New HVDC LCC replica platform to improve the study and maintenance of the IFA2000 link

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Abstract-- **The HVDC (High Voltage Direct Current) project called IFA2000 for "Interconnexion France Angleterre 2000MW" is an HVDC LCC (Line Commutated Converter) interconnection composed of 2 links 1000 MW each, with DC voltage +/- 270 kV between France and England operating since 1986. Due to the ageing of the convertors and the obsolescence of the control cubicles, a complete refurbishment of the thyristor valves and the control & protection system of both links have been undertaken in 2011 by Areva T&D. At the same time RTE decided to create a real-time simulation laboratory in order to reinforce its activities in studies, expertise and maintenance of HVDC and FACTS (Flexible Alternative Current Transmission Solution) projects. In 2012, the first Hypersim simulator was installed in the laboratory and in 2013, 3 SVC (Static Var Compensator) physical control system replicas were commissioned. Since that date, the laboratory has continued to growth with the installation of 2 others SVC replicas and 2 HVDC-VSC (Voltage Source Converter) replicas for the France-Spain project. These new equipment have been extensively used to analyze and solve abnormal behavior of the systems, or to update version of HVDC/SVC control system. In this context, IFA2000 replica has been ordered in 2014 to Alstom Grid. It is a long term investment for IFA2000 control system maintenance and for complex EMT studies requiring a high level of accuracy of the HVDC system. This paper presents the main drivers for RTE to create a real time simulation laboratory regarding its experience of HVDC/SVC control system testing and maintenance. It focuses on the IFA2000 replica project by providing technical description of the replica. The real time model developed to test and validate this platform is also described. Simulation results and real time performances are discussed as well as the impact of this replica on the operation and the maintenance of IFA2000 interconnection.**

Keywords: **Real Time Simulation, Electromagnetic transient studies, Power Electronics controller replica, High Voltage Direct Current technology.**

I. Introduction

The IFA 2000 interconnection, in operation since 1986, is composed of 2 separate links rated 1000 MW each. It is used to export and import energy between France and Britain upon market demands. This HVDC scheme is 73 km long in route, with 70 km between the two ends. The undersea section consists of 46 km long 270 kV submarine cables, laid between Folkestone (UK) and Sangatte (France), arranged as two fully independent 1,000 MW Bipoles, each operated at a DC voltage of ±270 kV. Cables are laid in pairs in four trenches so that the magnetic fields generated by the two conductors are largely cancelled. A complete refurbishment of valves and control system was performed on both links from 2010 to 2012. In the specifications of the refurbishment project, RTE required an EMT model of the link. This model was used to analyze an event that led to serious damages to the equipment a few months after refurbishment. This event started with a wrong DC current measurement. It was followed by a valve bypass and a single pole failure of the main AC circuit breaker (CB). One link was out of service during several weeks to solve the problem. The EMT offline model developed by the manufacturer for the dynamic performance tests has been used to analyze this event. It failed to reproduce the transients after the valve bypass. It was not possible to justify the single pole failure with the EMT offline model. The initial state before valve bypass was also quite difficult to reproduce. Even with the support of the manufacturer it was not possible to get a good match between the real measurement and the offline simulation. Nevertheless the event has been successfully reproduced with a physical control replica installed in the manufacturer factory. The bad performances of the EMT offline model was due to many differences between the real control software and the control model. It was practically impossible for the manufacturer to update the model after the onsite commissioning for many reasons: software version tracking, issues related to the Operating System required to run the EMT offline model and the people involved in the initial development of the model had left the manufacturer company.
The specifications of the EMT offline model that was required by RTE were clear but no technical solution have been found to update the model.

This experience proved again that RTE had to put in place solutions to be able to analyze the HVDC systems behavior in a long term basis. This is why the purchase of the IFA2000 control system replica has been decided even when the refurbishment project was ended.

