Châteauguay Interconnection SVC Refurbishment: Real-Time Hardware-in-the-Loop Commissioning Study Experience

P. Le-Huy, A. Abdellaoui, K. Gauthier, H. Akremi

***Abstract*—Châteauguay interconnection between Hydro-Québec TransÉnergie and New York Power Authority, a 2x500 MW back-to-back HVDC and radial connection of generating units from the Beauharnois substation, is in operation since the early 80's. The HVDC control and protection systems were refurbished in 2009. In 2017, one of the two SVC was completely refurbished and equipped with a fully digital control system. This paper highlights the critical role of real-time simulation studies for the successful commissioning of Hydro-Québec's main transmission system equipment, such as SVCs and HVDCs. It also illustrates the post-commissioning usefulness of control system replicas to perform additional multi-replica studies to optimize operating strategies of the Châteauguay interconnection.**

***Keywords*: Electromagnetic transient, hardware-in-the-loop, HVDC, simulation, static var compensator, real-time.**

I. Introduction

HYDRO-Québec TransÉnergie (HQT) was one of the first transmission system owner (TSO) to deploy static var compensators (SVCs), installed primarily in the James Bay transmission corridor [1]. These devices are used to regulate transmission voltage and enhance system stability by means of variable reactive power absorption or generation [2]. SVC installations rely on mechanically or thyristor-operated reactive elements (i.e. thyristor-controlled reactors (TCRs) and thyristor-switched capacitors (TSCs)) to provide or absorb reactive power in order to raise or lower the point of common coupling (PCC) voltage.

SVCs are also used to provide reactive power support for HVDCs. Additionally for Chateauguay interconnection, the SVCs are critical to ensure successful converter active power recovery following a severe voltage dip on the 120 kV side. Châteauguay SVCs' voltage control system was specifically designed to mitigate the risk of commutation failures during active power recoveries while at the same time improving the overall voltage profile of the system under both steady state and transient conditions.

The configuration of Châteauguay-Beauharnois complex is illustrated in Fig. 1. A twin back-to-back 500 MW line-commutated HVDC connects Châteauguay substation (315 kV, HQT, Québec, Canada) to Massena substation (120 kV, New York Power Autority (NYPA), New-York, USA). Beauharnois generating units are connected to NYPA sytem via four 120 kV lines. SVC101 and SVC102 are connected on the 120 kV side of Converter 1 and 2 respectively. Each SVC has an operating range of -99.2 to +166.2 Mvar.

Constructed in the early 80's by a BBC/Siemens consortium, the HVDC was refurbished in 2009 by ABB, who replaced the analog control system to a fully digital one (MACH2). However, no overhaul of the SVCs was done since their original commissioning in 1984.

In 2017, SVC102 underwent a massive overhaul as everything except the inductors/capacitors and electric yard apparatus were replaced. Siemens replaced the analog control system with a fully digital one duplicating all the control functions and strategies of the previous system.

Like other SVC and HVDC project at HQ, a real-time (RT) hardware-in-the-loop (HIL) commissioning study has been performed with a control system replica of SVC102. However, because of the particular coordination between the SVCs and the HVDC converters, additional and comprehensive RT HIL studies have been conducted using the replicas of the HVDC controllers, the replica of SVC 102 controller and an accurate electromagnetic transient (EMT) model of SVC 101.

This paper presents HQ's experience during and after SVC102's RT HIL commissioning study. HQ view on RT studies is presented in the next section while various aspects of SVC102 RT HIL study are discussed in section III such as analog control identification and experimental setup. Details on how SVC102 HIL setup allowed a reassessment of operating strategies to lift a 200 MW restriction are presented in section IV. Finally, concluding remarks are given in section V.

II. Real-Time Study Goals

Real-time commissioning studies are performed after manufacturer testing (factory system tests, factory acceptance tests, etc.) but prior to and concurrently with field commissioning of major power system devices, typically FACTS or HVDC systems. In order to accomplish these

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studies, a detailed replica of the control system of the device under test is required as well as a real-time EMT simulator suited for the representation of the AC system at the PCC. Furthermore, real-time commissioning studies are usually realized in-house with the collaboration of the equipment supplier since modifications to both hardware and software might be required to fulfill technical requirements and specifications described in the procurement contract.

