Unified Modeling and Simulation Approach for Modular Multilevel Voltage Source Converters

P. Le-Huy, S. Casoria, O. Saad

***Abstract*—This paper presents a unified approach for efficient modeling and simulation in a multi-tool environment. The motivations are clearly defined and the approach is explained. While this method is applicable to a wide range of tools and applications, it is illustrated with Matlab/Simulink, for control system development, and two EMT simulation tools, EMTP-RV and Hypersim. The sample application is a point-to-point HVDC link based on modular multilevel voltage source converters: the EMT modeling of this technology is briefly presented as well as a complete control and protection system. The unifying agent in this example is the Simulink controller but the unified approach could be applied with other parts of the system and/or developed in other software. Results comparison is shown to be excellent and fully coherent, enabling this software to be used with full confidence in its respective niche applications.**

Keywords: Cascaded two-level converter (CTLC), electro-magnetic transients (EMT), HVDC transmission, modular multilevel converter (MMC), offline simulation, real-time simulation, voltage source converter (VSC).

I. Introduction

In order to cope with the rapid introduction and integration of new technologies in power systems, electromagnetic transient (EMT) simulation tools, both off-line and real-time, must adapt if the required time of the design cycle is to be reduced, since simulations are at the core of the planning, design, validation and commissioning processes. The newest generation of voltage source converters (VSCs) is the main driver for the latest evolutionary step in the EMT software community due to their use of a very high number of power electronic devices. This technology, known as modular multilevel converters (MMCs) or cascaded two-level converters (CTLCs), generates voltages with very low harmonic content and presents loss levels much closer to those of “classic” thyristor line-commutated converters [1][2][3]. Different modeling techniques have emerged for this modular multilevel technology [4][5][6] and each fills different roles in different simulation tools but all should give coherent results given identical control systems. That idea is the basis of the presented unified approach for the EMT modeling and simulation of power systems.

The proposed paper presents a design approach that covers the whole EMT-based development cycle and focuses on the collaborative simulations that integrate models from different simulation tools to shorten the various design steps and ensure coherent and accurate results through cross-validation. This approach is applied to the study of an HVDC link based on CTLCs where the control system is designed in the Matlab/Simulink environment and initially validated with the Matlab SimPowerSystem (SPS) toolbox. Thereafter, this controller is exported into C code using Simulink Coder (SC) and integrated into EMTP-RV and Hypersim (both operating on standard personal computers) for off-line planning and integration study simulations. Finally, to close the loop, the same power system schematic could be effortlessly ported to the real-time hardware platform of Hypersim for real-time studies, thus providing a complete cycle of simulation and cross-validation. Most often, this last real-time simulation step also implies the presence of a control system replica of the device under test for hardware-in-the-loop simulations. Furthermore, other software-in-the-loop controllers (or replicas if available) could also be included in the simulation for controller interaction and coordination studies.

The paper opens with the motivations and details of the suggested approach, including the different tools involved as well as how to interface external components. MMC/CTLC modeling is briefly presented while the control and protection system, the unifying component in this work, is presented in more detail. The description of the HVDC system used to illustrate the integrated approach is then given along with simulation results and the paper closes with the usual summary and concluding remarks.

II. Unified Modeling and Simulation Approach

A. Motivations

A wide range of advanced industrial-grade EMT simulation software is available today, each with a different data input method and different library of models. There are methods to adapt user-files or model data from one tool to another but automatic data exchange and cross-compatibility are currently not available. This is a major drawback in today’s industry, since it is often required in the same organization to perform studies using several different software tools or to integrate models developed by equipment manufacturers using proprietary tools or other incompatible packages.

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To cope with this reality, large efforts must be made to adapt, or even develop from scratch, a similar model or control system which must then be validated and benched against the original. These extra steps obviously involve added costs that may not have been anticipated in the project or study budget.

