New Hydro-Québec Real-Time Simulation Interface for HVDC Commissioning Studies

François Guay, Pierre-André Chiasson, Nicolas Verville, Sébastien Tremblay, Per Askvid

***Abstract* — HVDC links are now used in many power systems. These links may be monopolar or bipolar and back-to-back or multi-terminal. The control systems of HVDC converters are now fully digital and all communications between internal systems are also digital and integrated into most manufacturers' equipment. Digital technology is used in HVDC control systems for many functions such as control, protection and measurement.**

This paper describes the means by which hardware and software for "digital link" communication are implemented into real-time power system simulation platforms. It presents the setup and performance of a real-time hardware-in-the-loop (HIL) simulator replicating Hydro-Québec's Madawaska back-to-back HVDC line-commutated converter (LCC).

The paper focuses on the advantages of using a replica in HVDC projects. Such advantages include support during commissioning, protection testing, control optimization, and meeting the challenges faced between factory system testing (FST) and site acceptance testing (SAT). Implementation of an off-line simulation model is also shown and the advantages of having one discussed.

***Keywords*: Real-time simulation, Electromagnetic transient studies, HVDC controller replica, Factory system test (FST), Control and protection system, Hardware-in-the-loop (HIL).**

I. Introduction

In order to facilitate the installation, maintenance and operation of control and protection systems in HVDC and FACTS devices, more and more manufacturers, transmission system operators and HVDC system owners purchase replicas of real control systems and protection cubicles. They are usually installed in dedicated simulation laboratories.

HVDC controls are very complex and require thorough validation before installation in the field and integration into an existing AC grid. One of the objectives is to guarantee that the control meets the functional requirements of the power utility. Hydro-Québec has been developing and using a digital real-time simulator for many years in order to validate, certify and study this kind of equipment are presented in [5], [6] and [7]. Conventional HVDC control system testing with a real-time simulator requires a huge number of analog-to-digital converters or logical signals in order to interface the control system to the simulator.

A new way to implement this interface is to leverage the existing communication network of modern control systems and use a serial interface called a "digital link" as explained in [4]. Given its importance and value in the simulator environment, this new serial interface, running under the PCI Express (Peripheral Component Interconnect Express, PCIe) communication protocol, has been integrated into Hydro-Québec's real-time digital simulator. This paper presents the work conducted at IREQ, Hydro-Québec's research institute, to integrate adaptations of this new technology into to the real-time simulator. In the near future, the digital link approach could be attractive for integrating FACTS controllers, like static VAR compensator (SVCs) or voltage source converter (VSC) control systems, since it simplifies connection with a digital real-time simulator, an otherwise arduous task due to the large number of signals required by the external equipment.

The paper explains and justifies in Section II the new digital link approach to interfacing a real-time simulator for real-time commissioning studies. Section III overviews the Madawaska HVDC upgrade project, discusses why a replica is needed and useful for the project as discussed in [1]-[3], and presents aspects of the real-time modeling required. Section IV presents an off-line HVDC model based on the same software as the replica and very useful for studies with no replica. The real-time control system replicas and off-line simulation model are compared to show similarities in their behavior as discussed in [3]. Section V presents the Madawaska commissioning studies using real-time simulation and gives example factory system tests and their results. Section VI presents concluding remarks.

II. New approach to interfacing a Real-Time Simulator

A. *Hydro-Québec power system simulators*

Power system simulators are strategic tools used by Hydro-Québec engineers and researchers for planning and operating the Hydro-Québec transmission system, integrating renewable energy like wind power plants described in [8] and [10], testing new concepts and training technical staff. Expertise in power system simulation at IREQ, has grown mainly through the development and operation of real-time simulation technology (Hypersim) and modern off-line simulation tools for studying electromagnetic transients and power electronics

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[9] at its facilities (EMTP-RV software and SPS toolbox).

The IREQ laboratory now has many controller replica for SVCs, series compensators (SC), synchronous condensers. For HVDC systems:

- Multi-terminal Québec – New England (2000 MW), refurbishment in 2015-2016
- Chateauguay (1000 MW), refurbishment in 2009
- Outaouais (1250 MW) commissioning in 2008

The Hypersim simulator [5] includes many tools, such as a graphical user interface (GUI), an automatic task mapper/code generator, a waveform analysis display tool (ScopeView) and an automatic batch testing tool (TestView) with a database. Real-time simulations run on an SGI parallel computer. The platform is based on Intel Xeon processors and SGI's NUMAlink processor interconnect.