A. Objectives

For HQ, in-house real-time commissioning studies of major power equipment are deemed essential for several reasons:

- To validate that all functional requirements are met.
- To verify the control system behavior in all plausible grid conditions and during specific network events.
- To fine-tune settings for optimal and safe operation of the device.
- To explore new settings, new operating modes or new contingency responses without compromising the integrity of the power system.
- To reproduce real power system events or problems in order to find and evaluate possible ways to cope with such occurrences.
- To train field operators and technicians with a realistic platform.
- To validate field commissioning tests before actually performing them in the field to ensure safe testing and avoid costly surprises.
- And, lastly, to reduce and possibly avoid field commissioning delays.

If deficiencies, unsuitable controller actions, off-specification characteristics or incorrect settings are identified, corrective actions are taken. If possible, user-defined parameters are adjusted to correct the controller's behavior. However, if the problem cannot be addressed that way, the equipment supplier is asked to make appropriate corrections to rectify the situation. Both software and hardware modifications might be required but the former is more common and much more convenient to implement. This goes back and forth for several iterations to iron out all problems.

The replica setup is also a very useful tool for operator and technician training as it allows them to familiarize themselves with the equipment's control system and how to interact with it on the operational as well as the maintenance level.

As stated earlier, part of the real-time testing is performed concurrently with the field commissioning: planned field tests are validated with the replica setup to ensure safe field testing and avoid dangerous situations to both personnel and hardware. If potentially dangerous transients are observed in simulations, the field tests can be modified to avoid such transients or additional precautions can be taken to reduce their impact.

In the case of SVC102 refurbishment project, the control system replica costs were reduced by retasking the Siemens control system replica from a previous HQ-Siemens SVC project to suit Châteauguay SVC102 specificities: instead of purchasing a complete control system replica, a second IO rack was added to the existing replica. More details on this feature are given in section III. B.

Another limiting factor is the availability of in-house expertise in power system dynamic behavior and electromagnetic transients as well as familiarity with real-time simulation tools, signal conditioning and hardware-in-the-loop setup. Such a spectrum of knowledge is not gained overnight but has to be acquired the hard way. Ultimately, the required investment is very advantageous since it deepens one's understanding of his power system, ensures that all device specifications are respected and helps in exploiting installations to their full capabilities.

B. Pros and Cons

Real-time commissioning studies have many obvious advantages such as reduced field commissioning time and optimal operations from the get-go since much of the setting tuning and troubleshooting are done with the replica. On the other hand, such studies may not be feasible by all utilities as it involves additional costs and requires in-house expertise and know-how.

From a return on investment view point, RT HIL studies marginally increases the overall cost of the project while substantially reducing the risks during commissioning. Additionally, significant expertise and operational experience are acquired in the process, facilitating operation and troubleshooting over the lifetime of the equipment. This expertise is also useful for subsequent commissioning projects.

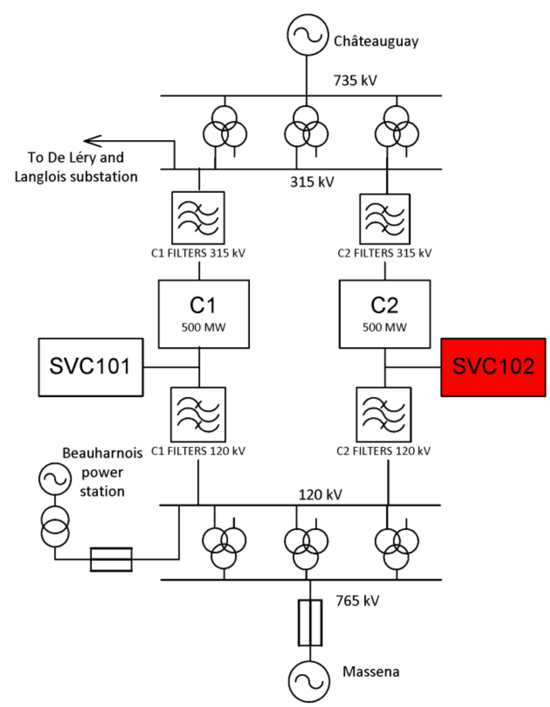

Fig. 1. Schematic of Châteauguay interconnection illustrating both converters (C1 and C2), their 315 and 120 kV filter banks (the icon represents both series and shunt filter banks), Beauharnois power station synchronously connected to NYPA power system and both SVCs: SVC101 with analog control system and SVC102 refurbished with digital control system.