Although there is a thrust towards unified and wideband methods in EMT simulation software, different tools will continue to coexist due to competition among software vendors, computational performance issues, established databases, various extensions in application fields and, more importantly, corporate culture and market/business pressure. It is not uncommon to use certain software because it's the "de facto" tools in a certain field, even if internally other tools are preferred, or because the "change management" cost is too high.

To reduce the cost of this multi-tool reality, a different approach must be taken. To do so, several paths can be followed such as a common data information format and an application programming interface (API).

A major source of difficulties when using several simulation tools is the difference between parameter input methods: depending on the level of details, the nature and quantity of required parameters may vary and "parameter translation" may be necessary, an operation that requires intimate knowledge of the tools involved. A possible solution for this problem resides in a common data format where the required parameters for several different levels of modeling, from short-circuit to highly precise transient analysis, are present: since each tool would take from the data file the parameters required by its solver, a single data file could be used for all tools. The Common Information Model (CIM) [7] is a possible approach and can be augmented and reused for EMT-type applications. However, data portability, while highly desirable, is only a part of the solution since it does not allow benefiting from the numerical capabilities and model implementations available in other software.

Another very promising path to facilitate multi-tool work is the definition of common or standard API. A standard API would allow EMT (or other types) software to easily interact with each other but it would require establishing a standard set of communication channels for each type of simulation. These channels would allow the exchange of electrical signals as well as control signals and parameters and other information related to the numerical methods. The standard should be flexible enough to allow different levels of sophistication as different tools employ a wide range of solvers and numerical techniques and methods.

While this paper does not offer a common data format or an API standard definition, it does offer a good example of API-based modeling and simulation approach: Simulink is used to develop a complete control and protection system, which is then incorporated into EMTP-RV and Hypersim. In EMTP-RV, the API is implemented through a dynamic library approach while in Hypersim the source code is directly integrated into the simulation code.

B. EMT Simulation Tools

Power system simulators are strategic tools used by Hydro-Québec engineers and researchers for planning and operating the Hydro-Québec transmission system, integrating renewable energies, testing new concepts and training technical staff. Hydro-Québec Research Institute's expertise in power system simulation was built up mainly on the development and operation of real-time simulation technologies (Hypersim) and modern off-line simulation tools for studying electromagnetic transients and power electronic-based equipments (EMTP-RV software and SPS toolbox).

Hypersim [8][9][10] is a real-time/offline EMT simulator (SGI supercomputers are required for real-time but offline simulations can be done on personal computers). It uses the classic nodal approach with automatic partitioning of the power system equations. The computational burden is automatically mapped to the available processor cores. Hypersim sports several interesting features (see cited references for more details) but the one exploited in this paper is its ability to incorporate external codes such as dynamic or static libraries in addition to the external C code.

EMTP-RV [11][12][13] is the restructured version of the well-known electromagnetic transient program EMTP. EMTP-RV uses a new approach for assembling network equations: sparse modified-augmented-nodal analysis. Performances are enhanced through the use of a Jacobian-based nonlinear solver that eliminates topology restrictions and exhibits a higher rate of convergence. The EMTP-RV solver allows the inclusion of external libraries and, if allowed by the external code, they can also be integrated into the iterative and critical damping adjustment (CDA) algorithms.

C. Interfacing with External Code

Hypersim uses a code generation approach to simulate a network configuration. The code for the components and models present in the network is generated and assembled to generate an executable that will be simulated. So it is a straightforward process to incorporate and embed in this process an external code such as the one generated with the SC.

The EMTP-RV program is a stand-alone application and has a closed code architecture. It uses a different approach to incorporate an external code [14][15]. The idea is to make public the internal methods used in the hosting application for implementing models which allows DLL-based external model equations to be inserted into the actual solution system and equations without any limitations. Linear and simultaneous solutions and complicated model implementations are achieved in the same way as the actual models in the hosting code and use the same services and memory access. In the case of EMTP-RV, the external methods will be called at each iteration to update its equations and thus participate in the actual simultaneous solution (if iterative solver support is available).

