Detailed Full-Bridge Modular Multilevel STATCOM Modeling for Real-Time Commissioning Studies

P. Le-Huy, O. Tremblay, P. Giroux, J.-C. Soumagne, D. McNabb

***Abstract*—Modular multilevel converters (MMCs) have several highly desirable features for SVC applications but they present a major challenge for electromagnetic simulation tools due to their extensive use of power electronic devices and complex topology. This paper presents the latest work conducted at Hydro-Québec's Research Institute to adapt its simulation tools to cope with MMC-SVCs. Following a discussion on the importance of real-time commissioning studies for major equipment such as SVCs and HVDCs, a real-time capable modeling of the full-bridge MMC suited for SVC application is presented. Furthermore, Hypersim's iterative engine is briefly discussed and the generic control scheme used for the sample application is shown. A fully-detailed typical full-bridge MMC-SVC is used to demonstrate the proposed modeling.**

***Keywords*: Electromagnetic transient, FACTS, full-bridge modular multilevel converter, power electronics, real-time, simulation, STATCOM, static var compensator, voltage-source converter.**

I. Introduction

HYDRO-Québec TransÉnergie (HQ-TÉ) is one of the early adopters of static var compensators (SVCs), installed primarily in the James Bay transmission corridor [1]. These devices are used to provide voltage regulation and enhance system stability by means of variable reactive power absorption or generation [2].

Early SVC installations relied on mechanically or thyristor-operated reactive elements to provide or absorb reactive power (i.e. thyristor-controlled reactors (TCRs) and thyristor-switched capacitors (TSCs)) in order to raise or lower the point of common coupling (PCC) voltage.

HQ-TÉ's SVCs are approaching the end of their operational lifetime and many are scheduled for refurbishment in the near future. Moreover, HQ-TÉ is planning to add SVCs to its transmission system to further improve overall system performances. For the time being, all these projects are based on the use of "classic" SVC technology (i.e. a combination of TCRs and TSCs) but eventually newer technology, such as modular multilevel converters (MMC, based on voltage-source converters (VSCs)) operated as SVCs [3], will be integrated into the Hydro-Québec power transmission system.

The MMC-SVC technology uses several hundreds of fully controllable power electronic switches (typically IGBTs) to synthesize amplitude-varying voltages in order to modify the generated (or absorbed) reactive power. Compared to older VSC technology, the MMC provides spectrally purer waveforms that reduce or eliminate the need for AC filtering, lower overall losses and improved reliability through inherent redundancy. However, as with all power electronic intensive applications, this technology presents several computational challenges for electromagnetic (EMT) simulation tools.

This paper presents the work conducted at Hydro-Québec's Research Institute to prepare and adapt its real-time EMT simulation tools for the commissioning studies associated with such systems. This kind of study is done with a replica of the control system hooked up to a real-time EMT simulator in a hardware-in-the-loop (HIL) configuration. At Hydro-Québec, real-time commissioning studies (in addition to all acceptance testing) are deemed essential to validate the behavior of the device-under-test (DUT) and accelerate the field commissioning.

Modular multilevel VSCs for SVC applications usually employ full-bridge power modules to synthesize the required voltage waveforms. As a single modular VSC-SVC contains more than 50 power modules, the computational burden is far greater that associated with the simulation of a "classic" thyristor-based SVC. Nonetheless, precise and detailed modeling is required in order to achieve all the real-time commissioning study objectives.

The present paper is divided as follows: the objectives of real-time commissioning studies are explained and justified in the first part. From that discussion, the need for detailed and accurate models should be clearly understood. The second part of the paper describes the full-bridge modular multilevel VSC, its modeling, as implemented in Hydro-Québec's real-time EMT simulator (Hypersim), and a generic control system suitable for such systems. In section IV, the modeling of a complete MMC-SVC installation adequate for commissioning studies is presented (i.e. all required power devices: breakers, surge arresters, filters, etc.) and used for the application

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example. Power system disturbances are then performed on this setup and results are commented. Finally, concluding remarks are given in section V.

