Hardware in the loop simulations to test SVC performances on the French Grid

Y. Vernay, C. Martin, D. Petesch, S. Dennetière

***Abstract*-- In the last 4 years, 5 Static Var Compensators (SVCs) have been installed on the French Grid and in 2015, a 2000 MW France – Spain High Voltage Direct Current (HVDC) Modular Multilevel Converter (MMC) link will be commissioned. Moreover, several other HVDC links have been decided and some others are under considerations. Thus, power electronics controllers will have more and more influence on the grid reliability and performances in the next years. In this context, for every HVDC or Flexible AC Transmission System (FACTS) project, RTE has decided to acquire replicas of each power electronics controller and to build a real time simulation laboratory called SMARTE located in Paris La Défense. Replicas are connected to a Hypersim real time simulator to perform hardware-in-the-loop simulations with electromagnetic transient (EMT) detailed models. This paper focuses on the use of SVC controller replicas through 2 topics realized in 2014 in the SMARTE platform: improvement of SVC model in offline simulation tools and SVCs interaction study with 3 replicas connected to the same real-time simulator.**

***Keywords*: Real Time Simulation, Electromagnetic transient studies, Power Electronics Controller Replica, Static Var Compensator.**

I. INTRODUCTION

Across Europe, TSOs are adapting their networks to enable and support the rapid changes in the energy mix and the integration of renewable energy. In France, RTE is accelerating the development of interconnections links with neighbours' countries and several projects involve power electronic based equipment such as HVDC links and static VAR compensators. In the longer term, the share of power electronics connections into existing AC systems will significantly increase due to the massive penetration of inverter-connected renewable plants as well as the development of DC links embedded in the AC grid. These trends strengthen the need for research and development activities to model, study and mitigate potential interaction issues between close HVDC converters. To support these activities, numerical tools are needed that offer detailed modeling of HVDC components and controls while maintaining a good compromise between robustness, accuracy, and flexibility.

The usage of electromagnetic transient analysis tools (EMT-type) to test new technical solutions is continuously gaining in importance. EMT studies performed for the installation of new equipment into the grid are to ensure highest levels of reliability and availability. EMT-type simulation tools (offline and real-time) must provide valid simulation results, advanced visualization and analysis capabilities to power system engineers. A consequence for RTE is a direct involvement in the development and improvement of such tools as explained in [1]. Furthermore collaborations with École Polytechnique de Montréal in Canada and École Centrale de Lille in France have been established for the development of models and tools suitable for EMT-type studies for Modular Multilevel Converters. Some models are presented in [2] and [3].

After the commissioning of HVDC and FACTS devices, manufacturers usually provide customers with a black box model of their control systems. These models suitable for EMT simulations are difficult to maintain during the lifespan of equipment for the following reasons: the models are usually based on a specific version of a simulation tool that might not be supported in the future, the models usually use static libraries that can only be compiled and linked with a specific compiler version, the models cannot easily follow changes in the actual control systems because manufacturers do not necessarily maintain modelling expertise on long term basis.

The solution is to continuously update control system models for replicating real controllers and related updates. This is a time consuming activity and another possibility, presented in this paper, is to use manufacturer supplied physical replicas of control systems.

To validate the various modelling approaches for the different range of phenomena and to demonstrate interoperability and the absence of detrimental interactions, RTE decided to use hardware-in-the-loop architectures, with actual replicas of the physical control systems. For this purpose, a hardware-in-the-loop test facility called SMARTE, which uses the Hypersim simulator, has been set up in Paris la Défense. The Hypersim [4]-[5] software is a real-time hardware in the loop simulation platform used for the simulation and testing of control systems. A collaboration agreement on the development of Hypersim has been established with Hydro-Québec in 2012 to share development efforts and expertise.

RTE aims to expand this facility to meet its future project needs and to participate in future developments and improvements of the simulator.

II. SMARTE LABORATORY DESCRIPTION

In order to facilitate the maintenance and operation of control and protection systems in HVDC and FACTS devices,

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replicas of actual control system and protection cubicles are acquired during the project phase and installed in the SMARTE real time simulation laboratory. A replica is an exact copy of the actual control cubicles installed on the site. Two types of replicas can be ordered: Study and Maintenance.

A. *Study replica*

The study replica is dedicated to functional verification, dynamic performance and protection studies. The replica is delivered 6 months before the commissioning of the real installation and is used for network studies between Factory Acceptance Tests (FAT) and Site Acceptance Tests (SAT) to test the control algorithms. These investigations may lead to updates or even modifications in control algorithms.