Hypersim is a real-time/off-line EMT simulator rich in interesting features. SGI supercomputers are required for real-time simulations but off-line simulations can run on personal computers. Hypersim uses the classic nodal approach with automatic partitioning of power system equations. The computational burden is automatically mapped to available processor cores. A very useful feature exploited in this study is external code support, e.g., dynamic or static libraries as well as external C code.

The IREQ simulator laboratory now has many SGI architectures based on the UV100 and UV2000 platforms. Hydro-Québec is constantly improving the simulation capacity of the laboratory. A new generation of SGI Altix UV300s with faster Intel Xeon processors and the new NUMAlink is now available and integrated into the simulator platform for future replica and power system studies.

B. Conventional I/O

Since the early 2000's, standard PCI/PCIe cards with digital signal processing (DSP) and digital converters have been installed in the real-time platform to provide external analog and digital input-output (I/O). This allows the simulator to be connected to external control devices, as shown in Fig. 1.

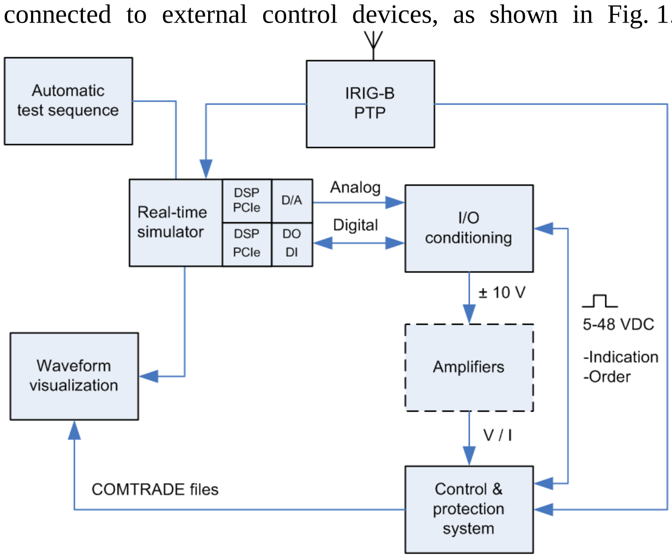

Fig. 1 – Interface with conventional I/O

Amplifiers may be required to connect the simulator to the equipment, depending on the required signal conditioning.

C. Digital link

In 2012, Hydro-Québec started the refurbishment of the Multi-terminal between Québec and New England, commissioned in 1986. Given this coming project, it had been decided to have a full replica of the control system and protection with local control and master control. Thus, the engineers started working on the possibility of using a new communication scheme between the real-time platform and the Multi-Terminal control system.

Regarding this, the option to communicate using the PCIe technology was evaluated. This was already available in control system. The signals don't need to be converted and after re-converted for the control system. To integrate this new communications into the real-time simulator, all analog and digital components (digital converters, cables and I/O conditioning) were replaced by a digital link using PCIe interface communication architecture, as shown in Fig. 2.