D. *Approach*

Since the motivations, tools and interfacing methods have all been described, the modeling and simulation approach per se will now be described. For the purpose of this paper, the unification factor is the control and protection system of an HVDC link. It was developed and tested in Simulink with SPS for the electric part. Instead of duplicating this control system in each environment, the Simulink Coder [16] is used to convert the Simulink controller into C code for Hypersim and to create a dynamic library for EMTP-RV.

This method ensures an identical control system in all three software environments, which is crucial as the behavior of power electronic intensive devices is dictated by their control system. It would be futile to hope for exactly the same responses if the controllers are not the same.

As mentioned earlier, it is often required to do several studies of the same system with different tools to explore various aspects of system performances. The approach presented here minimizes the "translation" work, and the associated error risk, and brings coherence to the simulation results. As the controller's behavior is the same, differences in results are therefore attributable to the level of details in each tool and the simulated phenomena.

The tools used in this work were chosen because of local availability: the idea of integrating a part of the simulation from one tool into multiple others is applicable whatever the tools. Instead of a Simulink controller, it could be a controller from a vendor's specific development tool integrated into a stability tool or other EMT simulators. Furthermore, instead of being unified by the same controller, the simulation tools could reuse the same device model (e.g. wind or solar power plant model).

III. MMC/CTLC MODELING AND CONTROL SYSTEM

The MMC modeling techniques used are described in detail in the following subsection while a full-fledged control system is presented in subsection B.

A. *MMC/CTLC Modeling*

As illustrated in Fig. 2, a MMC/CTLC is composed of several fundamental units, usually referred to as power modules (PMs), submodules, or cells. A PM is essentially a half-bridge two-level converter, as seen in Fig. 3(a). A large number of basic units are then stacked to create each of the six converter arms. A serial reactor is placed in each arm and, in some cases, a second harmonic filter is also added in each of the phases.

The operating principle of this kind of converter is fundamentally simple: the high-level control system determines the voltage waveforms to be synthesized and these are then translated into a certain number of active and inactive PMs per arm by the low-level control algorithms. An active module inserts its capacitor into the circuit while an inactive one shorts its terminals. Each arm can be considered as a variable voltage source. The following section describes in more detail the control system.

In SPS, two PM models were used: an average model, which neglects the rectifier effect of the diodes, was used early in control system tests, and a complete model, similar to the one in Hypersim (Fig. 3(b)) was used for the start-up sequence and blocking tests. When porting this modeling to Hypersim, considerable efforts were made to enhance the execution speed in order to respect real-time constraints [17]. As for EMTP-RV, the detailed model, described in [5], was used in this work to fully exploit EMTP-RV's precise solver.

B. *Control System*

Based on [18][19], the various subsystems of the main control are shown in Fig. 4 and are briefly described below. The "high-level" functions are discussed first followed by pulse generation, referred to as "low-level" functions.

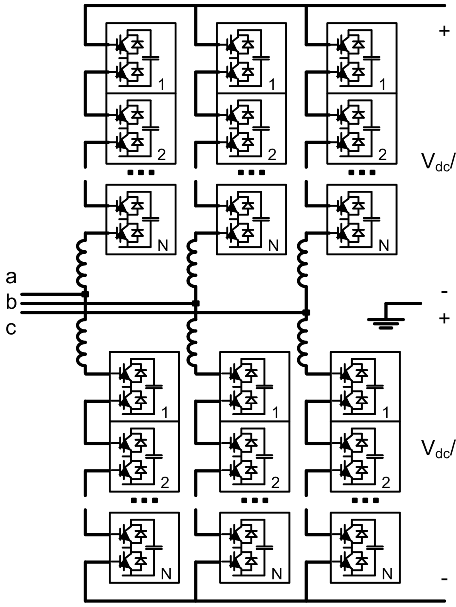

Fig. 2 Conceptual diagram of the MMC/CTLC topology.