The study replica is provided only with equipment relevant to network studies and redundancy is not included.

From a utility point of view the modelling of HVDC control systems for EMT studies is a quite complex task because actual controls may run on multiples platforms (CPU, DSP, FPGA…) and thus simulation on a single CPU would require too much time. Moreover, the HVDC controls are based on algorithms that are protected by manufacturers due to intellectual property rights. Therefore, replicas are useful to perform network studies without any simplifications or assumptions in control systems. Off-line or real-time control system models can be also validated with replicas.

For the time being, 3 study replicas of SVC controllers from 2 different manufacturers are installed in the SMARTE laboratory and HVDC replicas are expected to be installed for the next year.

B. *Maintenance replica*

The Maintenance replica is intended to help the preparation of on-site maintenance operations and operator trainings. The preparation of maintenance operations includes testing and validation of the upgraded system version before field implementation.

In order to perform preparations for maintenance, a validation of the upgraded control system, fault diagnostics and training of operators, the Maintenance replica includes a set of control and protection cubicles identical to the original cubicles in the converter substations with the same interfaces, including any redundant equipment implemented in the converter cubicles.

The Maintenance replica is delivered during the commissioning of the actual control system cubicles.

Currently, 2 SVC maintenance replicas from 2 different manufacturers are installed in the laboratory. This paper will focus on the use of study replica.

III. SVC DESCRIPTION

RTE’s SVCs have various designs depending on local network requirements in terms of reactive power and response time. They are roughly composed of a power transformer with several branches connected on the low voltage bus bar:

- Thyristor Controlled Reactor (TCR)
- Harmonic Filter
- Mechanically Switched Reactor (MSR)
- Mechanically Switched Capacitor (MSC), which can also be connected to high voltage bus bar.

Circuit breaker elements (MSR and MSC) permit to extend SVC reactive power band in a cheaper way than full thyristor SVC but also with a slower time response.

This paper will introduce 3 different SVC projects connected to the 225kV substations of Domloup, Merlatière and Cheviré which are, all 3, situated in the West of France.

SVC configurations are presented in Fig. 1 and Fig. 2 showing connected branches depending of SVC susceptance request.

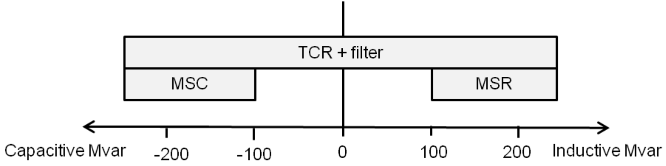

Fig. 1 Domloup SVC and Merlatière SVC configuration

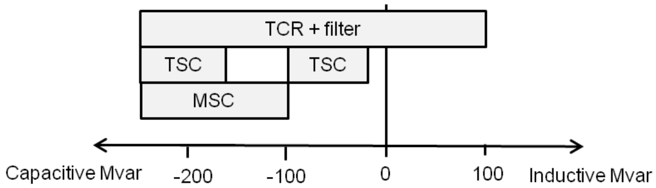

Fig. 2 Cheviré SVC configuration

IV. IMPROVEMENT OF SVC OFFLINE MODEL

A. *Real time simulation for validation of offline control system modelling*

Hardware in the loop simulation allows very accurate simulation of HVDC and FACTS and therefore is a good reference to validate other types of modelling using numerical model of controller. The validation of controller model was much more difficult before the creation of the laboratory as only a limited number of site measurements were available and were not always suitable for EMT model validation.

On the other hand, real time simulation does not offer the flexibility of off-line tools as simulation has to run on a specific real time server with controller cubicles in the simulation loop. From RTE’s point of view, real time simulation has to be a way to improve offline tools instead of replacing them.

A generic model of SVC has been developed by RTE in EMTP. The objective was to have a simple and easily adjustable model with a very good accuracy for the main control loops of the controller. A first model has been created for one SVC project and re-adapted for two other SVC. For each SVC project, two types of modelling are considered: detailed model and average model.

1) *Control model*

Control system modelling is identical in detailed model and in average model. Only main control loops of the SVC have been taken into account. In a first stage, voltage regulation mode and current limitation are considered for the closed loop control and fixed susceptance mode for the open loop control as presented in Fig. 3.