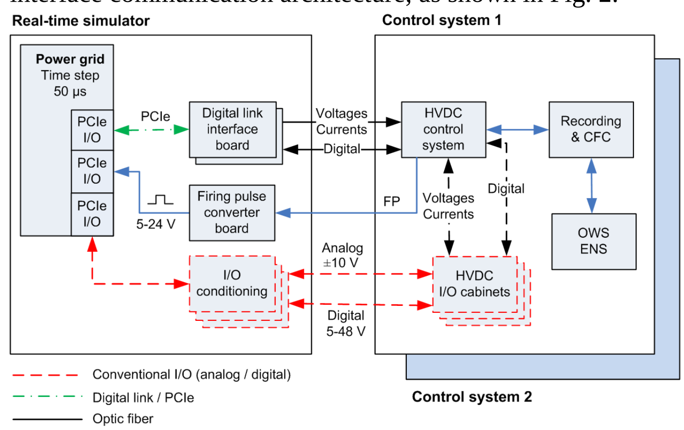

Fig. 2 –HVDC control system interface

To connect with the real-time simulator, a digital link interface board is used to emulate the I/O hardware layers and transfer all values to the real control system. The board has many DSP capability, a PCIe core interface (Gen2 x1) for the real-time simulator interface and the EDMA (Enhanced Direct Memory Access) controller. The same board performs linearization if the real-time simulator's time step is not the same as the I/O sampling time step required by the control system. The approach involves transferring at every time step from one memory (real-time simulator) to another memory (control system) via PCIe. Each interface board can receive and transmit to the real-time simulator up to 128 analog and 512 digital signals. Voltage and current data is in 32-bit floating point format and logic values use a single bit.

D. Digital serial link performance

Data is transmitted over the PCIe bus through EDMA. There are two EDMA channels that transfer data: one to transmit data to the control system and the other to receive data. The purpose of using EDMA is to optimize PCIe access and to offload the CPU in real time. The challenges are to minimize PCIe memory access and optimize PCIe throughput with the EDMA controller. Both EDMA channels can transfer at the same time during the time step. Presently, the digital link is using PCIe Gen1 (2.5 Gbps) x1, achieving a throughout of 210 MB/s. For a typical 50 µs HVDC simulation, the amount of data transferred is approximately 1 KB per board, which requires 5 µs. In the future, transfert time will be greatly reduced by using PCIe Gen2/3 with multiple lanes.

E. Cost-effective solution

There are many advantages to using a digital link in a power system simulator. The first is to remove all of the I/O hardware layers in the real-time simulator (I/O boards, signal conditioning and amplifiers) needed to communicate with the HVDC control system. This significantly reduces the number of cabled connections between the simulator and the replica.

The replica's footprint is divided approximately by 50 % in the laboratory because no I/O cubicles are needed. In addition, no calibration is required since no scaling factors are needed for analog values. The overall cost of the replica and the real-time simulator interface are also reduced. The factory system testing of the control system can be started earlier in the project schedule because all the I/O setup of the system is a very complex task the project.

The Hydro-Québec Multi-Terminal is now refurbished and is considered a very successful project. All sequences/configurations have been tested with the real-time simulator using the digital link communication (over 2000 signals are exchanged). A single simulation schematic was used as it supports all possible configurations and is able to simulate all the required reconfiguration sequences. The unavailability period of the HVDC, required for commissioning at site, was reduced by two weeks.

III. Madawaska upgrade project

A. Madawaska HVDC converter station

Madawaska station with its back-to-back HVDC converters, is located on the Gaspé Peninsula of Québec near the New Brunswick boarder in Canada. Its two 12-pulse unipolar converters were commissioned in 1985. The 350-MW facility is used to export energy to or import energy from New Brunswick. The rated DC current is 2,700 A and rated DC voltage is 131 kV. The overload capability is 400 MW at 0°C and 435 MW at -10°C.

TABLE I
Key Madawaska data

Year commissioned	1985 (GE), 2016 upgrade (ABB)
Power rating	350 MW Overload 435 MW
Number of poles	1
AC voltage	Hydro-Québec side: 315 kV New Brunswick side: 345 kV
DC voltage	±131 kV
Type of link	Back-to-back
Main reason for HVDC	Asynchronous grids
Application	Interconnecting grids

This HVDC link is critical for Hydro-Québec. The main objective of the upgrade project is to keep exactly the same functionality and characteristics as the existing control system, while improving system reliability and reducing converter station maintenance.

B. Study replica

The replica, dedicated to functional verification [1]-[3], dynamic performance (DPS) and protection studies, was delivered six months before commissioning the actual facility. Between factory system testing (FST) and site acceptance testing (SAT), i.e., commissioning, many tests were conducted with the replica:

- Transient faults and control system recovery
- Study of HVDC–AC grid interaction
- Commissioning procedure trials
- Real power system events replayed or simulated
- Operating strategies
- Optimization and settings (RPC, VDCOL, etc.)

For the Madawaska project, the replica was installed with A and B control and protection system redundancy and also with the VCU interfaces connected the simulator.