III. CHÂTEAUGUAY SVC102 RT HIL STUDY

This section presents three elements specific to Châteauguay SVC102 RT HIL study: identification and characterization of Châteauguay SVC101 analog control system, control system replica retasking for SVC102 and multi-replica testing.

A. *Identification of SVC101 Control System*

Prior to SVC102 refurbishment, a rigorous identification and characterization of Châteauguay SVC101 were performed to fully understand all operating mode and to extract the exact parameters of the various functional blocks. Such endeavor was necessary to faithfully duplicate the exact behavior of the analog control system and ensure coherent response from both SVC101's analog and SVC102's digital control system.

Field measurements were taken on various test points in SVC101's analog circuits, down to the operational amplifier level, to extract the transfer functions of all elements forming the internal control loops and those related to the priority control strategy. This meticulous analysis of SVC101 circuits allowed significant improvements to its simulation model that was thereafter validated by comparing its output to field measurements (see Fig. 2).

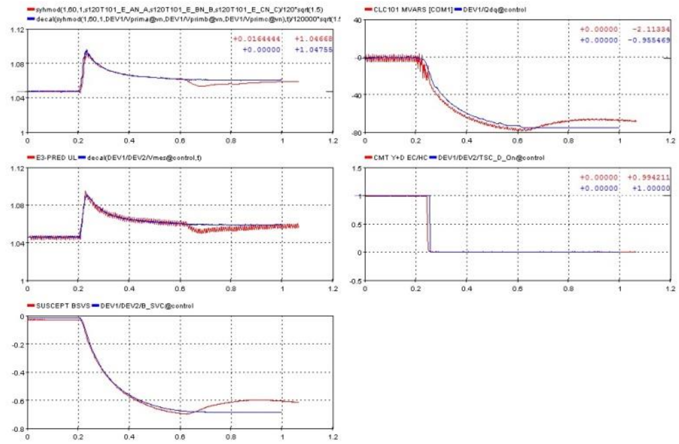

Fig. 2. EMTP-RV SVC101 model behavior (blue) compared to field measurements (red). Left column: direct-sequence voltage (p.u.), measured voltage (p.u.) and SVC101 susceptance (p.u.). Righ column: reactive power (Mvar) and TSC state (delta winding). The EMTP-RV model does not represent the current order ramp during the startup sequence, hence the difference at 0.6 s.

B. *Control System Replica Retasking*

In the call for tenders for this project, HQ asked a solution with full control system replica and one that would reuse, or retask, the control system replica of a previous project in order to cut cost and expedite the whole process. Simple and rapid toggle between both SVC configurations was a requirement for this second solution. Siemens was awarded the contract as they chose to implement this second solution on the Bout-de-l'Île (BdI) replica, a previous HQ-Siemens SVC project.

The BdI and the Châteauguay SVCs have different topology: the BdI SVC has 6-pulse TCR/TSC and filters while the Chateauguay SVC102 has 12-pulse TCR/TSC only. These topology differences warranted a different IO rack in the replica but otherwise it is the same in both cases.

To toggle between both configurations, the following steps must be executed (see Fig. 3):

- Shutdown the control system completely;
- Change the control software memory cards (3);
- Change the control system connection to the proper IO rack (7 cables);
- Change operator workstation hard drive;
- Change SCADA system memory card;
- Reboot the control system.

As for the real-time simulator, the steps are the same as loading a regular schematic to simulate:

- Start Hypersim software;
- Load schematic;
- Load IO configuration file;
- Start simulation.