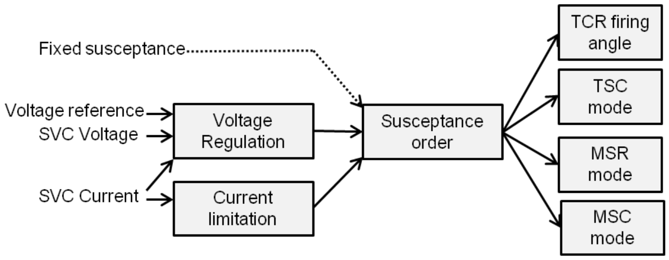

Fig. 3 SVC generic control model

This simplified control allows representing major SVC behaviour in running mode. The control system of this generic model has to be easily tuned from a project to another and therefore cannot be exhaustive in terms of controller functionalities compared to real SVC control. For more detailed or complex studies, two levels of modelling are still available: EMT model provided by the manufacturer using black box controller and real time simulation with study replica. Black box controllers provided by manufacturer are more complete but more difficult to use especially in a large scale network modelling study involving several controllers.

2) Detailed model

Detailed model represents all power system components of the SVC such as: main transformer, circuit breakers, TCR, TSC, MSR, MSC and current harmonic filter. This model is the same as the one used for real time simulation. It is specific for each SVC project and requires accurate data. Non-linear components such as transformer saturation and surge arrester can be taken into account and are required for the study of several EMT phenomena.

Comparisons between detailed model and real time simulation with replica have been realised with dynamic tests to validate the generic control model of SVC. During these tests, the generic control model is adapted to a specific SVC project often by just tuning gain parameters and less frequently by modifying control loop. To do so, internal variable of the replica code are used to understand actions of the different control system functions. These variables are for example: “SVC susceptance order” or “TCR firing angle”. They are useless for the real time simulation but are very valuable for the knowledge of the control system behaviour.

Voltage step tests are a good way to test the validity of the numerical model control as it corresponds to a sudden modification of the voltage reference and thus induces a strong reaction of the closed loop control.

Fig. 4 shows the SVC voltage responses of the real time simulation with replica (red curve) and the detailed model (blue curve) for a 6% positive variation on the reference of the voltage regulator.

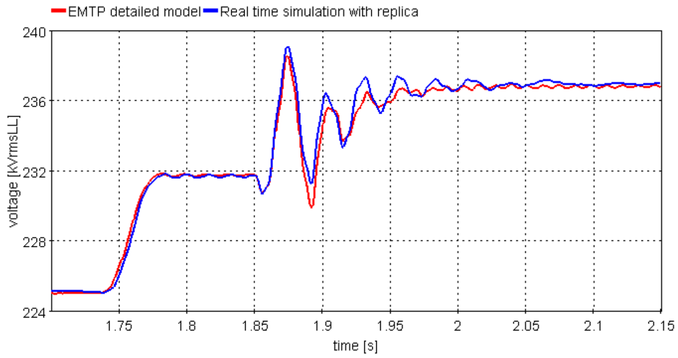

Fig. 4 Domloup SVC voltage response for 13,5 kV sudden variation of the voltage reference; red curve: EMTP detailed model; blue curve: Hypersim simulation connected to SVC study replica

EMTP detailed model gives a similar response as real time simulation with replica for this event. The severe transient observed at 1,85s is due to MSC switch-on. The model has been validated through numerous tests of this kind.

3) Average model

The detailed model is able to accurately assess EMT phenomenon in the SVC itself and in its close neighbourhood but requires long computation time. This computational effort is partly due to complex and non-linear components. In addition, the simulation time step has to be small enough (typically 50µs is a maximum). And also because this model is not initialised and therefore needs a minimum time at the beginning of the simulation to reach its operating point. Therefore to speed up EMT simulation of SVC an average model has been developed at RTE. This modelling is dedicated to large system study where SVC is not the main point of interest of the simulation in terms of transients but has to be taken into account as a voltage regulator in the studied zone.

Components in average model do not have physical representation: a variable inductance in parallel with a variable capacitor are controlled by the SVC control system and are directly connected to the high voltage bus. Those ideal controlled LC components are not included in EMTP-RV library. They have been created using a fixed inductance (or capacitor) connected at the secondary side of an ideal transformer with a ratio controlled and thereby represents controlled impedance through the equation (1).

$$Z_{svc} = \frac{Z_{fixed}}{ratio^2} \tag{1}$$

This method achieves efficient CPU time reduction by a factor of 3 compared to detailed model for the same time step. It is to note, that average model can be used at longer time steps than detailed model. Also, initialization is easy to implement for this type of model which use classic linear components. The model can run load flow simulations and initializes its intern control values to start time domain simulations in running mode at any operating point without any transients.