C. Site maintenance replica

Site replicas did not have the new digital link but included all the real system's standard I/Os. Site replicas were designed to:

- Help prepare on-site maintenance jobs
- Train operators and new employees (same HMI)
- Test and validate the system software upgrade before rollout
- Test hardware replacement parts before installing them in the real system

D. Description of power system modeling

One major objective in real-time simulation is to simulate in detail all elements (filters, PLCs, breakers, disconnectors, transformers, arresters, etc.) in order to have the best representation of the converter station and power system.

The Madawaska detailed model as presented in appendix VIII, with AC equivalents on both the Québec and New Brunswick sides, has complex nodes since all breakers and disconnectors had to be modeled. To achieve the real-time performance required, a modeling technique with decoupling elements had to be used. In this case, a decoupling element PLC_HQ_DEC at the transformer primary as shows in Fig. 3, including the PLC filters, was used. Incorporating the decoupling technique created three major tasks: one for the Québec AC system, another for the DC converters with thyristors valves including the transformers, and a third for the New Brunswick AC system.

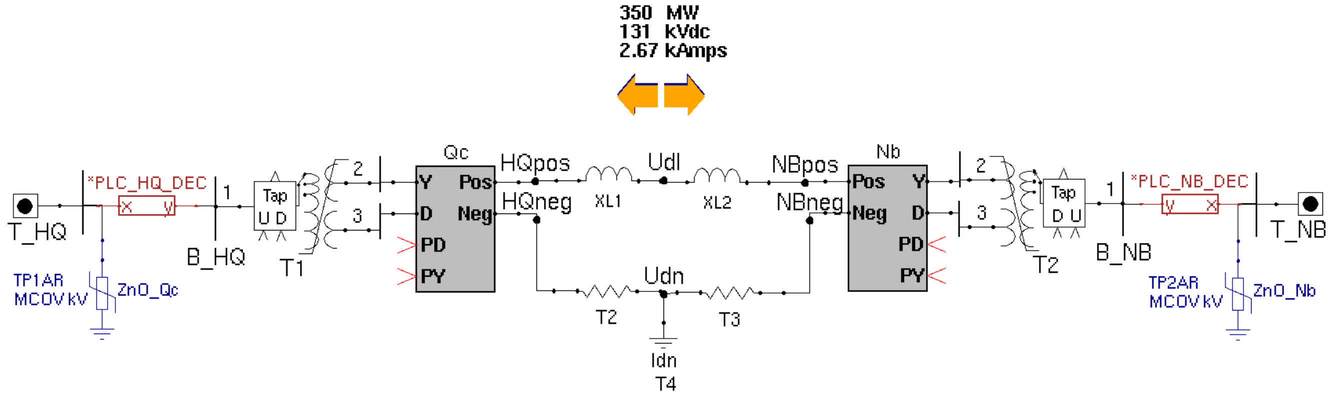

Fig. 3 – Madawaska back-to-back detailed model.

TABLE II
PARAMETERS OF THE MADAWASKA HVDC BACK-TO-BACK SYSTEM

AC systems	Hydro-Québec	New Brunswick
Vbus (kV_{L-L})	315	345
Short-circuit level (MVA)	2,130 (S_{scmin}) 3,930 (S_{scmax})	1,320 (S_{scmin}) 1,990 (S_{scmax})
AC filters (Mvar)	12th and 24th 212	12th and 24th 222
Shunt reactors (Mvar)	85	2 x 55
Transformer (kV_{L-L}) Yg-D1-Y	315/55/55	345/55/55
$S_{nominal}$ per phase (MVA)	134.2	134.2
Impedance at main tap (%)	14.4	14.4
DC smoothing reactor (H)	0.05	0.05

Detailed electromagnetic transient (EMT) models of Madawaska ran in real time at 50 µs. The real-time model has more than 468 analog outputs (system A & B) like bus bar voltages, breakers, filters and arrester currents. 344 digital outputs and 340 digital inputs exchanged with the control and protection system. Given the large number of signals (more than 1,000), it was decided to use the new digital link to interface the controller. We have used nine digital link interface board to connect the replica to the real-time simulator installed in only one cabinet.