II. Real-Time Commissioning Studies

Real-time commissioning studies are done 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 do this type of study, a detailed replica of the control system of the DUT 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

At Hydro-Québec, in-house real-time commissioning studies of major power equipments are deemed essential for several reasons:

- To validate if all functional requirements are met.
- To verify the control system behavior 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.
- The replica setup offers a realistic platform for the training of field operators and technicians.
- To validate field commissioning tests before actually executing 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. This part of the commissioning study is usually done prior to field commissioning.

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

As stated earlier, part of the real-time testing is done 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 people and hardware. If potentially dangerous transients are predicted by the simulations, the field tests can be modified to avoid such transients or additional precautions can be taken to reduce their impact.

B. Pros and cons

All in all, real-time commissioning has 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.

At the financial level, it marginally increases the overall cost of a project because of the cost of the replica, the conditioning hardware, the labor required for the study as well as the real-time simulator. These additional costs roughly add up to a small percentage of the overall cost of the project, depending on the type of installation (SVC, HVDC, etc.) and the complexity of the replica (e.g. fully redundant with all protection devices, without redundancy of some or all control features or stripped of some protection levels.) These additional costs may seem unacceptable to some but they should be regarded as an investment and a risk-reducing measure: (1) as an investment because the utility gains invaluable knowledge about the working of their new installation, a vast amount of hands-on experience on how to operate and tune the control and protection system and assurance that all specifications are met; and (2) as a risk-reducing measure since it makes for more efficient field commissioning with much fewer surprises, problems and delays.

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. In the long run, 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.

C. Size of simulated systems

Another important aspect is how to determine what needs to be included in the simulations to adequately evaluate the DUT. It is not an easy problem and the solution is rarely of the type "less is more"…

Several factors will determine the size of the simulated power system but the three most important will be discussed. One of the foremost is the limitations imposed by the real-time simulator used; there are several of these and each imposes different constraints. Another major factor is the level of knowledge of the power system. If essential parameters for key components such as transformers, power lines, static and dynamic loads are not available, a simple network equivalent is preferable. Again, the level of detail of the equivalent is a function of how well one knows his system and what his real-time simulator can take.

Unlike the two first factors, which usually tend to reduce the size of the simulated system, the third element, the proximity of other FACTS or HVDC systems or a system with multiple PCCs with an AC system, such as a multi-terminal HVDC system, may require a larger simulated power system to include neighboring devices that may interfere with the operation of the DUT or to adequately represent the dynamic of the AC system. It is wise to verify the absence of controller interaction, from several different systems and/or from a system that feeds on an AC system at multiple points. However, real-time simulator limitations can prevent such verifications due to the sheer size or complexity of the required simulations.

From the previous discussion, it may be concluded that there is no absolute rule to determine the size of the simulated power system and that each case will be different as each factor will have different weighting due to the specific needs of each study. For example, in one case the DUT may be connected to a very strong network far away from other dynamic devices and in a second case a very harmonic-sensitive equipment may be near the PCC: in the former, a simple network equivalent should be adequate while the latter will require more detailed modeling that goes beyond the immediate surroundings of the DUT.

III. Full-Bridge MMC-STATCOM

In the last few years, several papers have been published on modeling MMCs used for HVDC point-to-point links, multi-terminal systems and meshed DC grids [4][5][9]-[11]. These topologies typically rely on half-bridge power modules (PMs) placed in a double-star configuration (i.e. two common DC buses) suited for HVDC operation but they could also be used as a SVC. For SVC applications, MMC generally rely on full-bridge PM chains connected either in delta or wye [3][6]. The explored topology in this paper is the delta-connection.

A. Power Module and Topology

As illustrated in Fig. 1, a typical MMC-STATCOM is composed of delta-connected full-bridge PM chains. The number of PMs in each chain typically comprises between 10 and 30 PMs and is a function of several factors such as the power rating of the power electronics, the harmonic level specifications, the exact low-level control scheme, etc.