Comparisons have also been realised with real time simulation connected to SVC replica controller. Fig. 5 represents the same voltage step as presented for detailed model.

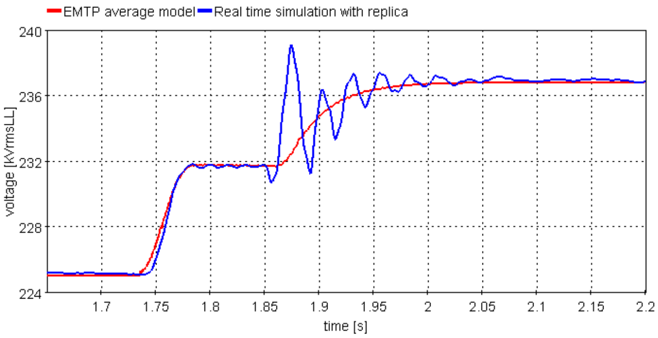

Fig. 5 Domloup SVC voltage response for 13.5 kV sudden variation of the voltage reference; red curve: EMTP average model; blue curve: Hypersim simulation connected to SVC study replica

The EMTP average model is able to reproduce the general aspect of the voltage step response compared to detailed model in real time simulation with replica. Of course, switching transients are no more observable as well as non-linear behaviour of transformer saturation or harmonics content of SVC current.

B. Unique control model for all simulations tools

Real time simulation may require other controllers than replicas installed in laboratory. For example, SVC and HVDC far from the study point of interest may have an impact on the simulation results but do not require to be simulated using replica. In the same way, machine regulation controller, protection relays or point-on-wave switching devices have to be taken into account for some studies but do not always have a level of complexity that justify a replica investment. To do so, real time simulation tools, always provide control blocks libraries to implement controller model in simulation. However, real time simulation tools offer rarely the opportunity to re-use controller modelling already developed in EMT offline tools. This point is challenging for RTE because many EMT controller models, like SVC controller presented in the previous section, have been realized in the last years and a re-modelling of these controller in real time simulation tool would be time consuming and might not accurately reproduce the same behaviour. This multiple modelling does not guaranty the coherence between simulation tools which is an important issue for a TSO which will have to realize simulations with various simulation tools for one project.

To answer this problem, Matlab Simulink was chosen for controller modelling. Indeed, Simulink Coder combined with Target Language Compiler (TLC) files enables to generate and customize C/C++ code from any Simulink model to make it compatible with EMTP or Hypersim. In addition to ensure the uniqueness of the models between different simulation tools, these interfaces allow to increase model performance by providing optimized code and to expand target tools functionalities (all Simulink control blocks are now available in EMTP and Hypersim).

For EMTP in particular, the most appropriate solution to integrate external models is to use the EMTP compatible DLL (Dynamic Link library) module. The Simulink/EMTP interface, developed by RTE, automatically compiles the code into an EMTP compatible DLL file at the end of the code generation process. A library has been developed in EMTP specifically for Simulink model to redraw the Simulink component with appropriate inputs and outputs by selecting the DLL file. This interface provides an additional feature: the possibility to specify tunable parameters in the Simulink circuit such as gain or constant values. These parameters will be tunable directly in EMTP, into Simulink device form. This saves a considerable amount of time avoiding model generation for every change of parameters values. The Simulink/EMTP interface is compatible with almost every EMTP features such as statistical simulations or named values for tunable parameters. Nevertheless, there are some limitations. The fundamental time step of Simulink model is not tunable and direct loops are not supported. For the first point, a Simulink model is generated for a specific sample time. It is still possible to run a simulation in EMTP if EMTP time step is a multiple or a divisor of Simulink time step. Regarding direct loops, a workaround is to introduce a unit delay inside feedback loop. Thus, the algebraic loop is broken and Simulink allows code generation.

V. SVC PERFORMANCE STUDIES USING REAL TIME SIMULATION

The western part of France is considered as a weak zone of the French grid in terms of power generation units leading to voltage stability issues. In the last years, a large number of capacitor banks and 5 SVCs have been installed to maintain and control voltage in this zone during networks events. Domloup, Cheviré and Merlatière SVCs are all connected to the 225kV grid and are situated very close from each other. Questions have risen about possible impacts of one SVC on the performance of a neighbour SVC. To consider it, a modelling of the west part of the 225kV French grid has been realised in Hypersim connected to 3 SVCs study replicas. Different events have been simulated to evaluate SVCs response in this zone. Modelling choices and some simulation results are presented in the following sections.

