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Innovative Wide-Area and Local Voltage Control of Dynamic Shunt Compensation Devices to Prevent Voltage Collapse

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SUMMARY

Hydro-Québec has identified Wide-Area Control System (WACS) as a key smart grid initiative able to significantly increase the voltage stability of its grid. In this context an innovative project for wide-area and local voltage control of shunt compensators was initiated. This project is part of Hydro-Québec's WACS and Wide-Area Measurement Systems (WAMS) smart grid innovation initiatives. Its main objective is to implement a complete closed loop control system on Hydro-Québec's network to optimize the reactive power support from the installed dynamic shunt compensator fleet, which includes Static Var Compensators (SVCs) and Synchronous Condensers (SCs), following major disturbances. Once put into operation, this solution can prevent voltage drop in the load area.

The outcome of this fruitful project is the so-called «Global and Local Control of Compensators» (GLCC) control system which is based on IEEE C37.118 synchrophasor technology and Intelligent Electronics Devices (IEDs). Applied to each shunt compensator of Hydro-Québec's network, this robust voltage control system consists in measuring major voltage variations in the load area and adjusting the set point operation of each shunt compensator accordingly, thus avoiding voltage collapse resulting from extreme contingencies.

The complete GLCC control solution was intensively tested in simulation using PSSE software. Moreover, an experimental pilot project was commissioned on a test bench replica of the system and also tested in real time using Hydro-Québec's Hypersim digital simulator. In 2014, field tests of the GLCC in closed loop were conducted on a -230/+660 MVars SVC. The results of this pilot project were deemed conclusive and the deployment of this new voltage control system to all shunt compensators of Hydro-Québec's grid has been initiated.

KEYWORDS
Power System - Voltage Stability - Wide-Area Control - Reactive Power - Shunt Compensators - Real-Time Digital Simulation - IED - IRIG-B - IEEE C37.118

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INTRODUCTION

Wide-Area Control and Monitoring Systems (WACS/WAMS) are now a priority for power utilities in regards to control, protection and reliable operations of the bulk power system. In fact, following the August 14, 2003 Northeast blackout it was established by the North American Electric Reliability Corporation (NERC) that a wide-area monitoring system based on phasor measurement could have helped to identify and prevent this major voltage collapse [1-3]. As a result of this incident, the support for smart grid technologies became a federal policy in the USA with the Energy Independence and Security Act of 2007. This act subsequently authorized the Smart Grid Investment Grant (SGIG) program to promote the development of smart grid technologies, tools and techniques. From these technologies, wide-area measurement and control were identified as key elements to improve the power system reliability and visibility. Therefore, the North American SynchroPhasor Initiative (NASPI) was put in place as a collaborative effort between NERC, utilities, researchers, vendors and academics to advance the deployment and use of phasor measurement applications in power system [4-6]. Likewise, the engineers and researchers from Hydro-Québec have been actively developing and probing new ideas for wide-area measurement and control applications for several years. Innovative techniques for synchronized phase angle and frequency measurement were developed in the 1980s and a wide-area monitoring system based on Phasor Measurement Units (PMU) was commissioned in 2004 for GPS-synchronized angle, frequency and harmonic distortion measurements [7-8]. New approaches for wide-area control of power system oscillation damping and voltage stability using phasor measurement technology have also been elaborated along with original Special Protection Schemes (SPS) solutions [9-14].

In continuity with this work, an innovative research program in control and automation of power systems called CGART (a French acronym) has been initiated by IREQ, Hydro-Québec's research institute. The main objective of this program is to improve the overall system performance of the Hydro-Québec grid by adding new control strategies and SPS to existing power equipment and installations. A leading control project to emerge from this innovation program is the so-called «Global and Local Control of Compensators» (GLCC) project for wide-area and local voltage control of shunt compensators. This novel WACS system is designed to control the coordinated action of all the static Var compensators and synchronous condensers connected to the Hydro-Québec grid. The role of this cutting-edge control solution is to temporarily change the voltage set point of the compensators upon detection of a voltage collapse in the Montréal load area, thus improving the overall voltage stability of the grid.