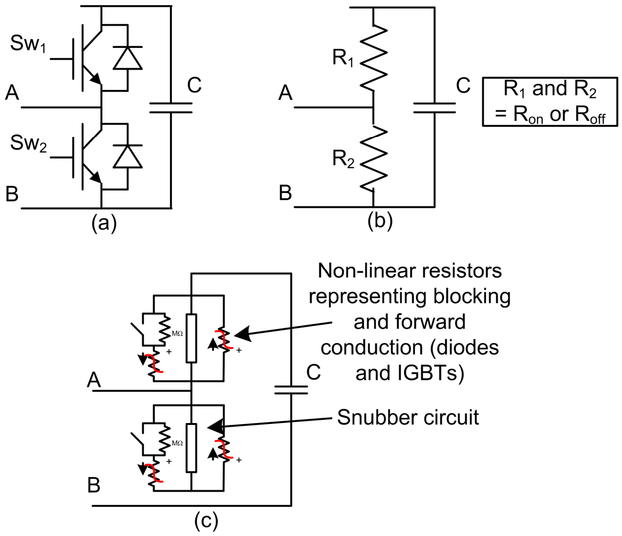

Fig. 3 (a) Simplified PM content; (b) SPS/Hypersim and (c) EMTP-RV PM modeling.

The measured AC and DC signals (voltages and currents at the PCC and at the valve side of the converter transformer, DC voltages and currents at the converter poles) are inputs to the “Interface & Transformations” (IT) subsystem. The signals are sampled and held to respect the control cycle time. To avoid noise errors, the signals are filtered and then normalized (per unit system, or pu). Through Clarke transformation, the three-phase stationary coordinate system is translated to the two-phase α-β stationary coordinate system. When necessary, the signal measurements on the primary side should be rotated by ±π/6 according to the transformer connection (YD11 or YD1) in order to have the same reference frame for both sides of the transformer. Subsequently, α-β quantities are mapped to the dq0 domain through Park transformation. In this case, however, zero-sequence components are not considered since they are blocked by the transformer’s delta connection. A three-phase phase-lock loop (PLL) provides the phase angle for the d-q reference frame. The d-q components are aligned with the active power and reactive power respectively.

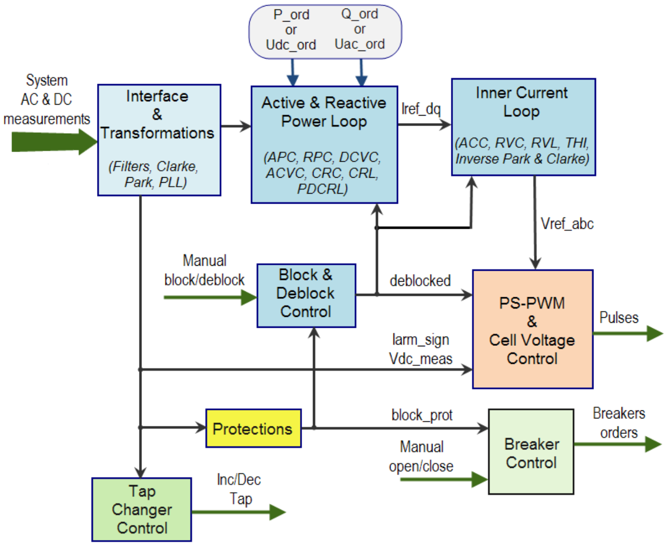

Fig. 4 Block diagram of the complete control system

The “Active and Reactive Power Loop” subsystem contains different PI-based regulators (with anti-wind-up and feed-forward) which provide current references to the “Inner Current Loop” (ICL). The “Active Power Control” (APC) function regulates the active power flow (P_ord) at the PCC. The APC works in a complementary fashion with the “DC Voltage Control” (DCVC), which instead regulates the DC voltage (Udc_ord).