This type of simulation is quite unusual as real time simulation often focuses on single controller behaviour and therefore requires a limited network modelling. As more and more controllers are inserted in power transmission system, in a near future, it will be ever more difficult to analyse or predict dynamic performance of single controller in a restricted study zone. Interaction between close FACTS/HVDC systems or HVDC links inserted in a meshed AC grid will take a bigger part in network exploitation studies and will have to be considered using this type of large scale modelling.

A. Network modelling description

One of the objectives of this first study was also to improve real time study methodology and to identify network components which have to be taken into account to analyse the performance and possible interactions between 3 nearby SVCs. Fig. 7 in Appendix illustrates network modelling done in Hypersim:

- 20 substations on the 225kV grid
- 3 substations on the 400kV grid
- 31 lines (constant parameters or PI circuit for very short lines)
- 6 saturable 400/225kV autotransformers

- 4 power generation units (transformer, synchronous machine and regulations associated)
- 3 detailed model of SVC connected to replica

One SVC replica connection consists of approximately 90 input and output signals (IO) between the replica and the real time simulator.

Boundaries of the study zone are modelled using 50Hz equivalent voltage sources with short circuit impedance, no coupling effect between those boundaries has been considered. The network situation has been set using data of the load flow simulation software “Convergence” used at RTE. This network situation corresponds to a maximal load demand in the area with the 4 power generation units from Cordemais in service. Less than 0.5% error on buses voltage has been found between Convergence and Hypersim load flow. However, up to 20% of error has been observed for short circuit power, leading to the conclusion that the network modelling is not large enough yet or that coupling between boundaries have to be taken into account for an accurate short circuit power representation. For the first step of this study, the size of the modelled zone has been considered sufficient.

Cordemais thermal generation units are connected one substation away from Cheviré SVC. They have been modelled as their dynamics is lower but in the same range of order as SVCs which have a response time typically around 100ms for the voltage regulator. This generation unit model takes into account the synchronous machine model and the machine regulation associated.

Voltage and speed regulation of the Cordemais thermal generation units have been modelled in Hypersim to accurately evaluate the synchronous machines’ dynamic response. Fig. 6 shows this modelling in Hypersim. To guarantee study coherency between off and online EMT simulation, the control blocks of the machines’ regulation are realized in Matlab Simulink using data from existing control modelling in the electromechanical software used at RTE (EUROSTAG). For each Cordemais thermal unit, these models represent the detailed dynamic response of the:

- Automatic Voltage Regulator (AVR)
- Exciter
- Speed regulation

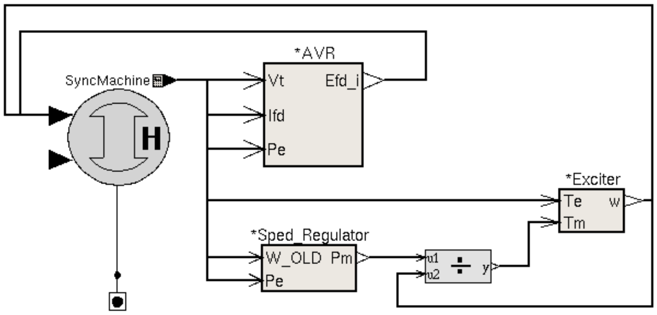

Fig. 6 Model of one of the Cordemais thermal units implemented in Hypersim

C-code is generated and implemented automatically in EMTP and Hypersim. Validation tests are run on a simplified circuit (synchronous machine linked to a voltage source) to check the coherency of the regulation’s behaviour obtained in EMTP/Hypersim and EUROSTAG.

B. *Real time performance*

The system is simulated in real time using a time step of 50µs. This time step is typically use for SVC control test application in real time. 13 cores of SGI UV100 server (E7-8837 Intel Xeon CPUs at 2.67 Ghz) are required to simulate the whole system: 7 for the AC grid and 6 for the SVC detailed modelled and communication inputs/outputs.

C. *SVCs performance for 400kV line fault*

Various network events, such as transformer fault, line fault or bus bar fault, have been simulated to observe SVCs reaction and to bring out modelling choices which have to be considered for these type of interaction study.

SVCs responses for a fault on one of the two 400kV lines between Cordemais and Domloup 400kV substations are presented during the fault in Fig. 8 and after the fault in Fig. 9. For each SVC, positive sequence voltage, reactive power and TCR firing angle are observed.

The 400kV line permanent fault, see Fig. 8 in Appendix, has a strong impact on the 3 SVC’s substation. The 3 SVC control systems order to connect capacitive components such as TSC or MSC and to limit their TCR current by suddenly increasing firing angle.