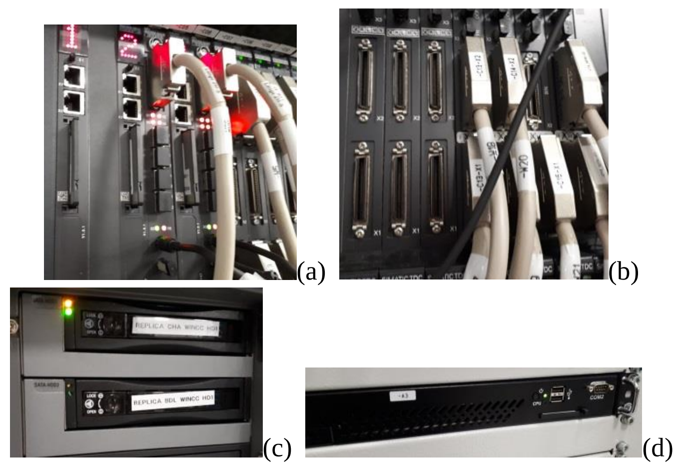

Fig. 3. Toggling between the two configurations involves (a) changing the control software (3 memory cards), (b) rerouting the IOs to the proper IO rack (7 cables), (c) switching the operator workstation hard drive and (d) changing the SCADA memory card.

All things considered, untrained personnel can complete this procedure in less than 30 minutes, including the time to shut down the replica and to reboot it.

This control system replica retasking, the first one in HQ's RT simulation lab, may seem trivial or anecdotal but it provided several benefits. First of all, reusing the control system replica cabinets allowed a substantial reduction of the RT commissioning study cost, hence reducing the cost of the whole project. Furthermore, it allowed saving precious floor space in the RT simulation lab and RT simulator resources (computing and IOs). However, both systems cannot be used simultaneously but the probability of such occurrence is low.

In summary, retasking control system replicas is financially sound for both the utility and the vendor and, for the latter, can even be a strategic move during calls for tenders.

C. *Real-Time Simulator and Multi-Replica Setup*

During the RT HIL commissioning study, the SVC102 control system replica was connected to Hydro-Québec's real-time EMT simulator, Hypersim. It is a large-scale multiprocessor simulator used for power system studies and for the development, validation, tuning and commissioning of control systems [3]. The computational effort is automatically spread across available processing units using the natural propagation delay of the transmission lines. As a result, the large power system impedance matrix is divided into several smaller submatrices which can be solved in parallel by several processor cores without introducing any error, thus drastically improving the simulation speed [4]. For computational load reasons, the network equation solver of Hypersim uses piece-wise linear models to represent nonlinear devices such as power electronics and saturable elements and for improved accuracy an iterative solver is available [5]. Furthermore, reactive elements are reduced to a single admittance in parallel with a current source representing the reactive elements' historic values, exactly like the original EMTP [6].

The Hypersim simulator is not limited to real-time applications: if a hardware-in-the-loop configuration is not required, it can be used for offline simulations on any personal computer and, if multiple processing cores are available, the automatic task mapper will make use of them. In that case, the simulations are executed as fast as the processing unit can manage, which can lead to faster-than-RT simulations depending on the simulated power system and the processing power of the computer. This feature is highly desirable since it allows the groundwork for RT studies to be conducted without monopolizing RT hardware resources.

The schematic for the complete Châteauguay interconnection is presented in Fig. 4 while Table II gives the simulation content. The Beauharnois generating units are aggregated in an equivalent synchronous machine with its complete control system. The HQ and NYPA systems are each represented by a power system equivalent at Châteauguay 735 kV and at Massena 765 kV respectively. The HQ subsystems connected to De lery and Langlois substations are each modeled by a generator and a dynamic load. The complete back-to-back HVDC is simulated (C1 and C2 in Fig. 4) and it receives control and protection signals from the ABB control system replica (see Fig. 5). SVC102 is also connected to its control system replica while SVC101 is fully software simulated (both the electrical components and the control system). As illustrated in Fig. 5, both control system replicas are connected together to exchange control signals and both receive their respective voltage and current measurements from IOs in the SGI supercomputer.

The complete interconnection is simulated in RT with a 45 µs time step on an SGI UV100 sporting Intel Xeon E7-8837 CPUs (8 cores per socket operating at 2.667 GHz). 19 cores are required for RT performances. For adequate representation of saturation and surge arrester behavior, the iterative solver is enabled but it is limited to a maximum of three iterations per time step.