In APC mode, a “Power-Dependent Current Reference Limiter” (PDCRL) function is active: when a DC power reduction is detected, during a system fault for example, the PDCRL function limits the d component current reference in order to obtain a controlled recovery and provide support to the DC regulating converter. This support is essential when the AC fault occurs in the power system of the DCVC-operating converter. The APC also features a power order override that maintains the DC voltage within a predefined operating range.

The “Reactive Power Control” (RPC) regulates the reactive power (Q_ord) at the PCC. When this mode is not selected, the “AC Voltage Control” (ACVC) takes over and regulates the voltage amplitude (Uac_ord) at the PCC. The RPC includes an override control function that limits the RPC output to guarantee acceptable AC voltage. A “Current Reference Calculation” subsystem (CRC) transforms the power references (Pref and Qref), calculated by the regulators, to current references (Iref_d, Iref_q) according to the measured secondary voltages. The “Current Reference Limitation” (CRL), limits the current reference vector to a predefined area within the d-q plane, in order to respect the converter ratings. In DC voltage control mode, higher priority is given to the active power, i.e. the d component. In power control mode, d and q components, which translate to active and reactive power respectively, are treated equally.

In the ICL, the “AC Current Control” (ACC) function tracks the current reference vector (d-q components) with a feed-forward scheme to achieve a fast response during load changes and system disturbances. The “Reference Voltage Conditioning” (RVC) takes into account the actual DC voltage and the theoretical maximum peak value of the fundamental bridge phase voltage in relation to the former to adjust the reference voltage. To avoid over-modulation, the voltage reference is limited, within a circle of a defined radius, in the “Reference Voltage Limitation” (RVL) subsystem. In order to achieve better DC link utilization at high modulation indices, the sinusoidal reference signal is injected with a third harmonic component having a maximum amplitude of 0.155 pu without causing over-modulation (Third Harmonic Injection (THI) function). Finally, the inverse Park and Clarke transformations are used to generate the three-phase voltage references (Vref_abc).

The “Block/Deblock Control” (BDC) activates or deactivates the converter upon detection of a falling or rising edge respectively. In the blocked state, no firing pulses are sent to the power electronic devices.

“Breaker control” (BRKC) operates the converter’s main circuit breaker as well as the pre-insertion resistor’s auxiliary breaker.

The converter transformer turns ratio is controlled by the “Tap Changer Control” (TCC) subsystem to maintain the converter voltage and the modulation index within acceptable ranges.

The “Protection” (PROT) subsystem contains the necessary AC and DC protections that will block the converter in case of severe disturbances that could be harmful for the equipment. This subsystem can order, through the BDC and BRKC, a converter isolation sequence which consists of a deactivation of the VSC and a main breaker opening.

All the previous functions form what is referred to as the “high-level” control. The low-level functions translate the voltage references into firing orders for the power electronic devices. Phase-shifted pulse-width modulation (PS-PWM) is used: the voltage references, weighted by the Cell-Voltage

Control (CVC) according to each cell actual capacitor voltage, are compared to a low carrier frequency (3.37 times the AC system fundamental frequency). This carrier wave has a different phase angle for each PM.

The CVC ensures global balancing (the sum of cell voltages in all arms converge to the DC-bus voltage (pole-to-pole, Vdc_meas) and individual balancing (each cell voltage remains in the vicinity of its voltage reference). This function is implemented by means of a low-magnitude amplitude modulation (set proportional to the error between the cell-voltage reference and the individual cell voltage) that is added to the modulation reference voltages. Thus, overcharged capacitors are less activated during the charging part of the cycle (positive arm current) and more solicited in the discharging part (negative arm current), thereby greatly reducing capacitor voltage excursions. The same principle is applied to undercharged modules.