Fault clearance is done by tripping the 400kV line 100ms after fault ignition. The protection relays have not been modelled, a simple delay has just been set for opening time in circuit breaker models. In this simulation, we have not considered the automatic reclosing of the circuit breaker.

The 400kV line fault has generated an acceleration of Cordemais machines resulting in voltage oscillations on the grid. This oscillation is efficiently damped by SVCs on the 225kV grid. Fig. 9 in Appendix shows that the voltage remains stable after fault clearance for each SVC. During Cordemais machine stabilization, each SVC controllers adapt rapidly their susceptance in order to maintain voltage at its voltage reference setting. This is easily seen on TCR firing angle variation which has a direct impact on SVC reactive power. Synchronisation of different SVC branches is essential during this type of transients to maintain stability of SVC control. This is even more relevant when circuit breaker technology (MSR and MSC) is used in voltage regulation loop. Indeed, circuit breaker of capacitive or inductive components can create switching transients resulting in undesirable interactions with thyristor-controlled elements or SVC control itself. Moreover, circuit breakers are less flexible than thyristor and require several seconds to restore the energy of their command between two closings.

This type of sequence is rarely studied during factory test and even less during commissioning test where each test is often focused on a single components or function of the SVC.

VI. CONCLUSIONS

This paper has briefly describes RTE’s strategy regarding real time simulation activities. The SMARTE plateform has been installed in 2012 in Paris La Défense to host controller replicas of existing and future FACTS and HVDC project inserted into the French grid.

The use of real controller connected to real-time simulation is a unique opportunity to improve EMT offline models. Two level of modelling methods: detail model and average model have been developed and compared to hardware-in-the-loop simulation. To maximize benefit of every model development and to guaranty study coherence between simulation tools, questions have raised about sharing model between EMT offline and real time tools. This has pushed to use Matlab Simulink modelling to generate models for EMTP and for Hypersim.

An example of real-time study involving several replicas in the simulation loop has been presented. This type of study involving multiple controllers was until now rarely studied with real time simulator. From RTE’s point of view this trend will significantly grow in the next years as more and more power electronics devices controlling massive power flows will have to be inserted in the existing HVAC meshed grid.