This paper presents the development, the implementation and the testing challenges of this new GLCC infrastructure. The functionality and complete scope of the project are first presented followed by the description of the closed-loop hardware integration and the evaluation of the solution on the Hypersim real-time digital simulator at IREQ. Finally, the commissioning of the GLCC pilot project is presented and closed-loop field test results are described and compared with the corresponding real-time simulation results to highlight the valuable benefits and encouraging outcome of the project.

THE GLCC PROJECT

The need for a synchronized and robust solution to optimize the use of the existing shunt compensators on the Hydro-Quebec network comes from the following two principal observations.

First of all, Hydro-Québec's shunt compensation installation actually comprises 9 Synchronous Condenser (SC) and 14 Static Vars compensator (SVC) sites with a total capacity of about 7000 MVars capacitive and 4000 MVars inductive. These compensators play an important part in the voltage level control of the grid and its transfer capacity. For most of them however, their control strategies which rely on an independent voltage set point at each substation have remained unchanged since they were commissioned in the 1970s to the 1990s. In addition to these technological realities, the topology of the Hydro-Québec grid (see Figure 1) imposes significant challenges to ensure its reliability and security. As a matter of fact, the majority of the total installed hydroelectric capacity of 43 GW is located in the northernmost part of Québec, while about 60% of its load is located more than 1000 km to the south in the Montréal area.