Most of the RT commissioning tests were performed with only SVC102 and an equivalent power system because the majority of these tests do not require a representation of the HVDC. In that case, two SGI UV100 cores were required.

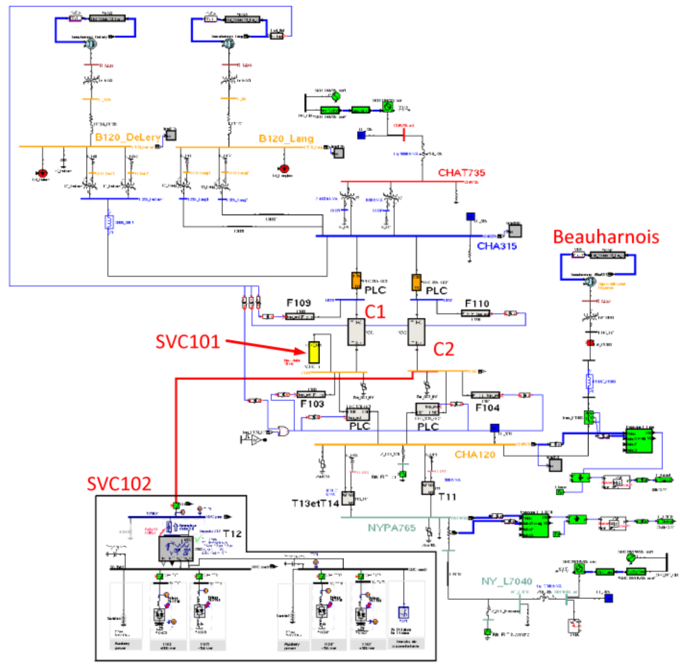

Fig. 4. Hypersim simulation schematic of the Châteauguay-Beauharnois interconnection.

TABLE I
COMPLETE CHÂTEAUGUAY INTERCONNECTION SIMULATION CONTENT

Nodes (5 simulation tasks with more than 50 nodes; highest node count for a task: 90)	413
Sources	103
RLCs	534
3-phase XFOs	34
Non linear (Inductances and Surge Arresters)	69
Switches (Thyristors, circuit breakers and disconnectors)	183
IOs	333
Computer Cores	19
Intertask Comms	216
Simulation tasks (both power system and control system tasks)	29

Fig. 5. Hypersim RT HIL setup with SVC and HVDC control system replicas: ABB HVDC and Siemens SVC control replicas and SGI supercomputer for RT simulation.

IV. Revision of Operating Strategies

Extensive field verifications have been performed on SVC 101 for a comprehensive understanding of Châteauguay SVCs' control system. The purpose was to implement in the digital controller of SVC102 an equivalent control strategy to the one in SVC101 analog controller and to improve the simulation models of SVC101 (Hypersim, EMTP and PSS/e).

Sensitivity studies with the revised simulation models have shown that the previous model were more restrictive than the improved one. This was mainly attributed to the simplified representation of the feedforward function of the control system.

In light of these results, RT HIL simulations were performed with both the HVDC and SVC control replicas and the improved software model of SVC101. The purpose was to validate the operating restriction of 200 MW on the HVDC active power when operating with a single SVC.

A. *Scope of the Study*

The power recovery performance of Châteauguay interconnection was evaluated by running several cases, as described in Table II, and checking for transient behavior without protective block or bang ramp lock activation. A successful converter power recovery is achieved when neither of these special modes is activated.

The tests were conducted with the control system replica of Châteauguay interconnection, with both converter operating at 500 MW each, and either SVC101 (full EMT modeling, enhanced control system model, RT) in service or SVC102 (control system replica, RT HIL). A conservative short circuit level, 4200 MW, was used instead of the commonly witnessed 6000 MW level in order to analyze a more severe case to unearth problems that would have been hidden by a more powerful system. Furthermore, all tests were conducted with 4, 6, 7 or 9 Beauharnois generating unit synchronized on NYPA system, as they affect the HVDC power recovery.