VII. APPENDIX

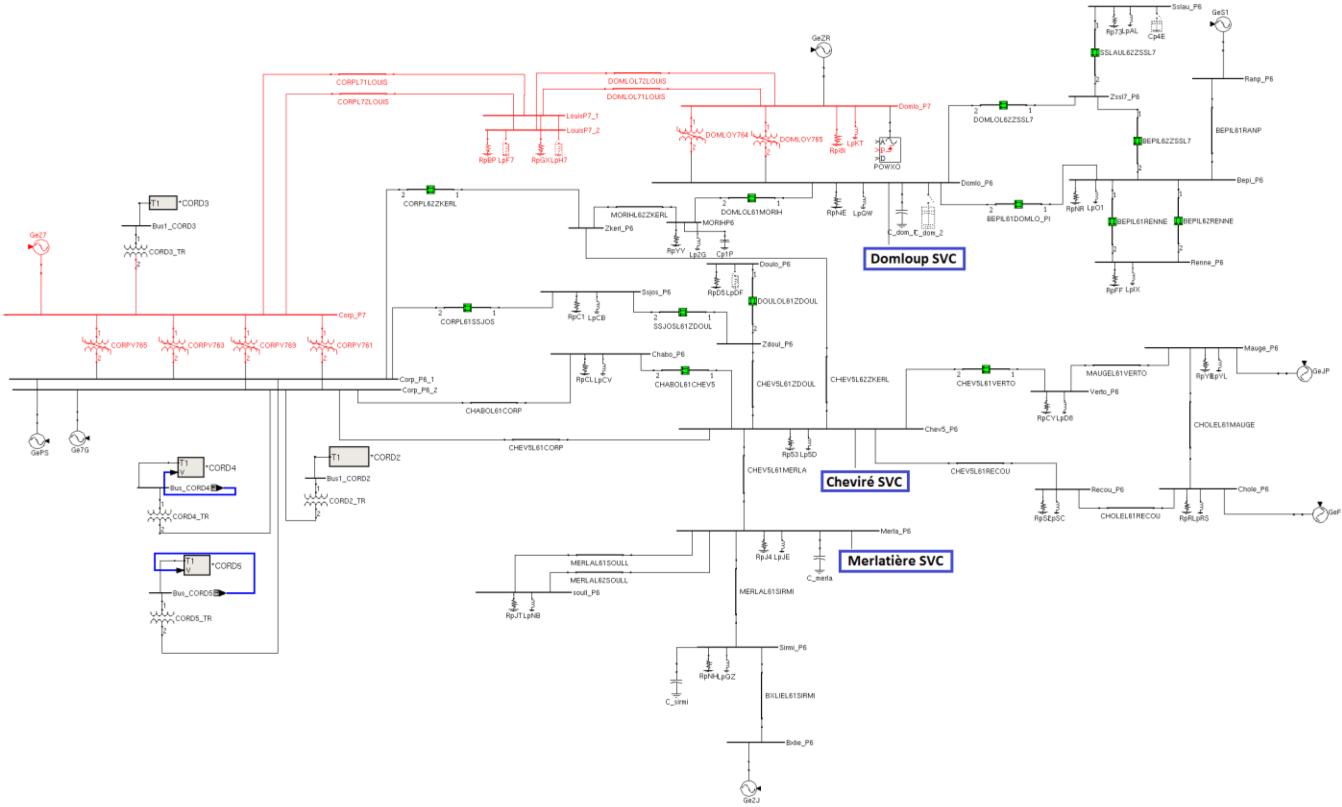

Fig. 7 Hypersim modeling of 400kV (red) and 225kV (black) network. SVC detailed models are not represented.