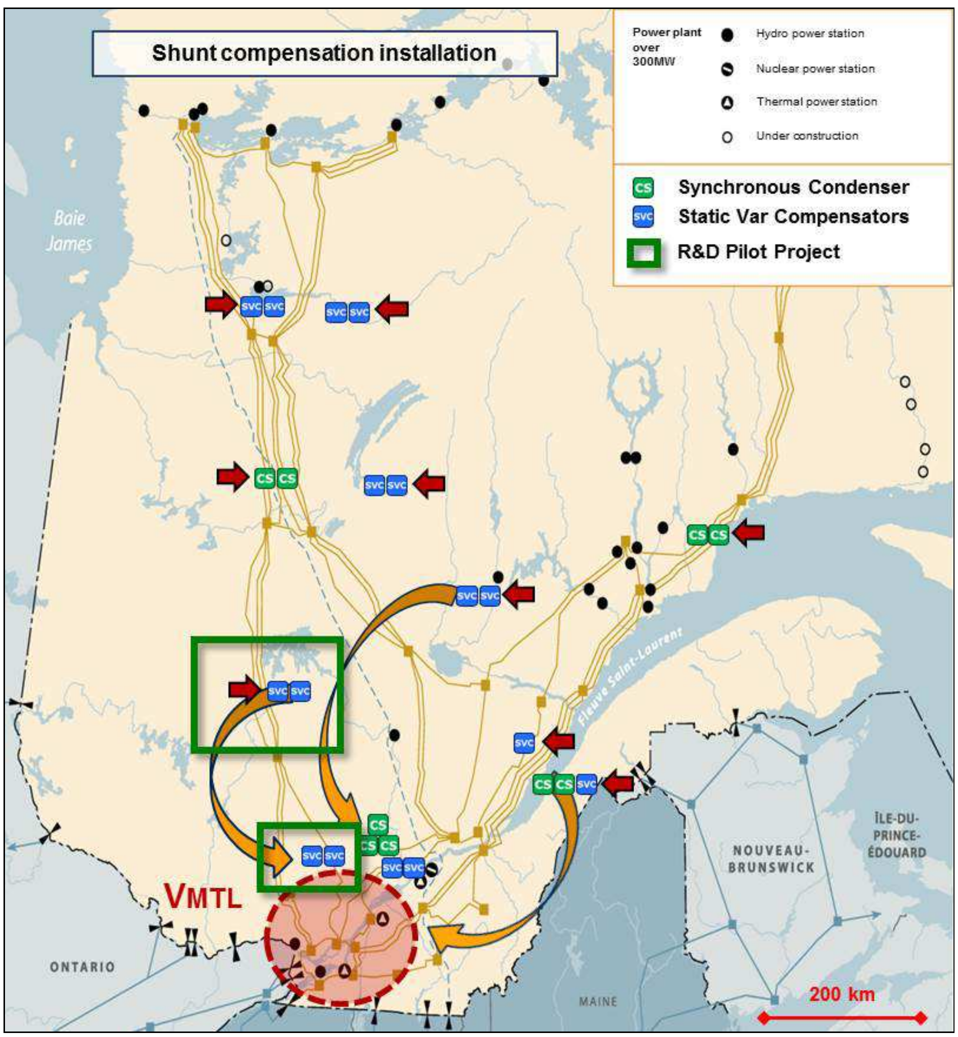

Figure 1: Hydro-Québec network with shunt installations and the GLCC control system

With the shunt compensators installed along the major 735 kV transmission lines it was necessary to develop a new WACS system that improves the contribution of the northern shunt element and the overall response time of the system, specifically for a voltage collapse situation in the load area. Following intensive simulation analysis using PSSE software in conjunction with innovative technology research and algorithms development, it is now established that the best and most cost-effective solution to these issues is the commissioning of a smart grid system that controls a synchronized action on the voltage set point of the existing SCs and SVCs without adding new power system equipment on the Hydro-Québec grid. As shown in Figures 1 and 2, the GLCC project merges two features dedicated to improving the voltage stability of the network namely, the global control strategy which is implemented on each shunt compensator of the grid and the addition of a local control strategy on the installations closest to the load area. These two control systems are independent of one another.

The global control strategy (in red in Figure 1) is based on the average voltage of the five main 735 kV Montréal substations (V_{MTL}). This information is calculated at the Hydro-Québec Network Control Center (NCC) and sent to each shunt compensator control substation where it is used as the main input for the control equipment. This data is communicated to the Substation Phasor Data Concentrators (SPDC) located at each shunt compensator installation in the form of synchrophasors by a Phasor Data Concentrator (PDC) located at the NCC.