IV. APPLICATION EXAMPLE

A. CTLC-HVDC Link Test System

A 1000 MW VSC-HVDC point-to-point link, using CTLC technology, was modeled in EMTP-RV and HyperSim (see Fig. 5). Both converter stations, ST1 and ST2, are composed of a 36 PMs per arm CTLC, its complete control and protection system (described in last section) and a YgD1 three-phase transformer with magnetic saturation. The stations are connected with a 600-km cable at ±320 kV. Equivalent networks at each end of this links are perfectly adequate to illustrate the unified methodology. A 10-µs time step is used for the electric system and the low-level control functions while high-level control subsystems operate at 50 µs. The control and protection system was developed in Simulink (R2012a) and imported in both simulation environments.

The dynamic performance of the link during a three-phase-to-ground fault disturbance at ST2 PCC bus is briefly analyzed.

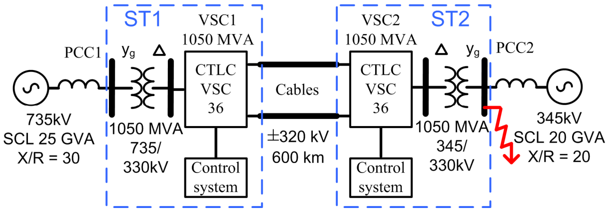

Fig. 5 1000-MW CTLC link between two equivalent networks.

B. Results

The start-up sequence of the link consists in activating VSC2 first (the pulses are applied to the IGBT switches), which regulates the DC voltage on the link while injecting 0.2 pu of reactive power (Q_ord = -0.2 pu) into the ST2 AC system. Subsequently VSC1 is deblocked: the active power requested from ST1 AC system is ramped up to 1.0 pu (P_ord = 1.0 pu) with no reactive-power exchange with the network (Q_ord = 0 pu). Data acquisition starts at t = 0 s when steady-state conditions have been reached. Fig. 6 shows the amplitude of important measurement signals in the control system at both stations (ST1 and ST2) in their vector form (after Park transformation) and a zoomed view of the phase A reference voltage (Vref_a ST2). The Hypersim (red) and EMTP-RV