Each full-bridge PM is composed of four IGBT/diode pairs and a single capacitor, as shown in Fig. 2. The terminal voltage of each module is determined by the state of the power electronics and can present three voltage levels: $+V_c$, $-V_c$ and 0, where V_c is the capacitor voltage. It follows that a stack or chain of N full-bridge modules can present 2N+1 different voltage levels.

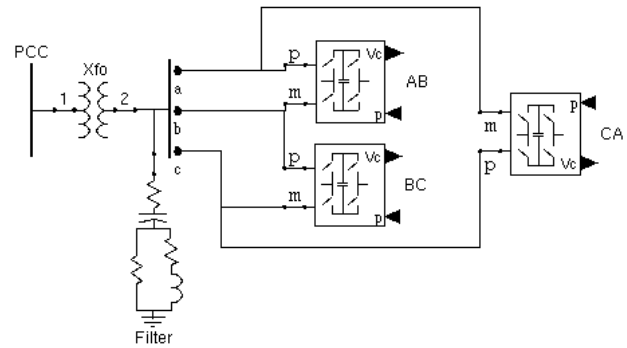

Fig. 1 MMC-SVC delta topology with filters.

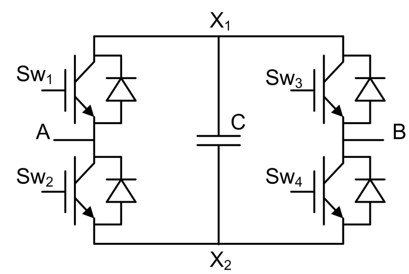

Fig. 2 Power module internal components.

B. Modeling

Hydro-Québec's real-time EMT simulator, Hypersim, is a large-scale multiprocessor simulator used for power system studies and for the development, validation, tuning and commissioning of control systems [7]. 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 errors, thus drastically improving the simulation speed [8]. For computational load reasons, the network equation solver of Hypersim uses piece-wise linear models for the representation of nonlinear devices such as power electronics and saturable elements. Furthermore, reactive elements are reduced to a real admittance in parallel with a current source representing the reactive elements' inertia, exactly like the original EMTP [9].

Direct simulation of the MMC structure with conventional EMT models yields very large systems of equations, resulting in impractical execution times, as demonstrated with the half-bridge MMC-HVDC in [10]. In the case of MMC-SVCs, fewer PMs are used but the mathematical complexity remains high if no simplifying scheme is used.

In the same fashion as in [11], MMC-SVC branches are represented with a Norton equivalent. In the modeling presented, the branch subsystem is then solved using a simple analytical solution derived from circuit laws instead of a full-fledged equation system solved by matrix computations.

Before constructing the arm equivalent, the module equivalent must first be determined. As mentioned earlier, each module contains four switching devices and a capacitor. Each switching device is represented by a R_{on}/R_{off} resistor and the capacitor by its EMT equivalent (current source in parallel with an equivalent resistor) as seen in Fig. 3 (a). Each module is then reduced to a single Norton equivalent (Fig. 3 (b)) where the equivalent resistance and current injection for a single module are derived as follows:

$$R_{eq} = \frac{R_{AB}\left(\dfrac{R_1 R_{AX_1}}{R_1 + R_{AX_1}} + \dfrac{R_3 R_{BX_1}}{R_3 + R_{BX_1}}\right)}{R_{AB} + \dfrac{R_1 R_{AX_1}}{R_1 + R_{AX_1}} + \dfrac{R_3 R_{BX_1}}{R_3 + R_{BX_1}}} \quad (1)$$

$$I_{eq} = \frac{R_c\left(\dfrac{R_2}{R_2 + R_4} - \dfrac{R_1}{R_1 + R_3}\right)}{R_c + \dfrac{R_1 R_3}{R_1 + R_3} + \dfrac{R_2 R_4}{R_2 + R_4}} I_c \quad (2)$$

where R_1, R_2, R_3 and R_4 are the switch resistances, which are equal to R_{on} or R_{off} depending on the switch state; R_c and I_c are the equivalent capacitor resistor and historic current injection respectively; R_{AB}, R_{AX1} and R_{BX1} are the delta equivalent of the elements connected between nodes A, B, X_1 and X_2, where the X_2 star point is suppressed. The arm equivalent is then simply the Norton equivalent of several modules linked together. The total admittance contribution is then

$$Y_{eqtot} = \left(\sum_N R_{eqx}\right)^{-1} \quad (3)$$

and the total equivalent current injection is given by

$$I_{eqtot} = Y_{eqtot} \sum_N R_{eqx} I_{eqx} \quad (4)$$

where R_{eqx} and I_{eqx} are the equivalent resistance and current injection of the x^{th} PM in the chain respectively.