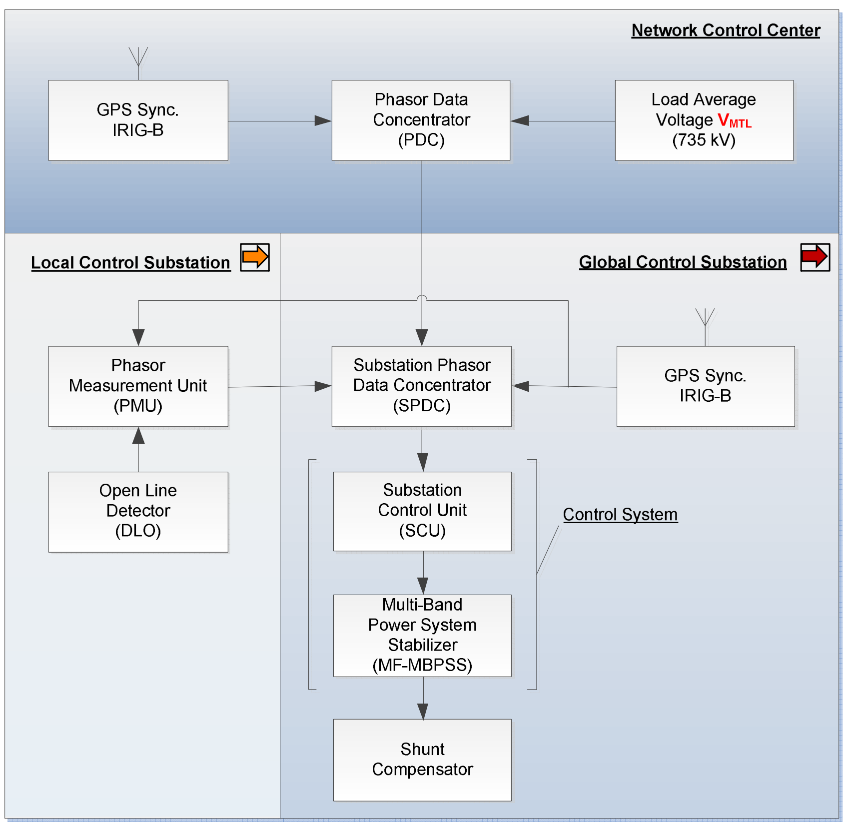

Figure 2: Hardware integration of the GLCC control system

The local control strategy (in orange) is based on the voltage level estimation of the nearest substation by the use of local measurements and the transmission line model characteristics. Specifically, voltage and current measurements are performed by PMUs that monitor every transmission line to the south taking into account the state of the corresponding line as provided by Open Line Detector (DLO) relay signals. This information from IEEE C37.118 compliant IEDs is then merged with the global control data in the corresponding substation SPDC. The local control strategy is used in dual functionality with the global control strategy only in the shunt compensator installation adjacent to the Montréal load area (see Figure 1) adding to the robustness of the GLCC strategy in case of a telecommunication malfunction between the substations and the NCC.

For this new WACS application, the PDC, SPDC and PMU hardware used in both control strategies are GPS-synchronized and connected through a country-wide dedicated telecommunication backbone meeting Hydro-Québec's strict performance requirements. From the SPDC, the electronic devices are the same for each shunt compensator installation (Figure 2). The main GLCC control consists in the Substation Control Unit (SCU) and Multi-Functional-Multi-Band-Power-System-Stabilizer (MF-MBPSS). In the installation using both control strategies, the SCU performs the calculations needed for the voltage estimation of the neighboring substation (V_{Local}) and also processes the average voltage data (V_{MTL}) of the Montréal loop transmitted from the NCC. The calculation of V_{Local} is performed in the SCU with the voltage and current synchrophasors from the sending end of each substation transmission lines where PMUs are connected. The line status is detected by the DLO and synchrophasors from lines that are in an open state are rejected from the (V_{Local}) calculation.

The V_{Local} and V_{MTL} signals are the main input to their respective local and global control strategy. Each of the control strategy is armed by a disturbance detector. Once armed, each control strategy has a set of rules that determine the permissive conditions to activate a corrective signal. This signal is forwarded as a ramp signal to the MF-MBPSS which controls the operation set point of the shunt compensator. The MF-MBPSS applies the control signal from the SCU by modulating the voltage reference of the shunt compensator while monitoring its voltage and power limitations. Consequently, each individual SCU and MF-MBPSS units have their specific settings depending on their location on the grid and the type of compensator they affect. Such control strategy enables the synchronisation and optimization of the entire reactive support of the Hydro-Québec dynamic shunt installations following severe contingences in the southern part of the grid.

REAL-TIME SIMULATION TESTS

These WACS control systems and algorithms are very complex and need to be thoroughly tested before their deployment on site. For this purpose, a complete hardware replica of the GLCC control system for a substation has been put in place at IREQ. The test bench installation was used for the SCU and MF-MBPSS algorithms development and validation. It was also used for the evaluation of the overall GLCC solution in real-time using the Hypersim environment for real-time power-system simulation.

The Hypersim simulator includes many tools such as a graphical user interface (GUI), a code generator, a waveform analysis display called ScopeView and a testing tool called TestView for automatic testing sequences, statistical or criteria analysis, generation of reports and database recording. The Hypersim real-time simulation runs on SGI parallel computers. For the GLCC evaluation, a 128-processors Altix 4700 is used at a 50 µs timestep. This simulator can run in real-time electrical networks of more than 750 bus bars with dynamic models of HVDC, SVC, SC, wind turbines, hydraulic machines, etc. The Hypersim simulator is also equipped with an IRIG-B time code receiver for time synchronization. Standard PCI cards with digital signal processors (DSPs) and digital-to-analog processors are installed in the SGI to provide external analog and digital input/output (I/O). This allows the simulator to be connected in closed-loop to external control devices.