IV. OFF-LINE MODEL OF MADAWASKA

A. *Off-line control system*

At the beginning of the project, Hydro-Québec request from the manufacturer an off-line EMT (EMTP-RV) and a stability model (PSS/E) for our study and planning department. For the EMT model, the off-line control system has to use the same software as the real system. For the Madawaska project, we have integrated the HVDC control system into the Hypersim off-line simulator and it's consists of a single main module that controls the rectifier and inverter.

This control is implemented through a User Code Model (UCM) interface. The UCM interface enables manufacturers to run external models in the simulation. For this, a model definition file must be provided to specify model characteristics and behavior, i.e., its parameters, I/O signals, state variables, the C code to execute at each simulation time step and a list of references to external libraries upon which the C code depends. The UCM model definition file is processed to create a block device on the schema (with model input and output pins) and also to generate all the code files it will need to simulate the model.

To implement the HVDC converter control system, a library file that uses the same code as that running in the real hardware was built using the virtual MACH system as described section B. A UCM model definition file was created, processed and added to the schema. Its input and output pins were connected to other required devices on the schematic. A software-in-the loop (SIL) implementation of the control was thus achieved. This allowed conducting studies and tests the system model in off-line before the hardware replica was installed.

B. *Virtual MACH system*

The virtual MACH system was developed by ABB Power Grids, Grid Integration, HVDC. Its purpose was to have an environment supporting the same control logic in EMT simulations, FST, replica and on site. This is a huge advantage since it gives realistic, accurate simulations throughout the process of developing the HVDC converter control system. Since constraints limit real-life testing, simulations are a major part of control system development.

Virtual MACH is used with a graphical programming language for control development and code generation. From the graphical programming language, code is generated for either the real hardware MACH system or off-line simulations. The control system logic and cycle times are kept the same for both to ensure the same behavior. The virtual MACH system has been used for over 20 HVDC systems delivered by ABB, making it highly reliable and trustworthy. The virtual MACH system was used to implement the same software converter control in both Hypersim and EMTP-RV. In the future, parallelization of the SIL will be required in order to be used in real-time simulations. This will reduce the replica cost as, for typical applications, a single converter station control system hardware replica would be required, the other station(s) would be simulated in real-time SIL.

C. *HIL vs. SIL model*

The superimposed waveforms in Fig. 4 clearly show that the results of both simulation tools are in good agreement. They differ slightly due to time step difference (real time, 50 µs; off-line, 40 µs) and to closed-loop delay compensation in the off-line model.

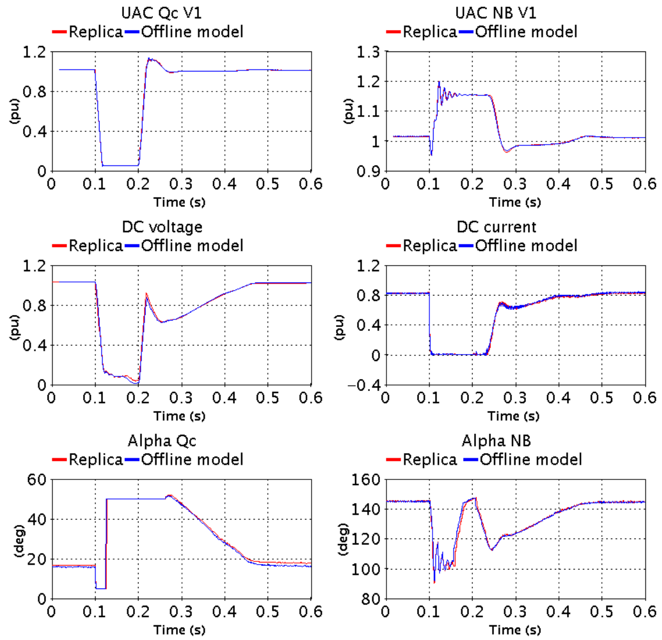

Fig. 4 – Simulation results of off-line model compared to replica

V. Madawaska Commissioning Studies Using Real-Time Simulation

During factory system testing, Hydro-Québec has an exhaustive list of tests to perform covering start/stop sequences, ramping, supervision, I/O loss, optic fiber loss, GPS, runback, backup trip, commutation failure, overvoltage, undervoltage, AC filter faults, DC faults, frequency modulation, last-line disconnect, RPC, transformer protection, auxiliary protection, etc. Important areas of FST that justified a replica for optimization and test functionality are presented below.