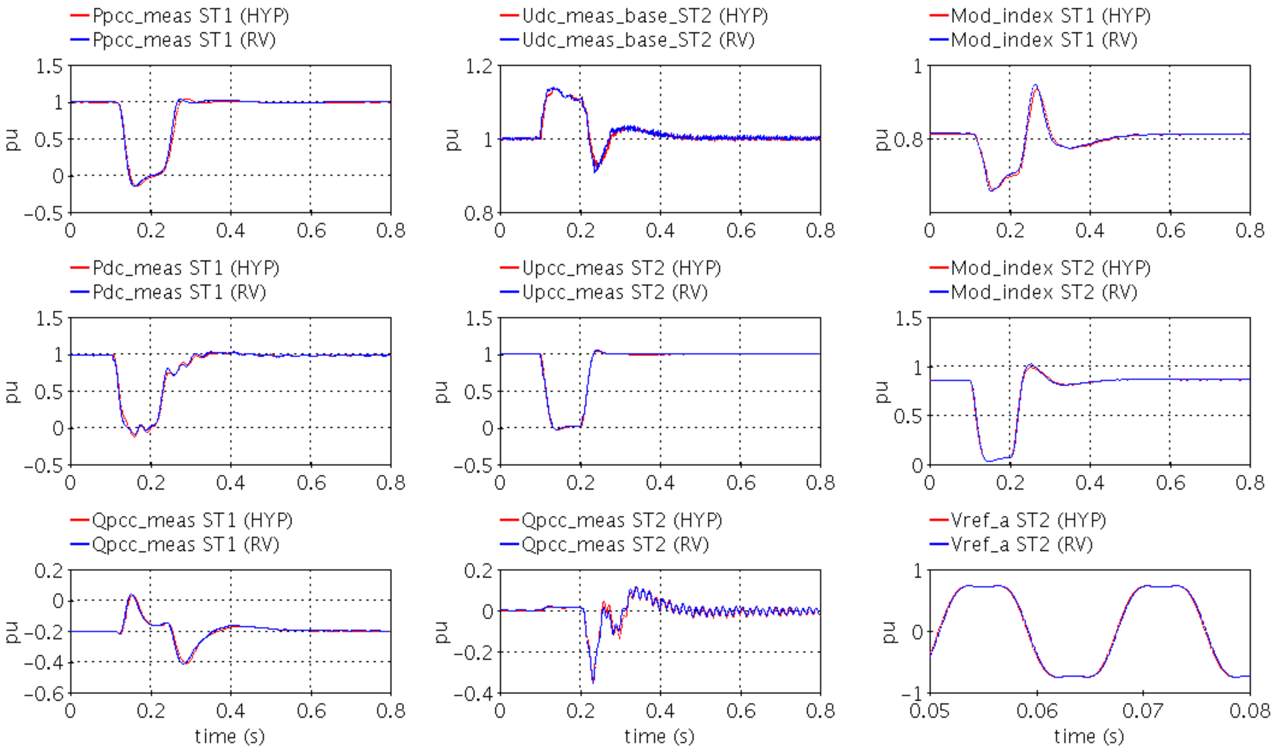

Fig. 6 Comparison of simulation results from HyperSim and Emtp-RV.

(blue) results are superimposed for comparison.

The tap changer control ensures that the modulation indices (Mod_index ST1 and ST2) are within the defined range by adjusting the transformer turns ratio. The zoomed-in signal of the modulation reference voltage illustrates a good correspondence between the two simulation results. The effect of the third-harmonic injection on the signal shape is clearly visible. A six-cycle three-phase fault is applied at ST2 PCC bus at t = 0.1 s. During this severe disturbance, the transmitted DC power (Pdc_meas) dips, activating the PDCRL function of ST1. This function mitigates the DC voltage increase by limiting (down to 0.1 pu, according to a static characteristic) the d component of the current reference when the DC power falls below a defined value (80% of P_ord). The DC-link voltage nonetheless peaks at 1.14 pu during the event as ST2 is enable to extract the energy sent by ST1 before the impact of the PDCRL function is felt. However, when the fault ends, the current limit is increased dynamically, and consequently the d component increases according to a defined first-order rate (Tc = 0.015 s). The system recovers from the fault within 0.4 s, with little or no overshoot in the AC and DC power. The 60-Hz oscillations observed in the reactive power measurement at ST2 are due to the presence of a DC component in the phase voltages introduced by the transformer saturation during the fault recovery.

From the superimposed waveforms, it is easy to see that the results of both simulation tools are in good agreement: the slight differences are due to differences in the PM modeling, nonlinear solver and CDA algorithm. With this unified approach, several study groups could explore different phenomena with different tools and, since the control system is rigorously the same, have complete confidence in the coherency of the results.

V. CONCLUSION

As power systems evolve, more and more complex devices with elaborate control and protection systems will be deployed to enhance performances, to increase power transmission capacity or to connect distributed power generation. All this apparatus will have significant effects on the power system. To study and quantify these effects, several tools will be used, from stability tools to detailed EMT simulations. In order to eliminate needless translation and validation work, a unified modeling and simulation approach, like the one exhaustively described in this paper, is highly attractive. A complete control and protection system, used at both ends of a CTLC link, was used to illustrate this approach. As the same controller was used in both tools, a precise iterative offline simulator and one optimized for real-time performances, results are consistent and each could be used to further study this DC link in each tool’s respective niche.

It is important to note that this approach does not apply only to EMT tools or control systems: the entire spectrum of simulation tools could benefit from it and, while it applies particularly well to control systems, other devices to unify the different tools such as distributed power generation devices could be used equally well.

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