For this specific hardware integration, the simulator provides currents and voltages to the current transformer (CT) inputs and voltage transformer (VT) inputs of the GLCC equipment through analog amplifiers. The MF-MBPSS control signal is sent back to the simulator through the analog I/O interface which affects the SVC and SC dynamic model behaviours in the real-time network simulation. Other control/status signals can also be exchanged with the control system for advanced testing. A total of 54 analog inputs/outputs, 18 power amplifiers and 10 logical inputs and outputs are used during the testing procedures. Adding to the Hypersim simulator environment, a designated programming platform is also required for the SCU and MF-MBPSS algorithms development by the IREQ researchers and for the hardware management and configuration of the PDC, SPDC, PMU, DLO, GPS clock and telecommunication switches. As a result of all these technical requirements, many connections between the GLCC equipment and the real-time simulator are required, as shown in Figure 3.

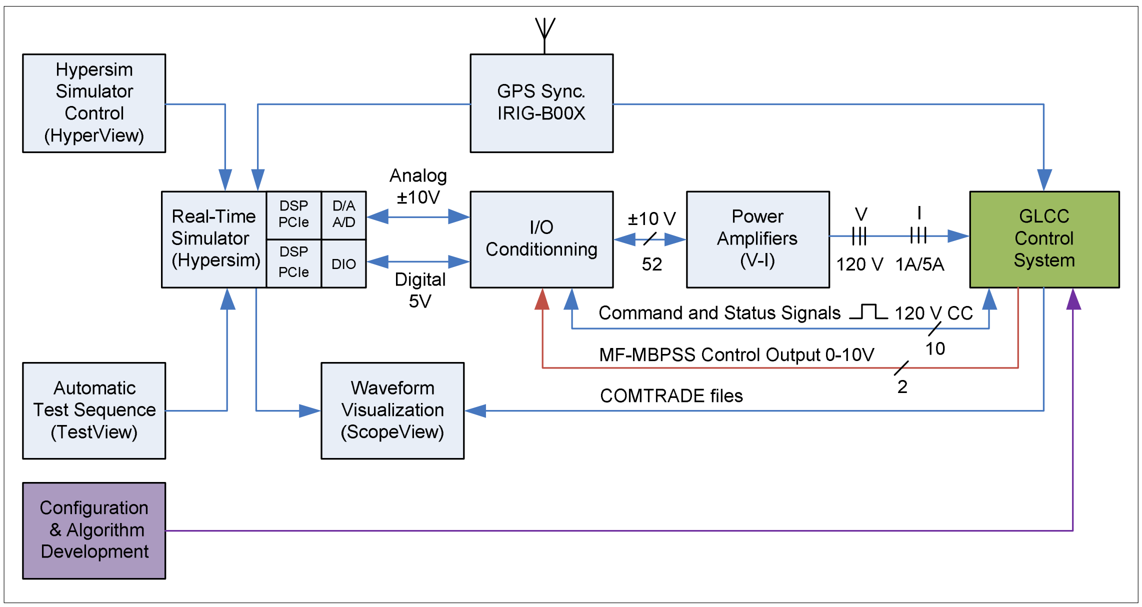

Figure 3: Hypersim real-time simulator configuration for the GLCC validation

In total, more than 8000 real-time tests were performed on the IREQ test bench replica of the GLCC system. To begin, performance assessment tests were carried out on each specific unit used in the GLCC control systems to ensure proper individual operation in addition to intensive reliability testing of the telecommunication network. Thereafter, simulations of the main Hydro-Québec network were performed with the complete GLCC control system connected in closed-loop to the Hypersim simulator, thus modulating in real-time the voltage set point of the dynamic shunt compensator models. Three main configurations of substation with shunt element have been tested this way. The first configuration consisted of a back-to-back double SVC of -230/+660 MVars at 735 kV of a substation feeding three transmission lines towards the load area. The second configuration was also a back-to-back double SVC configuration (-0/+600MVars) but for a substation connecting a pair of series compensated transmission lines to the south. Finally, the GLCC control system has been validated on a back-to-back SC installation of -400/+450 MVars at 735 kV with a standalone SVC. For each of these configurations, both local and global control strategy were validated from a reliability and security point of view. The reliability tests were conducted to evaluate the robustness and performance of the control system in the case of voltage collapse while the security tests were performed to verify its non-action in situations such as faults, line tripping, breaker fault, power oscillations, geomagnetic induced current (GIC), etc. Ultimately, the results were conclusive for all the network simulation cases, individual hardware evaluations and telecommunication tests.

FIELD TEST: PILOT PROJECT

Following the validation of the GLCC functionality on the Hypersim real-time simulator, a pilot project was initiated in order to assess the new control solution to an actual shunt compensation installation on the Hydro-Québec network. The aim of this pilot project was to validate the action of the global and local control strategy on a single SVC installation in a real operating environment. To do this, it was decided to install the GLCC control system at the La Vérendrye substation as shown in Figure 4 (zoom of Figure 1) where a back-to-back double SVC of -230/+660 MVars total at 735 kV is in operation.