A. *Last-Line Disconnect Protection*

Last-line disconnect protection was validated by simulation. This protection is critical because when the last AC line is lost on the inverter side, harmonic filters produce a very highly distorted voltage on the converter bus. As the AC current is measured directly in the bus arrester, the last-line condition can be detected by calculating the energy dissipated by the arrester, as illustrated in Fig. 5. This example presents a last-line disconnect case in import mode (Québec side is inverter) at full power (435 MW). The local breakers opens at 0.1 s. The converter is blocked after 89.3 ms.

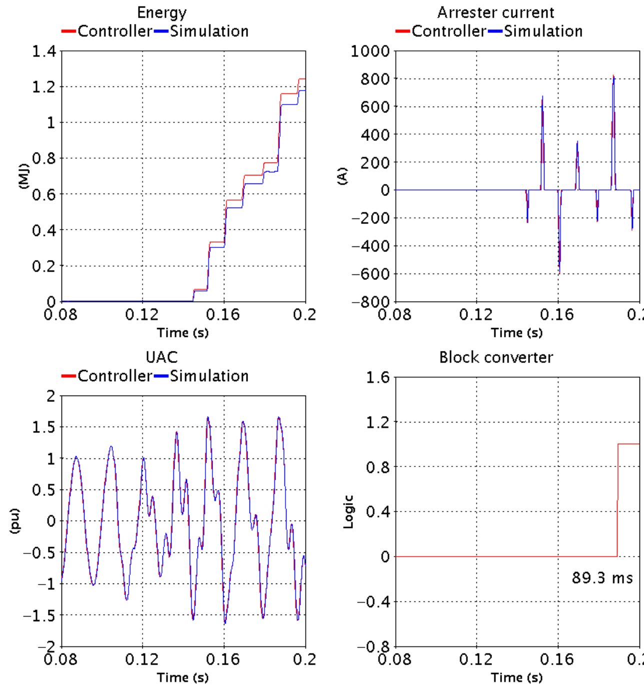

Fig. 5 – Real-time energy simulation vs. controller calculation

Numerous configurations were studied. The energy measurement was calculated into the real-time simulator and then compared to the real protection system. Based on this comparison, the protection was optimized to make sure that it acted as fast as possible in a remote islanded situation but did not act during temporary faults on the grid.

B. *RPC optimization*

Reactive power control (RPC) decides whether to switch filters in or out on both AC grids. The effective short-circuit ratio (ESCR) of both AC grids is usually low but can vary considerably based on the lines connected, contingencies and the load on the grids. Due to the large ESCR variations, the voltage variation on the grid when connecting the last filter at maximum power is significantly higher when the grid has the lowest ESCR (2.7) than when it has the highest ESCR (5.0). The conventional way to design this function is to use a dead band that is larger than the maximum voltage variation at lowest ESCR and maximum power. In this project, the short-circuit level is low and on the inverter side, an increase in voltage further decreases converter reactive power consumption as a constant gamma is used at all times. Considering these facts, the necessary dead band to avoid any pumping in all situations would be very large. Also, the lowest short-circuit level occurs during some contingencies, not under usual grid configurations.

A cost-effective solution was designed by ABB and Hydro-Québec based on the AC voltage variation measured after filter switching and how many filters were already connected. In principle, short-circuit levels of the system can be estimated from:

$$S \approx \frac{Q_{filter}}{\Delta V_{filter}} + \sum Q_{filters} \qquad \Delta V_{filter} \text{ in pu} \tag{1}$$

Unfortunately, the equation ignores the variation in converter reactive consumption following filter switching. Also, after one switching operation the next filter voltage variation must be predicted by the algorithm.