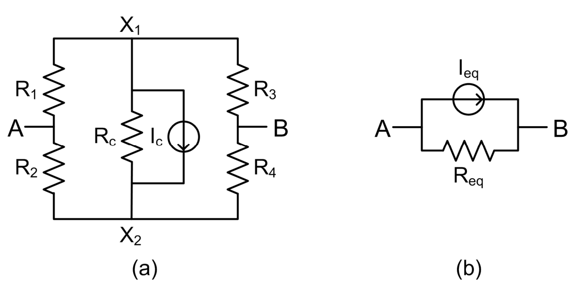

Fig. 3. Power module modeling (a) and equivalent (b).

Determining the exact conditions of each individual module is then simple since the current flowing between the delta nodes is easily calculated and all current injections of the modules are known. This task, by its nature, is well-suited for recursive divide-and-conquer algorithms.

This method has the characteristic of retaining all the operating details of the switch devices (i.e. IGBT/diode states, currents, voltages and parameters) since they are needed to determine the branch equivalent. Under certain circumstances, this level of detail may be unnecessary but, for real-time commissioning studies, the ability to represent abnormalities and parametric differences between branches and/or PMs is a major advantage.

Mathematically speaking, using this representation is quite advantageous since all the internal nodes are removed from the nodal equation system, hence reducing the admittance matrix size and the computational cost of its factorization or inversion, depending on the actual solver algorithm. Furthermore, computing the branch equivalent is a simple, albeit tedious, task that only requires the voltage at both extremities and prior knowledge of the operating conditions of the branch PMs.

C. Iterative Solution

To accurately represent the behavior of MMC systems, the natural commutation of the diodes must be taken into account which explains why the PM modeling in [11] and [12] includes an iterative solution to determine the status of all switches. This approach was then applied to all switching elements [13] and nonlinear elements [14] in Hypersim. For the purpose of the present paper, which is to present a "real-time commissioning-ready" modeling of the MMC-STATCOM, the surge arresters and the MMC-SVC branches are all handled jointly in the iterative solver. More details on the iterative solver can be found in [13] and [14].

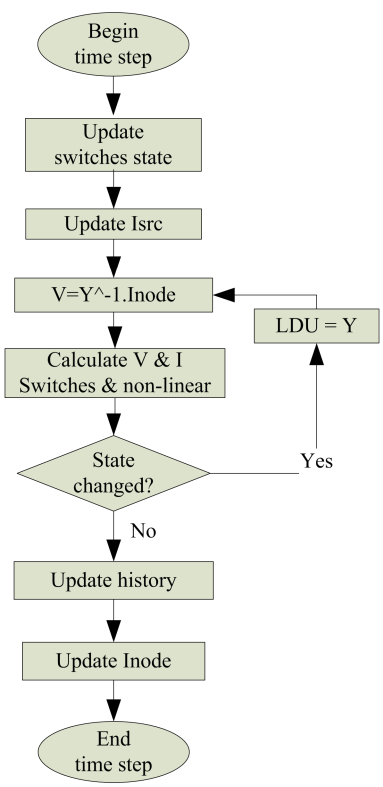

Fig. 4 Iterative engine flowchart.

D. Generic Control System

The scope of the current paper does not include MMC-SVC control design and a simple and generic control scheme is therefore presented for the purpose of the application example. As shown in Fig. 5, the measurement and synchronization unit provides the d-q components of the voltages and currents at the PCC as well as the positive-sequence value of the PCC voltage. The current regulator requires the d-q current references to generate the d-q components of the voltage to be synthesized. These references are provided by the cell voltage regulator for the d-axis reference and by the positive-sequence or reactive power regulator for the q-axis reference depending on the selected control mode. Several advanced schemes can be used for the pulse generation, which enhance performances at the cost of increased complexity, but the described controllers rely on nearest-level selection with an integrated capacitor-balancing algorithm (which tolerates a certain deviation from the nominal capacitor voltage value (Tol_{vcap})).