This paper presents several activities that have been set up to install and use the IFA2000 control replica. It is organized as follow: Section II. presents the refurbishment project. Section III. includes a description of the replica and general specifications. The interface with the real-time simulator is also described. Section IV. focuses on the EMT modeling in real-time. This topic required special care because this was the

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first experience at RTE of HVDC LCC modeling. In section V. the replica platform is validated with results obtained during factory tests and performed with RTDS. Validation with field tests are also provided. The usage of the IFA 2000 replica for maintenance activities is discussed in section VI. .

II. IFA2000 VALVES UPGRADE PROJECT

In 2011 and 2012, the converter stations were partially renovated to enhance the overall availability of the link and mitigate obsolescence issues. The full capacity of the renewed interconnection has been in commercial operation since 2012.

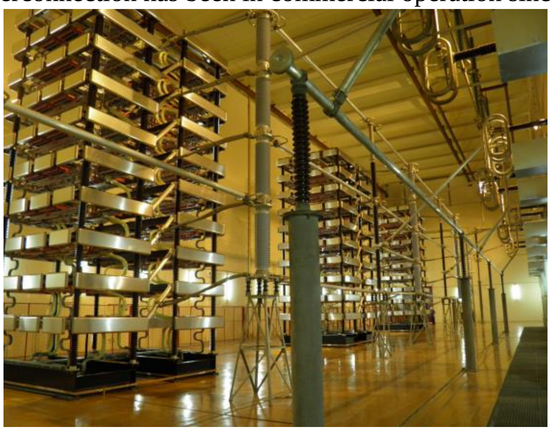

Fig. 1: IFA2000 valve hall after refurbishment.

It is one of the first HVDC refurbishment projects where the Control and Protection System has been replaced simultaneously with the converter valves. One of the main challenges of the project was that the two original converter stations were each of a completely different design which has required designing the replacement equipment to be compatible with both sides. The opportunity was also taken to incorporate new features into the control and protection system, such as optimized minimum DC current, renovated telecommunication system, frequency control to take advantage of increased revenues resulting from ancillary services.

The feedback from the link operation during the past five years showed the importance for the TSOs to develop HVDC skills internally in order to perform long term and optimized maintenance over the asset lifetime as well as proper troubleshooting in case of fault.

In that regard and as part of the life extension strategy, RTE has decided to procure a replica of the IFA 2000 Control System cubicles, which has been successfully commissioned in RTE's laboratory in Paris in January 2017.

III. REPLICA DESCRIPTION

The IFA2000 replica platform consists in 9 HVDC control system cubicles using Series V technology by GE. The cubicles hosts the different levels of the control system (station, bipole and pole) in 7 cubicles and 2 cubicles are dedicated to auxiliary system, control interface connections and TFR (Transient Fault Recorder).

Fig. 2: IFA2000 replica in SMARTE laboratory

The first objective of the IFA2000 replica was to afford the hardware setup to be able to run the same control code as on site. This point is of major importance to avoid any confusion for future code update tests and analyses of trips or unexpected situations. A second objective is to keep as much as possible the same hardware equipment as on site to use the replica as a mockup for maintenance and training activities. However, a cost effective solution has to be found to keep the most important functionalities of the HVDC controller without providing the full hardware setup as on site. As a result, only one type of lane redundancy at pole, bipole and station level have been implemented. This optimization allows us to simulate all the types of lane changeover and significantly reduces the number of control and protection boards resulting in cost and space saving. Architecture of the control system of the IFA2000 replica is presented in Fig. 3:

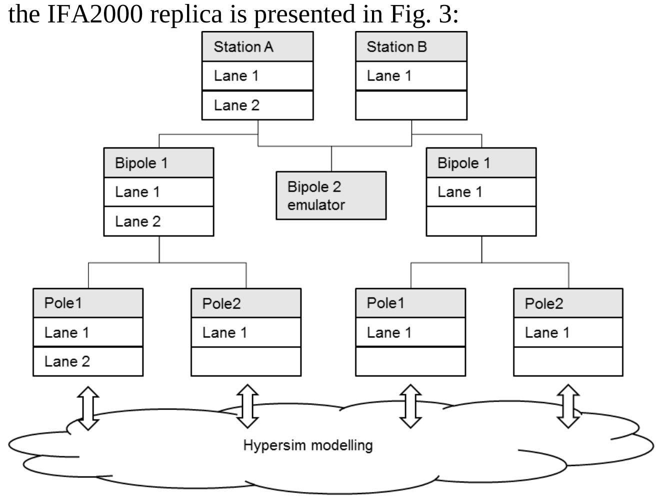

Fig. 3: IFA2000 replica architecture

Moreover, one can notice that the replica consists in only one of the 2 links of the IFA2000 interconnection. An analysis concluded that replica for only one link was sufficient to cover almost all RTE's needs in terms of events and network configurations. This solution has also been successfully applied for the France Spain HVDC VSC replica [1]. The modeling of the second link is discussed in the following section. This limitation has consequences on hardware as some parts of the control at the station level require signals from link 2 cubicles. To keep station control software as it is on site, a bipole 2 emulator has been designed for the replica application. This device only emulates the presence of the bipole 2 for the replica setup without any action on the real-time simulation.

The connection of replica to the IO (Inputs Outputs) interface boards of the real time simulator is realized with copper wires. Analogue ±10V and digitals signals +24V/+5V are used for:

- voltages and currents measurements
- thyristors pulses
- orders and status of the circuit breakers and disconnectors
- tap changer orders and positions for pole transformer
- Trip signals
- Record of analogue signals of controller (alpha and gamma angle for example).

In total, 275 outputs signals (114 analogue signals and 161 digital signals) are required for the real-time simulator as well as 140 input signals (37 analogues signals and 103 digital signals). This important number of IO signals has an impact on the design and on the cost of the real-time simulator. But, thanks to this full interface the same code and hardware as on site can be used on the replica.

Signals exchange between replica and real-time simulator is handled by 3 extension IO rack OP5600 [2] which are connected to the real-time simulator through optic fiber. The real-time simulator target is composed of 16 cores running at 3.2GHz (2 Xeon E5 CPU of 8 cores). This size of simulator is more than enough for performing real-time simulations involving the IFA2000 HVDC link and an AC grid of a few hundreds of 3-phase buses. Connection to a larger simulator should be considered if a study requires a very large AC grid modelling or a connection to many other control replicas of HVDC or SVC (Static Var Compensator).

IV. Real time simulation modeling

Before the commissioning in RTE laboratory, the replica has been tested in GE factory with an RTDS real-time simulator. The Hypersim real-time model of the IFA2000 link was prepared at the same time. The HV (High Voltage) devices have been modeled with the standard component models in RTDS and in Hypersim. Both software propose quite similar models for HVDC LCC simulation. Nevertheless some differences have been applied in the Hypersim modeling to improve accuracy. For instance the 4 DC cables are represented with wideband models of 20 poles in the admittance matrix and 40 poles in the propagation matrix using technics presented in reference [3]. It allows a good assessment of the transients during DC fault. This distributed parameter cable model decouples the calculation tasks of each side of the link in 3 cores: 1 core per converter station and 1 core per cable model [4]. The external AC network is limited to an equivalent Thevenin voltage source for preliminary tests. Future studies will required larger network representation using detailed network or Frequency Dependent Network Equivalents (FDNE) techniques like describes in reference [5]. However for commissioning tests, a simple AC network model is sufficient. Voltage and short-circuit power can be easily changed with such a simple equivalent.

The IFA2000 replica was the first project that requires HVDC LCC modeling at RTE. This is why special care has been taken to the model validity and real-time performances. First, a generic HVDC-LCC control system has been developed based on literature references [6]-[9] and tuned with IFA2000 characteristics. It has been developed in Matlab-Simulink and automatically imported in Hypersim as a standalone model.