A practical and reliable solution was necessary to solve this problem. The simplest solution, but a time-consuming one, is to run numerous converter ramp-ups and ramp-downs with different short-circuit values. The voltage variation data compiled after all filter switching operations could then be used to plot voltage variation versus the actual short-circuit values. It is then possible to establish a relation between the voltage variation of one filter and the next filter switching operation. Since the relation is not linear but nearly exponential, two piecewise linear segments were used to approximate the results for all filter variations, as show in Fig. 6.

Fixed dead bands are also used as maximum limits and have the priority under steady-state conditions after some time delay since short-circuit values can change. The results on the simulator and from on-site commissioning tests demonstrated that this innovative solution is very effective in providing good voltage control, depending on short-circuit values.

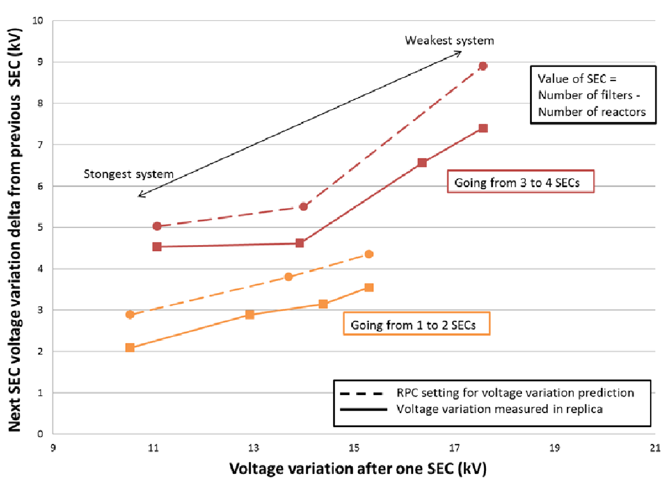

Fig. 6 – Predicted voltage variation for shunt element connection (SEC)

C. AC protection tests

An important part of testing on the replica was the AC protection tests. The old relays were removed during the refurbishment and their settings were ported to the new ABB MACH 3 protection system. Faults were simulated on every device in the AC switchyard (filters, PLCs, transformers, shunt reactors and busbars). The goal of these tests was to validate proper operation and speed of the protection devices, without disturbing DC link operation when possible. These tests revealed some issues and helped optimizing the protection scheme. They also proved beyond any doubt that the new system was performing well. To check reliability, Hydro-Québec ran the tests over a wide range of grid conditions. The issues encountered during these simulations made it possible to make changes early in the engineering stage, saving time and money for system and commissioning tests.

D. Post-commissioning investigation

The replica was later used to investigate harmonic interactions with the converter. Both AC grids have many special characteristics, including series compensation, wind generation, untransposed lines, weak short-circuit levels and harmonic resonance. All these elements affect the control systems in various ways. Using the real-time replica, harmonic interactions could be reproduced, which greatly facilitated the analysis of these issues. Improvements or corrections could be tested prior to making changes on site.

VI. Conclusion

This paper has briefly described the new digital link communication system integrated into Hydro-Québec's real-time digital simulator and optimized for real-time simulations.

Test results show that this new approach can be used to connect an external control system to a real-time digital simulator, yielding many advantages:

- The number of connections between the simulator and replica is greatly reduced.
- The footprint of the replica in the laboratory is smaller since no I/O cubicles are needed.
- The cost of the control system replica is reduced.
- No amplifiers or calibration are needed for signal conditioning.
- New I/O channels can be added if needed in the replica without any new hardware interface.
- Factory system testing of control system can start earlier in the project.
- The cost of the real-time simulator is also greatly reduced as very little IO hardware is required.

By using ABB's virtual MACH, the same control system could be implemented as an off-line model in Hypersim and EMTP-RV. The same control logic is also used in the hardware replica and on site. Results from simulations with the different tools agree closely. The advantages of having an accurate off-line model are that dynamic studies and validation of the software can be performed before installing the hardware control system. Once the control system replica is installed, more time can be spent on testing the hardware instead of also having to work on the software.

An example real-time HIL commissioning study was presented. This paper also overviewed how the real-time simulator has helped test and improve real control systems in such areas as reactive power control and AC protections. Installed permanently at IREQ, this tool has been tuned to reproduce site harmonics and unbalance. Lastly, the real-time HIL have reduced the Madawaska commissioning time at site by one week. Throughout the service life of Madawaska HVDC station, the replica will thus help analyze and find solutions to real on-site problems, as well as keep track of the development of the grids and their impacts on the HVDC system.