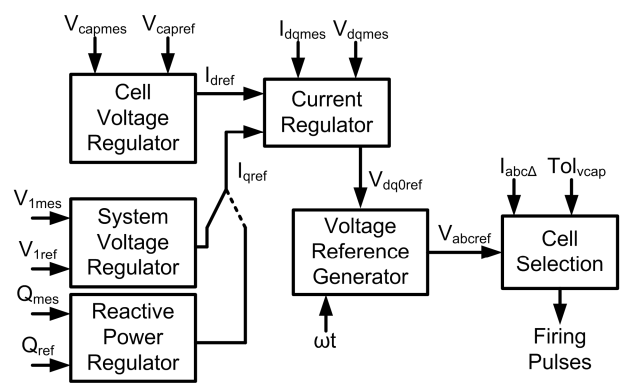

Fig. 5 MMC-SVC control scheme.

IV. Application Example

For the sample application, a system similar to Fig. 1 is used, as illustrated in Fig. 6. An equivalent network with a short-circuit level of 1 GVA feeds the 50-Mvar MMC-SVC through a 220/22 kV wye-delta lag transformer. Each point of the delta connection, as well as each branch of the delta, is protected with a surge arrester. The MMC-SVC is composed of 22 PMs per branch and the total energy stored in the SVC represents approximately 12.7 kJ per MVA of SVC. The necessary parameters to duplicate this simulation are provided in Table I. It is important to note that these parameters are arbitrary and are not based on any particular installation or project.

For the purpose of this example, the equivalent network can be programmed with various disturbances and fault breakers, which are not represented in Fig. 6, are placed at bus B1.

The MMC-SVC controller was developed in Matlab Simulink and is incorporated in Hypersim through the Hyperlink interface. A separate processing unit is used for the controller. All simulations presented in this paper were done in real-time on a SGI UV system.

For a preliminary study, the equipment supplier could provide a “black box” controller (Matlab Simulink protected model reference, precompiled static or dynamic library, etc.) and simulations could be done exactly as presented in this application example. Obviously, real-time commissioning studies require a replica of the controller which would be interfaced with the simulator through IOs.

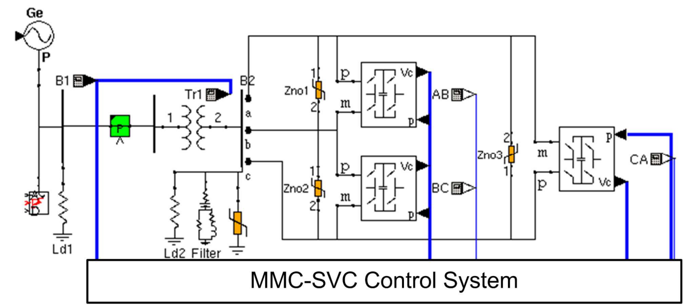

Fig. 6 “Real-time commissioning-ready” modeling of an MMC-STATCOM with a network equivalent at the PCC.

TABLE I

Sample Application System Parameters

Equivalent network	Value
Frequency	60 Hz
Voltage (line-line rms)	220 kV
Short-circuit level	1 GVA
X/R	7
Linear transformer	50 MVA
Connection	Y_g-Δ_{lag}
Ratio (line-line rms)	220/22 kV
X leakage	0.15 pu
R leakage	0.003 pu
MMC-SVC	50 Mvar
PMs per branch	22
Capacitor	7.5 mF
Capacitor nominal voltage	1.6 kV
Branch reactor	7.7349 mH
Reactor resistance	29.16 mΩ
R_{on}	1 mΩ
R_{off}	100 kΩ
Loads	
Ld1	10 MW
Ld2	5 kW
High-pass filter	
Q_{nom}	2 Mvar
F_0	300 Hz
Quality factor	10