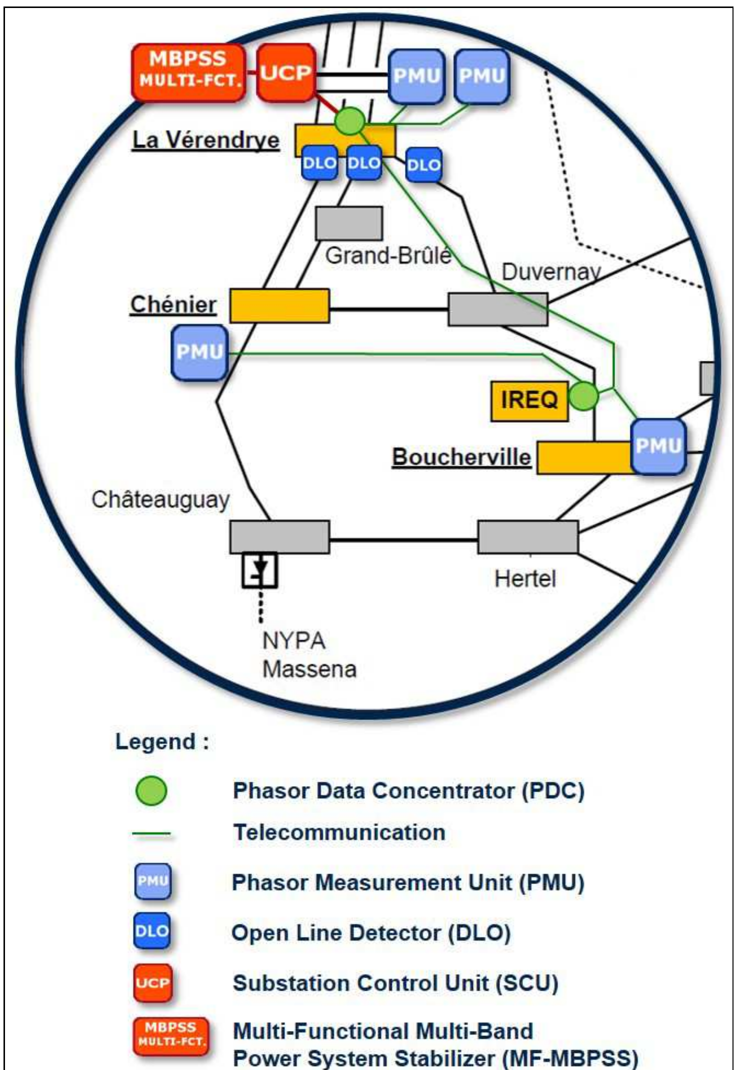

Figure 4: R&D pilot project installation of the GLCC control solution

At this substation, a full commissioning of the GLCC hardware solution shown in Figure 2 was implemented with all the connections needed to power equipment and a complete telecommunications network. For the specific needs of the pilot project, the load average voltage V_{MTL} was replaced by voltage measurements from PMUs located at the Chénier and Boucherville substations near the load area. These measurements were then sent to a PDC for synchronisation purposes and finally communicated to the La Vérendrye SPDC to be used by the global control algorithm of the SCU. For R&D purposes, it was also decided that the PDC of the pilot project would be located at IREQ in order to facilitate commissioning, wide-area monitoring and post-event analysis of the control system and also to compare the field tests results with those obtained with the Hypersim real-time simulation cases.

Once the commissioning completed, a series of tests first validated on the real-time simulator test bench were performed in the field with the joint assistance of employees from the La Vérendrye substation, the NCC, IREQ and Hydro-Québec TransÉnergie (TSO) engineers. This series of tests first included open-loop assessment of the GLCC security features versus shunt inductance switching, line tripping and voltage and power limitations of the control output. Open-loop tests were also conducted to validate the performance of the system with both SVC operations. Following the successful results of the open-loop tests, closed-loop validations of the global