Future work will explore how to adapt the digital link to suit the needs of VSC control systems. It would simplify the replica-simulator interface as it drastically reduces the number of physical connections. Furthermore, this approach will facilitate the development of new mathematical models or algorithm for fast real-time application by offloading calculations to processing hardware closer to the devices under test.

VII. APPENDIX

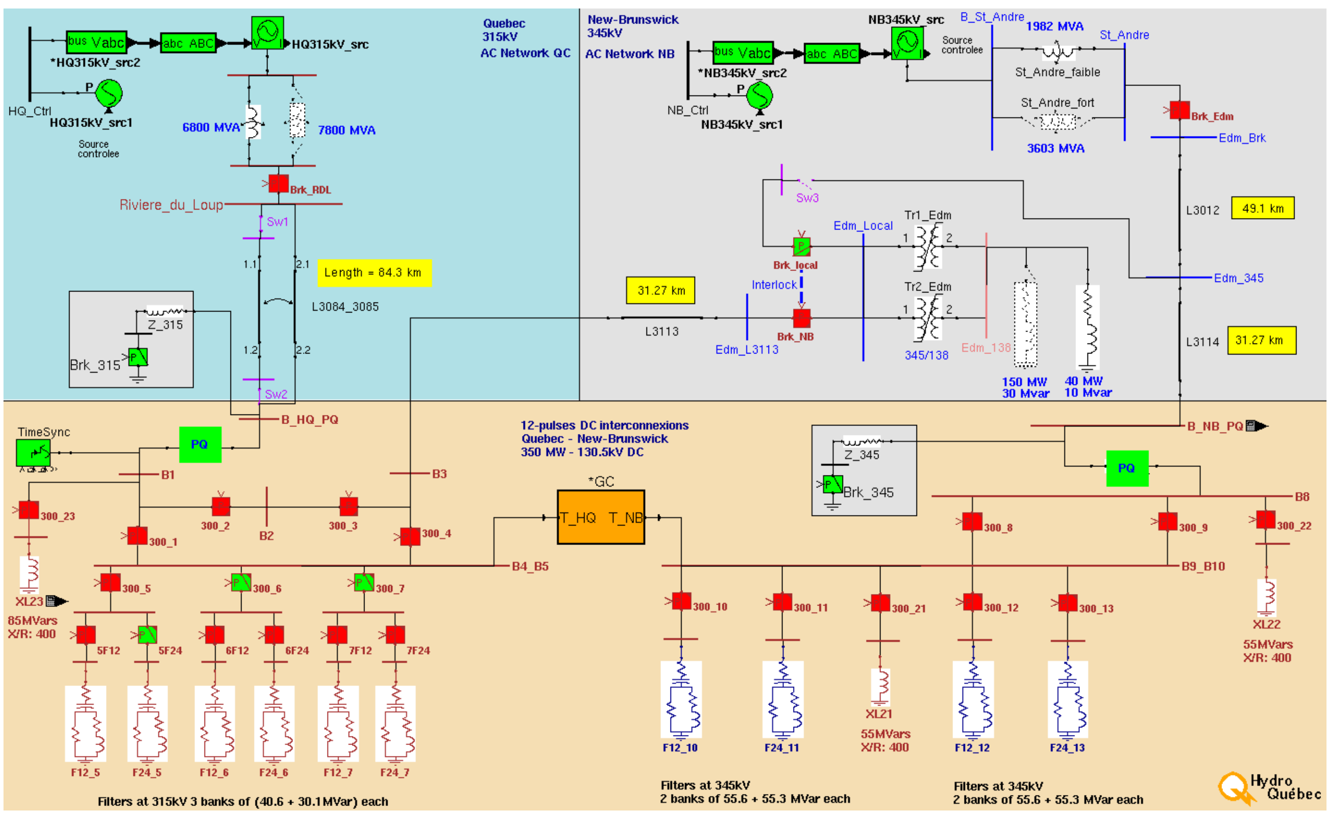

Fig. 7 – Madawaska real-time detailed model.

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