A. Positive-Sequence Voltage Setpoint Change

This first disturbance is a simple setpoint change for the positive-sequence voltage regulator to illustrate the normal operation of the MMC-STATCOM. Initially, as seen in Fig. 7, it operates in inductive mode as it regulates the PCC voltage at 0.95 p.u. (internal voltage of the equivalent power system is at 1 p.u.). At 0.1 s, the setpoint is stepped to 1.05 p.u. which brings the generated reactive power a little bit over 1 p.u. with a small overshoot. The SVC is then in full capacitive mode. This simple case is useful to demonstrate the normal dynamic behavior of the sample application system.

B. Equivalent Network Voltage Step

As the last section, the MMC-SVC is regulating B1 voltage at 0.95 p.u. while the network equivalent's voltage is 1 pu. To do so, it must operate in inductive mode at nearly 1 pu ($Q_{mes} \approx$ -1 p.u.). Then, in order to exacerbate the surge arresters, the equivalent network's internal voltage is stepped up to 2.5 p.u. at 0.1 s with a linear decay to 1 p.u. in 0.1 s as shown in Fig. 8. Since the MMC-SVC synthesized voltage is limited by the capacitors' voltage, the SVC is seen as a very inductive load (see bottom graph of Fig. 8). It is interesting to observe that the surge arresters effectively limit the overvoltage in the MMC-SVC to approximately 3 kV (second graph from bottom in Fig. 8); without them, the capacitors' voltage rises to approximately 4.5 kV.

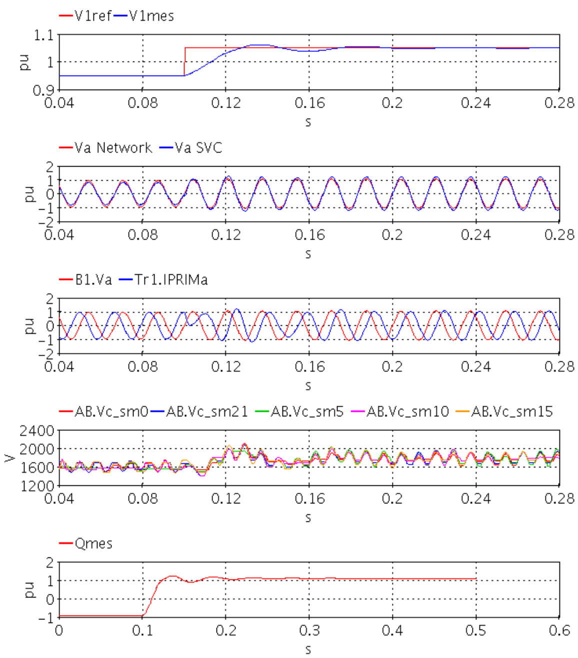

Fig. 7 MMC-SVC waveforms for positive-sequence voltage reference step at 0.1 s: positive-sequence voltage reference and measurement (top), network and SVC voltage (second from top), network voltage and transformer primary current (middle), sample of capacitor voltages from branch AB (second from bottom) and measured reactive power (bottom).

A more complete controller would have a protection system that would trip the whole SVC due to overcurrents (almost 10 p.u.!) as seen in the middle graph of Fig. 8.

Finally, this disturbance is useful for observing the impact of Hypersim's iterative engine: in Fig. 9, the red and blue waveforms are obtained when the iterative engine is turned on and off respectively. It is easy to see the importance of iteration in the representation of surge arresters for the modeling of MMC-SVC. Without the iterative engine, delays in the application of the correct admittance and current injection lead to uncharacteristic behavior, as in Fig. 9, and possibly to numerical oscillations depending on the simulated network.

These two disturbances are simple examples of what can be done in real-time commissioning studies. Extensive testing of the DUT is often required and fully detailed modeling as presented in this paper is essential to adequately measure response times, verify functional requirements and validate special operating modes.