and local control strategy were performed by creating isolated voltage drops at the Chénier substation. These tests were made possible by adjusting the operation set point of the Chénier SVC, which resulted in voltage level deviations between the La Vérendrye and Chénier substation.

A typical closed-loop field test result is shown in Figure 5, where the effect of the GLCC control system is observed for a 0.02 pu voltage drop created by tuning the Chénier SVC operation set point from +100 MVars to -500MVars. The impact at the load area is clearly seen as the voltage collapse is avoided when the voltage level and consequently the reactive power support at the La Vérendrye substation is accordingly corrected by the GLCC control output.

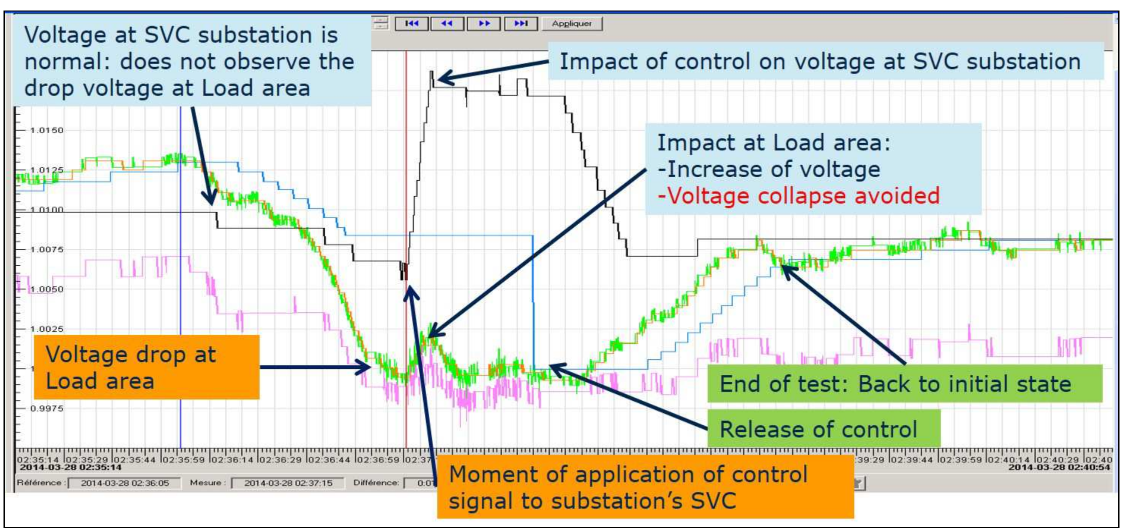

Figure 5: Field test result of the GLCC in closed-loop at the La Vérendrye substation

This result is also validated by comparing the behaviours of the signals obtained from the field tests to those collected during the real-time simulation of this specific test on the Hypersim simulator as shown in Figure 6. By comparing both Figures 5 and 6, it is observed that the behaviours of the signals obtained from the field test are virtually identical to those observed from the real-time simulation experiment. Hence, these results and their comparisons confirm both the validity of the GLCC control system on the actual network and the real-time testing environment on Hypersim. Ultimately, all the results from the pilot project were conclusive and the similarities between the field test signals and the corresponding real-time simulation results were also validated.