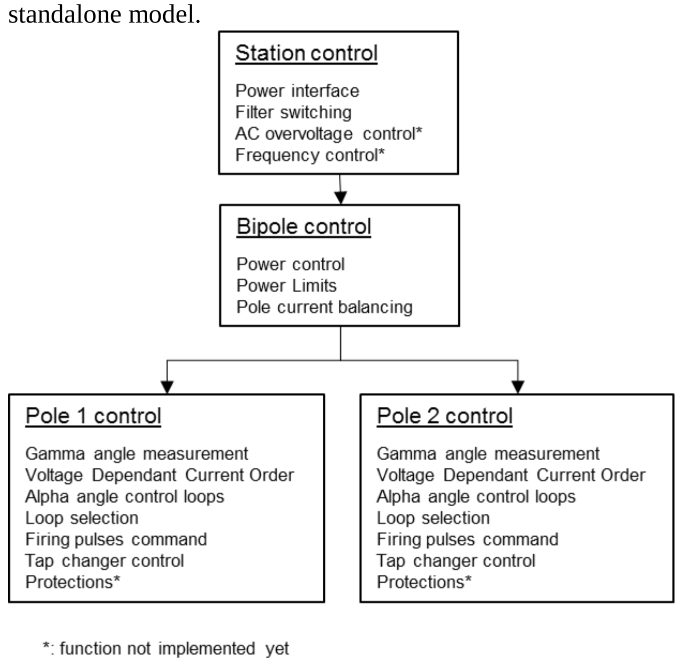

Fig. 4: Description and functions of the generic numerical Control Model

As presented in Fig. 4, this control model takes into account the main architecture of the real IFA2000 control. Some specific functions, like protections are not implemented in a first step of this work as the main requirement was to validate the power devices modelling. So the control development has been focused first on the steady state control loops. Those functions will be implemented in a second step with many comparisons against studies with the control replica.

Validation of the model has been conducted using the simulation setup presented in Fig. 5. Maximum execution times observed during real-time simulation were less than 30µs for cores 1 and 2 (power system components) and less than 15µs for cores 3 and 4 (digital control model) which is sufficient for HVDC LCC application. It requires typically a simulation time step of 50µs. Each wideband cable model run on a separate core (core 5 to 8) with an execution time around 2.5µs without impact on the sizing.

In addition to the preparation of replica commissioning, this model running in real-time is useful to model the second link when the first link is connected to the replica. Another solution to take into account the second link can be to use the replica in close-loop control for the first link and in open-loop for the second link. This solution might lead to stability problems and is valid only for symmetrical events for both links.

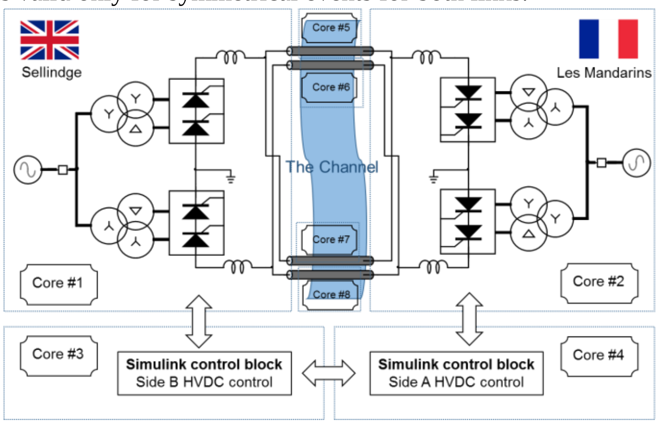

Fig. 5: Hypersim model validation with digital control model

This model will also be used in EMTP-RV which is the EMT offline simulation tool used at RTE., Thanks to the Simulink interface it is possible to import the same control system model in EMTP-RV. This feature guarantees the coherence of EMT models between offline and real-time simulation tools.

V. Replica Validation Tests

A subset of the Factory Acceptance Tests (FAT) realized on the real controls installed on site have been performed on the replica. Many tests have been realized in GE factory with an RTDS simulator and compare to the factory tests of the original project. This was required by RTE. During replica commissioning, the same tests have been performed with the Hypersim simulator and compared to the factory tests in order to validate the replica internal wirings and connection to the real-time simulator. Comparisons of simulations with real site events have also been performed. Validation with real-site cases is more relevant but not sufficient as the number of real cases to study is limited and always suffer from unknowns parameters, like fault impedance for instance, compare to factory tests were all the parameters are determined.