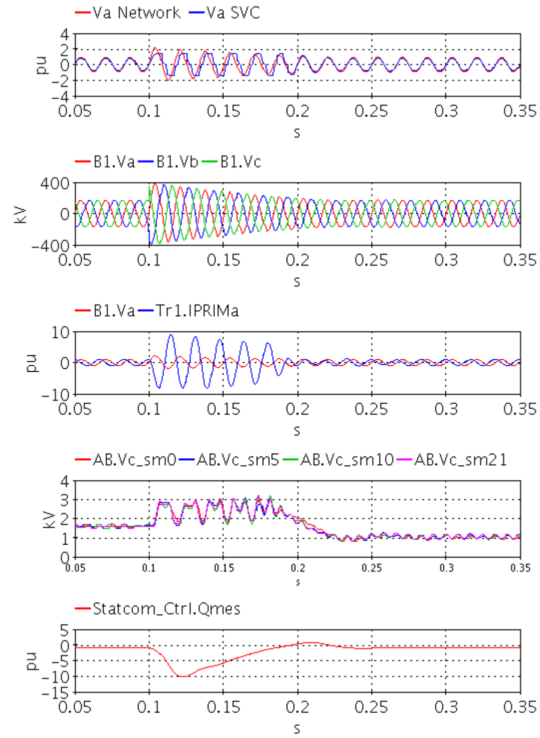

Fig. 8 MMC-SVC waveforms for a network voltage step at 0.1 s: network and SVC voltage (top), transformer primary voltage (second from top), network voltage and transformer primary current (middle), sample of capacitor voltages from branch AB (second from bottom) and measured reactive power (bottom).

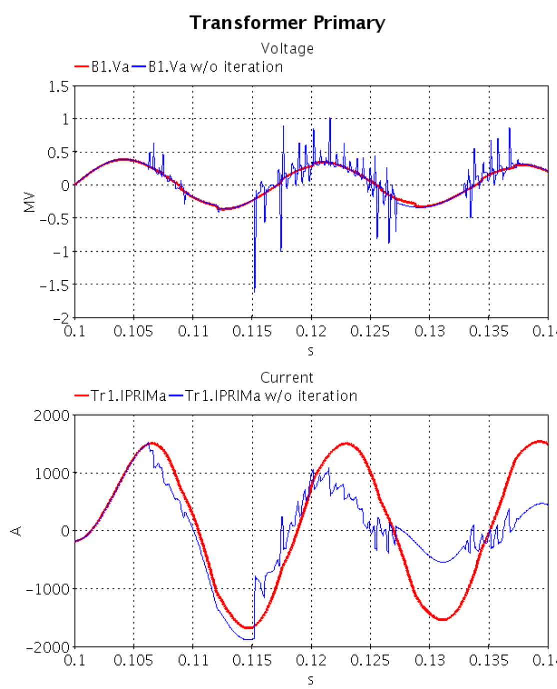

Fig. 9 Comparison of transformer primary voltage and current of phase A during the voltage step with and without iteration (red and blue waveforms respectively).

C. Real-Time Performances

The system content and simulation performances are presented in Table II. The sample application is simulated in real-time with a time step of 25 µs on two SGI UV processing cores (Intel Xeon E7-8837 @ 2.67 GHz).

TABLE II
REAL-TIME SIMULATION PERFORMANCES

CPU 1: Electrical system exec. time	19.2 µs
Electrical nodes	216
Passive elements	84
Nonlinear elements	6
Switches	271
Digital communications	264-in
Analog communications	78-out
CPU 2: Control system exec. time	7.5 µs
Digital communications	264-out
Analog communications	78-in

V. CONCLUSION

This paper presented how detailed full-bridge MMC-SVCs are implemented in Hydro-Québec's real-time EMT simulator, Hypersim. The reason for such detailed models was given in a discussion on real-time commissioning studies and their numerous advantages. Following this discussion, the actual full-bridge PM modeling, its relation with Hypersim's iterative solver and a generic MMC-SVC controller were presented. Finally, a sample application of a complete MMC-SVC installation running in real-time was subjected to several disturbances to illustrate the usefulness of the modeling and Hypersim's capabilities.

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