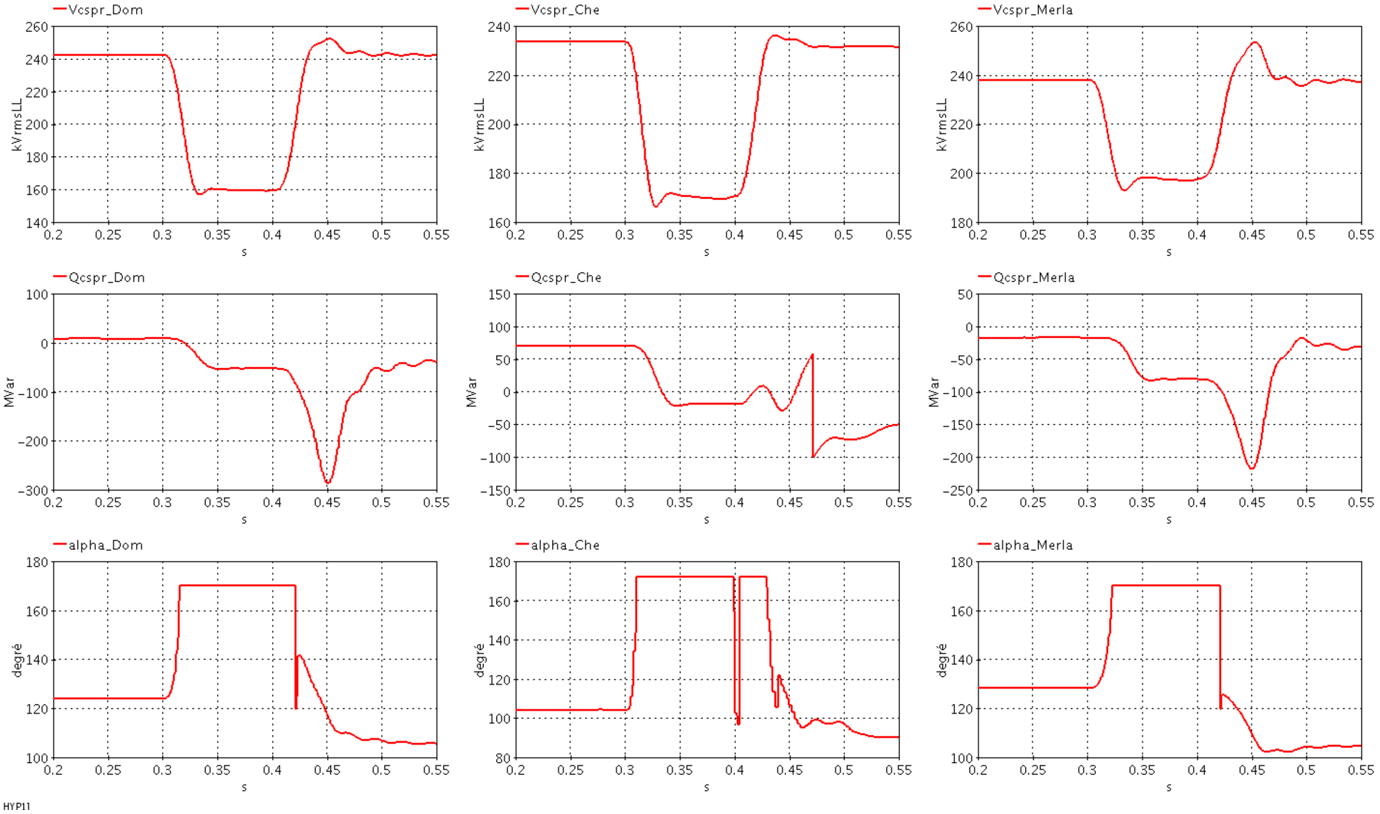

Fig. 8 System response during 400kV line fault and clearance; positive sequence voltage, reactive power and TCR firing angle of the SVCs of Domloup (Dom), Cheviré (Che) and Merlatière (Mer)

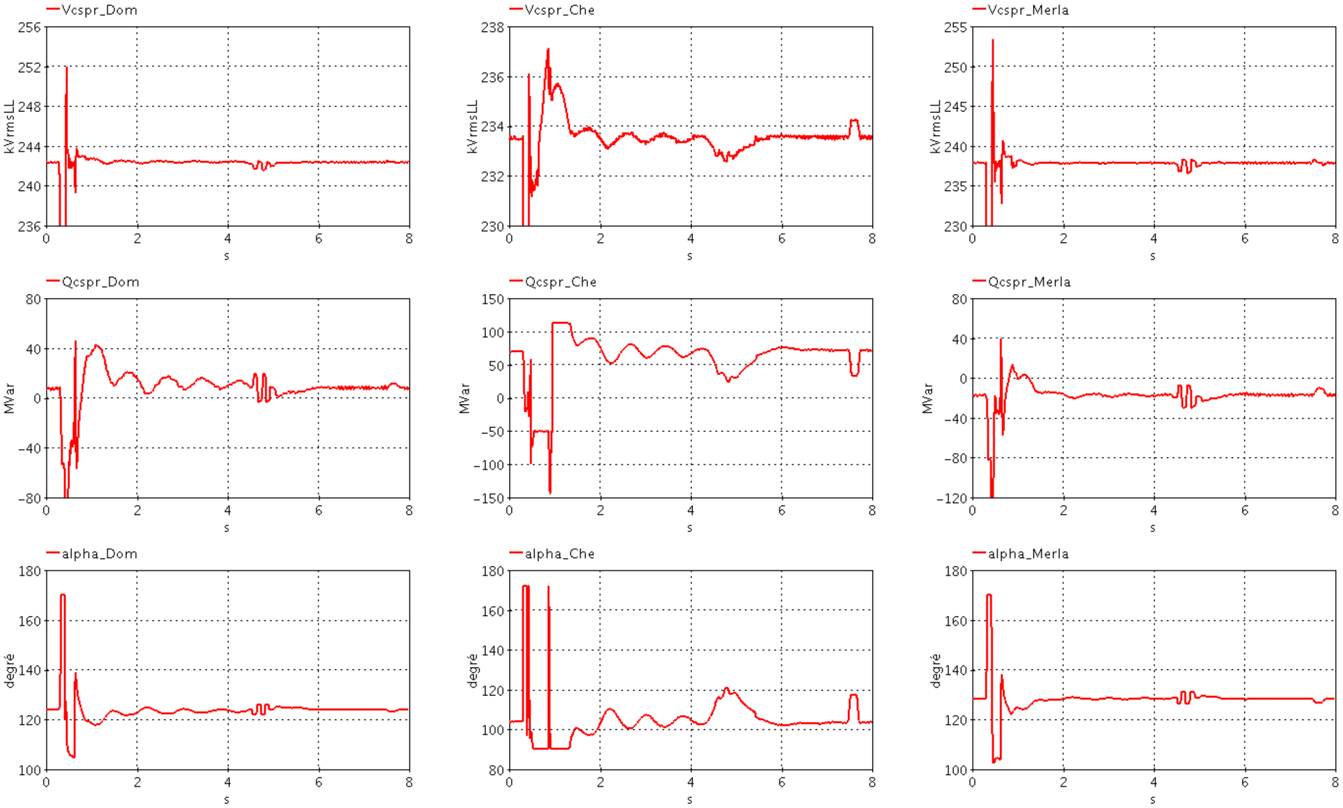

Fig. 9 System response after 400kV line fault and clearance; positive sequence voltage, reactive power and TCR firing angle of the SVCs of Domloup (Dom), Cheviré (Che) and Merlatière (Mer)

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