A. Commissioning tests

A typical fault test studied during factory tests is an AC single phase to ground fault at rectifier side in order to check the correct response of the AC under-voltage protection. In this case a 200ms single phase fault is applied at AC bus bar of the side B of the HVDC link as presented in Fig. 6.

According to the specification of this link, the converter shall not block for this type of fault. A correct behavior is observed with the replica validating the operation of the hard-in-loop platform but also a very good match is observed between results from factory with RTDS and from the commissioning with Hypersim.

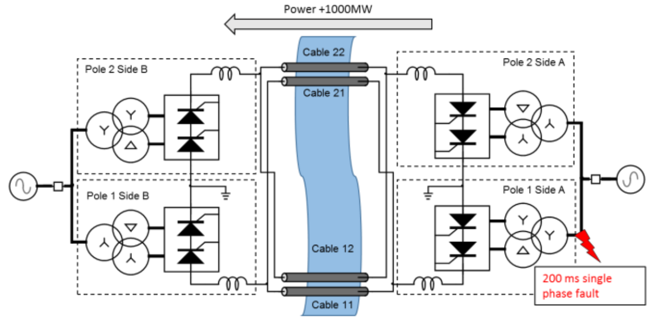

Fig. 6: Single phase, short duration fault test

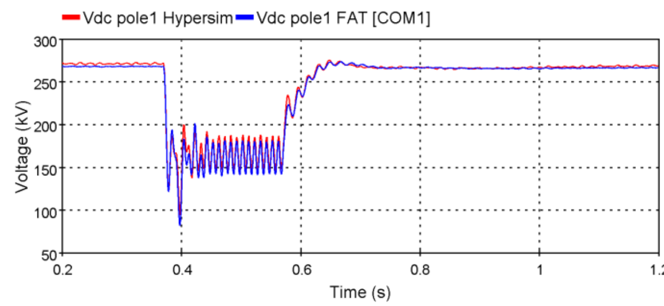

Fig. 7: Comparison of DC line to ground voltage at pole 1 for AC single phase short duration fault test

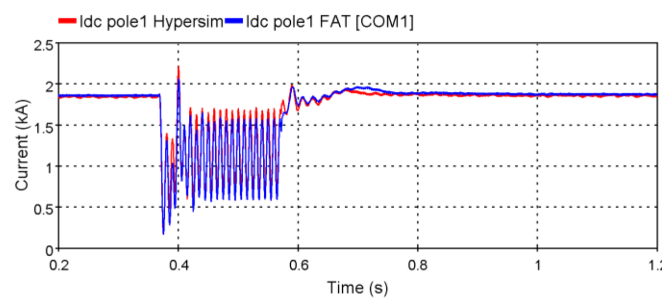

Fig. 8: Comparison of DC line current at pole 1 for AC single phase short duration fault test

Same procedure has been successfully repeated for all commissioning tests giving a satisfactory confidence in replica setup and in Hypersim modelling.

B. Cable fault event

In the end of 2016, the IFA2000 link has faced a major fault event on subsea cables during a sea storm period. Two pairs of cable, one for each link, have been damaged at separated time resulting in tripping of the two links. The link 2 was exporting 1000MW to UK when the first fault appeared on the cable 34 as presented in Fig. 9. The site measurements stored in the Transient Fault Recorder (TFR) of Les Mandarins HVDC station have been used to estimate the apparition time of the fault and nature (very low impedance fault). A direct cable fault to ground has been simulated resulting in a DC voltage drop and oscillations at pole 4. A satisfactory match of the voltage transient has been observed using the wideband cable models (Fig. 10). The voltage response using is Constant Parameters (CP) cable models is added to the figure to illustrate the impact of the wideband model.

