal 0.583 s after the fault occurs and Bank 1 is momentarily activated at bus 27. Then, the voltage is compensated up to about 0.75 pu. After the fault is removed, the voltage is recovered to its nominal value and Bank 1 is disconnected. In scenario 2, the fault is cleared almost immediately after its occurrence; thus, the voltage at the POC of the IBRs does not drop significantly; therefore, the capacitor banks are not switched on.

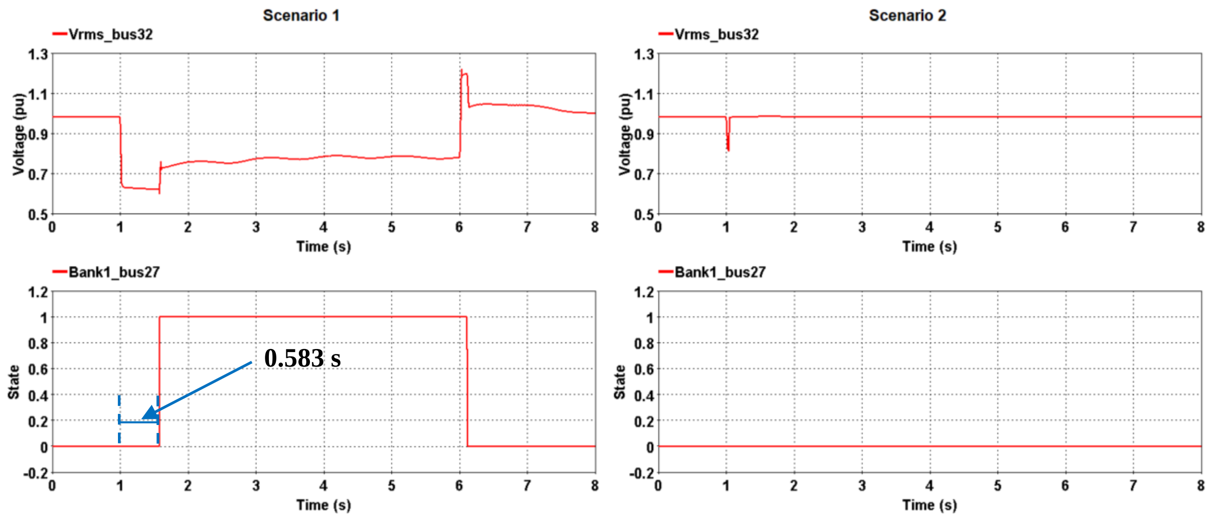

Figure 8. RMS voltage at the POC of WTGS1 and operation of Bank 1 for S1 and S2.

Computational performance results

To evaluate the computational performance of the HYPERSIM model on the cloud, the execution time of the simulation is monitored for one minute. Table 3 shows the execution time results obtained for each of the seven cores used during the simulation. Results show that the average execution time obtained when the simulation is running on the cloud is less than the simulation time step 50 µs, consequently the signal transmitted using C37.118 will be time stamped as per the standard using the 50 µs clock of the cloud. This is acceptable for controller HIL tests even if the ethernet communication speed between the cloud and the WAC is slower than actual communication systems considering that no dedicated communication channels are used for this test.

Table 3. Execution time of the HYPERSIM simulation.

Core ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Average (µs)	15.8	37.1	39.2	14.7	18.0	25.0	18.9

The same principle can be applied for very large grids with hundreds of IBRs and distributed Wide Area Control (WAC). Such technique offers possibilities to test the effect of integrating a very large quantity of IBRs leading to a very low inertia grid. It is worthwhile to note that the WAC software can be also implemented on the cloud to perform a fully digital SIL simulation before making HIL test with actual controller.

6. CONCLUSIONS

In conclusion, the integration of existing HYPERSIM real-time simulation technologies and the newly devised automated method for interfacing genuine OEM controller codes, paves the way for virtually real-time or actual real-time simulation of expansive power system models. These include those with low inertia due to large quantities of HVDC, FACTS, and considerable penetration of IBRs.

We've detailed two techniques in this paper that expedite EMT simulation:

1) **Utilization of proprietary clusters of high-performance standard computers.** This approach has proven effective, demonstrating the capability to simulate the 4000-bus Australian system at a speed thrice slower than real-time using 500 processors. It can also simulate the 1666-bus Hydro-Québec grid in real-time with less than 60 processors including all HVDC and SVC systems.
2) **Utilization of commercial cloud servers.** This approach has demonstrated its potential by facilitating Wide Area Control tests in HIL mode using actual controller hardware. The cloud-based HIL methodology uncovers a wealth of opportunities, including the ability to scale up simulation resources as required, and accommodating numerous specialists and departments that need to perform multiple studies simultaneously.

The benefits of this elevated simulation speed are manifold:

1) It enables the identification of critical scenarios for further real-time Hardware-in-the-Loop (HIL) analysis.
2) It expedites EMT planning and IBR connection studies. Near-real-time parallel simulations facilitate quicker assessment and optimization of power system plants, allowing more contingencies to be analyzed in a shorter time.

3) It empowers system operators with real-time EMT TSA tools or digital twins. Near-real-time simulations, performed at each 15-min interval, can deliver invaluable insights and tools for system operators to effectively manage and control power grids in real-world situations.

4) It reduces simulation turnaround times, assisting specialists in analyzing critical cases detected in the field or in simulation. This aids in identifying root causes of system instability and implementing mitigation strategies.

In essence, these breakthroughs in near to real-time and real-time simulation technology are instrumental in refining power system operation, control, and planning, which in turn enhances the stability and reliability of power grids.

It's noteworthy that these EMT simulation acceleration techniques, now incorporated in HYPERSIM, are being embraced by most offline simulation tools, including EMTP and PSCAD. This broad acceptance benefits all stakeholders engaged in power system analysis and simulation.

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