TABLE II
Summary of simulated contingencies

Contingency	1	2
Description	Fault **without** loss of equipment	Fault **with** loss of equipment
Fault Location	Châteauguay, 120 kV bus	Massena, 765 kV bus
Fault Types	ABCG, ABG, AC, AG	ABCG, ABG, AC, AG
Fault Point on Wave (ms)	0, 2, 4, 6, 8, 10, 12, 14	0, 2, 4, 6, 8, 10, 12, 14

B. *RT HIL Results*

Fig. 6 illustrates an example of a successful power recovery following the application of an ABCG fault at Massena 765 kV bus. Both converters have properly recovered, reaching their maximum power output after the first bang.

Fig. 7 shows the activation of successive bang ramps following the application of an ABCG fault at Châteauguay 120 kV bus. In this simulation four Beauharnois generating units were synchronized to the NYPA system. Upon the occurrence of three bangs within 60 seconds, a bang ramp lock is activated. However, for RT simulation efficiency the lock was disabled in the converter control replica to simulate multiple cases without interruption.

Simulation results have shown that with a minimum of 9 Beauharnois generating units, a high power recovery success rate was achieved for all configurations and fault types. It was then demonstrated that the 200 MW restriction on the active power of the HVDC interconnection was no longer required when operating with a single SVC.

V. Conclusions

The refurbishment experience of Châteauguay's SVC102 has demonstrated the importance of RT HIL studies during and after commissioning.

This paper presented three specific aspects of the Châteauguay RT HIL studies:

- The cost effectiveness of retasking an existing SVC control system hardware;
- The critical role of field tests for the comprehensive understanding and accurate modelling of SVC 101 control system;
- The implementation of the complete multi-replica setup of Châteauguay interconnection with Hypersim, the HQ RT-EMT simulator.

Finally, HQ's experience with multi-replica simulations to reassess operating strategies has been presented. Multi-replica RT HIL testing was instrumental in lifting Châteauguay interconnection's 200 MW operating restriction with a single SVC. Without both control system replicas, it would have been difficult to gather such strong evidences to remove this power restriction.

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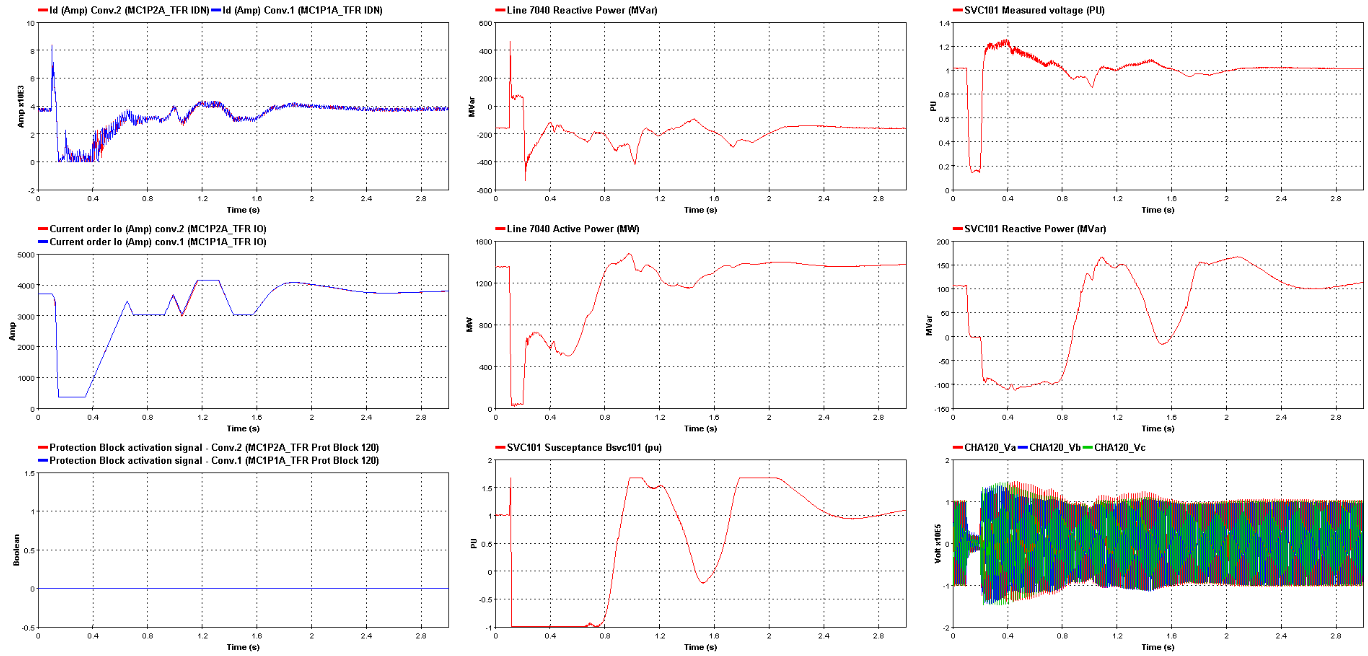