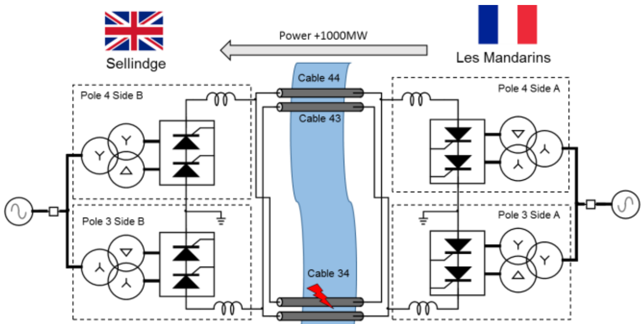

Fig. 9: Cable fault event reproduced with replica

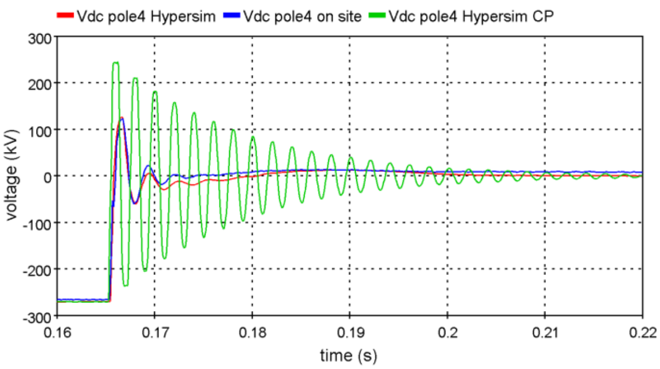

Fig. 10: Comparison of DC line to ground voltage at pole 4 during the cable fault

The result of the fault current peak at pole 4 also shows good estimation versus the measurement. The DC undervoltage is detected by the protection system which blocks the converters after a few hundreds of milliseconds.

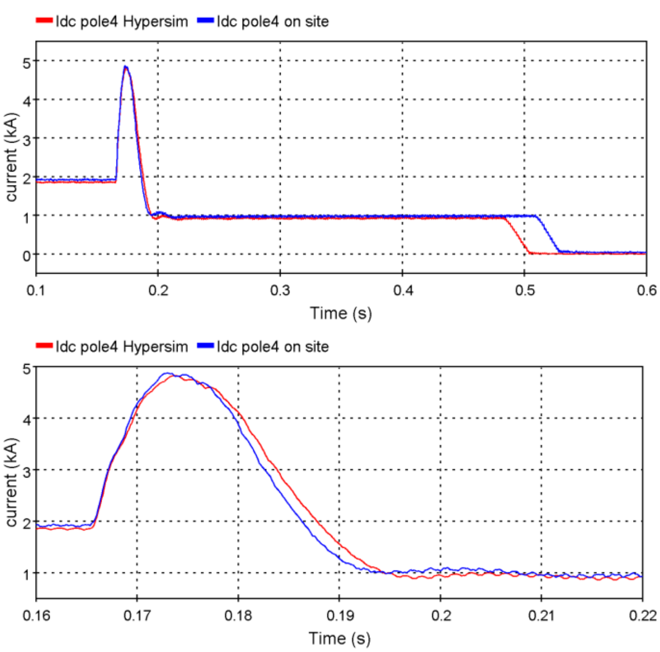

Fig. 11: Comparison of DC line current at pole 4 during the cable fault (wide and zoom)

The blocking sequence happens around 30ms sooner with the replica. This shift is difficult to explain as the communication chain between power equipements and control is not exactly the same between replica setup and site equipment. For instance, the replica does not include the Valve Base Equipment cubicle which is directly connected on site to the thyristors.

Internal variables have also been analyzed as the delay angle (alpha) which is used for thyristors firing on rectifier side. Very similar behavior is observed for the alpha angle at pole 4 as shown in Fig. 12.