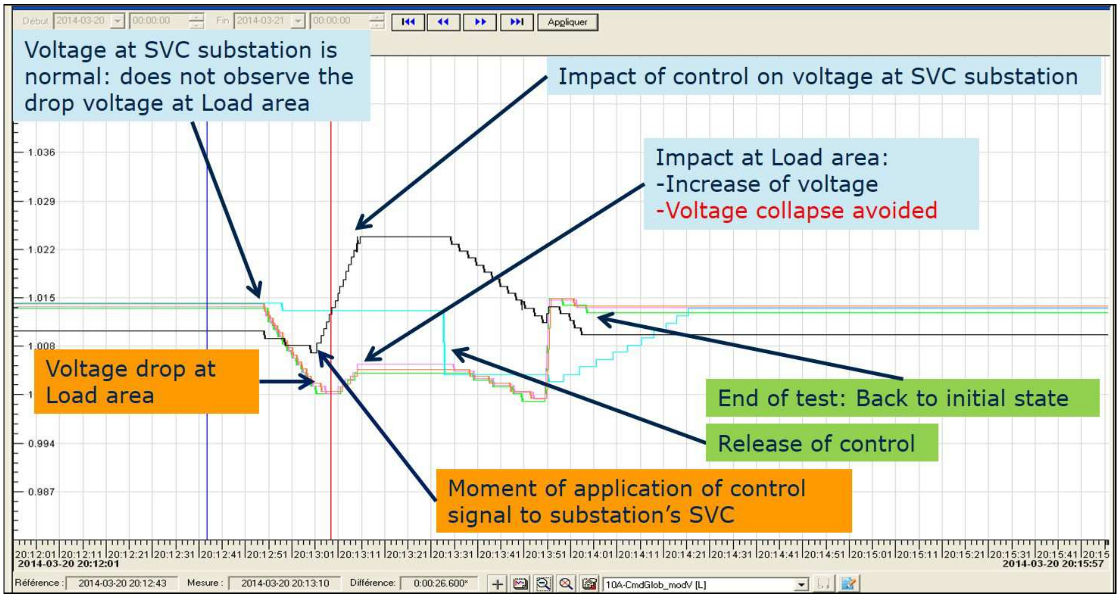

Figure 6: Real-time simulation result of the GLCC in closed-loop at the La Vérendrye substation

CONCLUSION

An innovative wide-area and local voltage control of dynamic shunt compensation devices to prevent voltage collapse has been developed by Hydro-Québec in the GLCC project. This new WACS solution was intensively tested in simulation using PSSE software and a complete hardware replica of the GLCC control system for a shunt compensator installation has been fully integrated and thoroughly validated on the Hydro-Québec Hypersim real-time digital simulator at IREQ, Hydro-Québec's research institute.

A pilot project has been commissioned and field tests results have been validated by the integration of the GLCC control system to an actual SVC installation with communication between the substations, IREQ and the NCC. The field tests results were validated by studying the control effect on the power system dynamic behaviour and by comparing these results to those obtained from real-time simulation.

In conclusion, the hardware in-the-loop real-time simulations and the field tests results demonstrate that the new GLCC control system is a robust, reliable and low-cost WACS solution that optimizes the reactive power support from the installed dynamic shunt compensators on the Hydro-Québec network. Following the successful GLCC innovation project, the deployment of this new voltage control system to all shunt compensators of the Hydro-Québec grid has been initiated.

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