Fig. 6. ABCG fault (0 ms point on wave) at Massena 765 kV bus with SVC101 in service only; 9 Beauharnois units in service (successful power recovery).

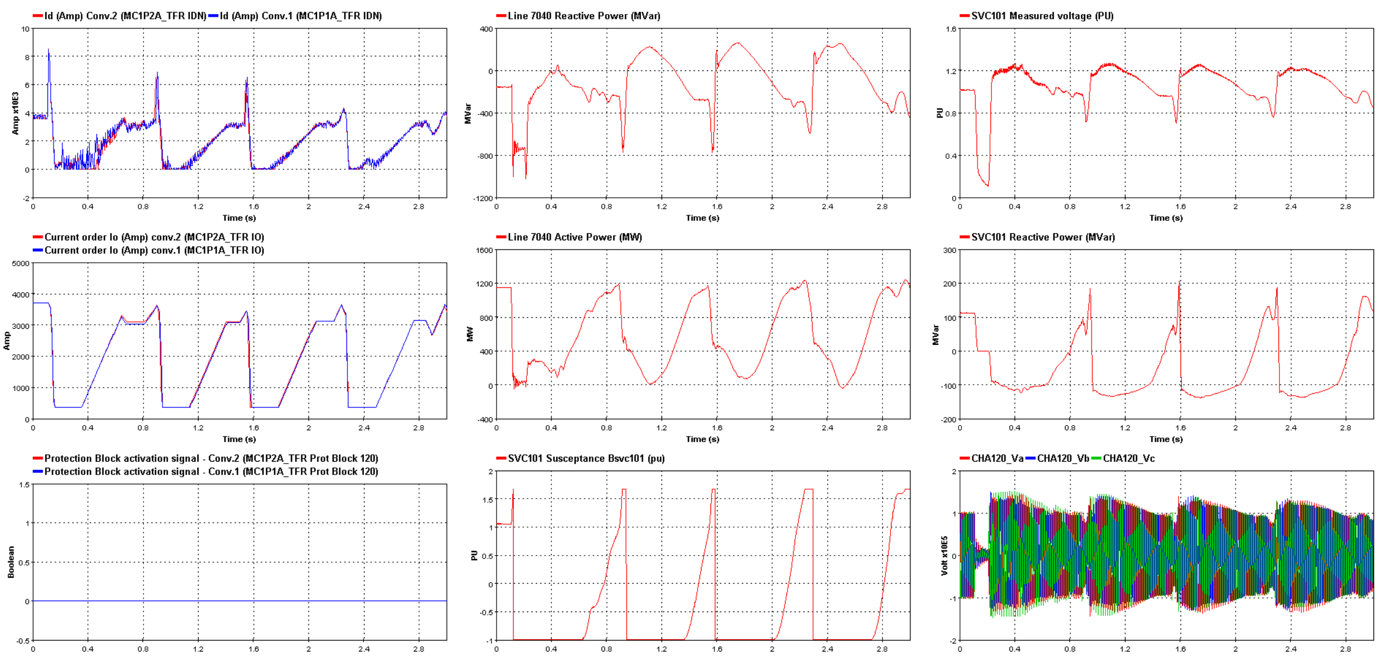

Fig. 7. ABCG fault (14 ms point on wave) at Châteauguay 120 kV bus with SVC101 in service only; 4 Beauharnois units in service (power recovery failed due to bang ramp lock activation). To speed up testing of all cases, the lock itself was deactivated but post-processing of results detects the numerous bang ramps and counts this as a failed power recovery.