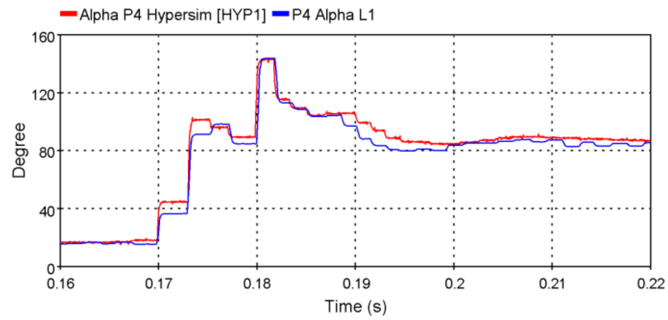

Fig. 12: Comparison of alpha angle at pole 4 during the cable fault

During the cable fault on pole 4, minor transients on pole 3 are observed on the DC current and voltage. This is confirmed with the replica simulation as seen on Fig. 13. As for the pole 4, the blocking sequence starts sooner with the replica.

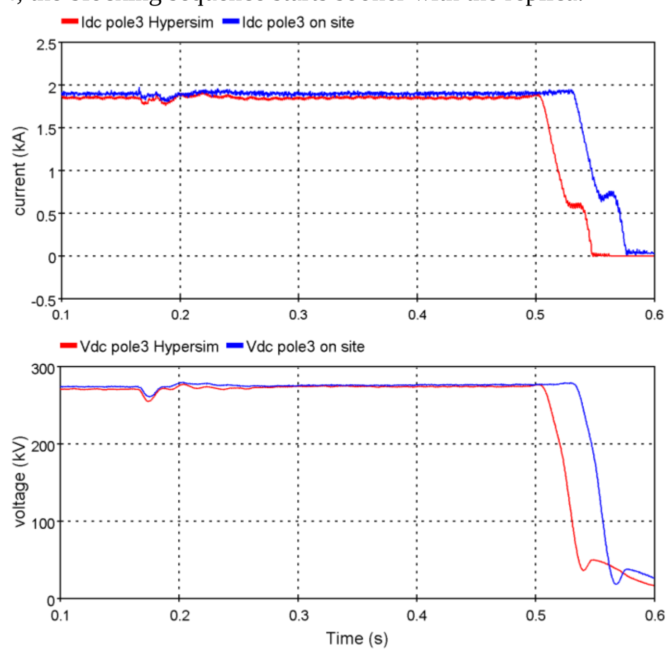

Fig. 13: Comparison of DC line current and DC line to ground voltage at pole 3 during the cable fault

VI. Maintenance improvement

RTE decided to be in charge of the maintenance of every HVDC / FACTS equipment installed on the French transmission grid. This solution has been compared with a solution relying on a long term maintenance contract with manufacturers. As a consequence specialized skills in HVDC systems are required in RTE to meet these requirements. The physical control replicas are a tremendous tool to train operators and engineers for maintenance activities. Trainings sessions are performed for local maintenance team and system operators. During these sessions they can learn how the system works, analyze simulated event or event recorded on site. Replicas are also used to test and evaluate the new software versions, and finally analyze any incident occurred on the HVDC system.

Replica offers the opportunity for maintenance teams, involved in HVDC installations, to learn and to practice before doing regular repair or even preventive maintenance. They gain in confidence to intervene efficiently just in time to avoid outages within the installation. The replica increase the availability of the HVDC system. System operators are also interested in using replicas in order to have a better understanding of the functionalities and performances of the system benefiting from the simulation advantages. They can do faults, change settings and modify grid topology that cannot be done with the real system. Replica are used as well to check the software version updates of the HVDC control and protections. In addition to manufacturer's tests, RTE's engineers have to evaluate all software modifications taking into account the electrical grid. Once the latest software version is validated, then it will be implemented on site. In addition, a remote access has been implemented in the lab in order to be able to download records on every HVDC/FACTS substations. When an event occurs on site the national maintenance team can access the control system on site in order to start the analysis very quickly. For instance they can have access to the local TFRs, trends and sequence of event recordings. It is presently used to have a better understanding of the HVDC system and find effective solutions in collaboration with manufacturer during warranty period of the HVDC system.

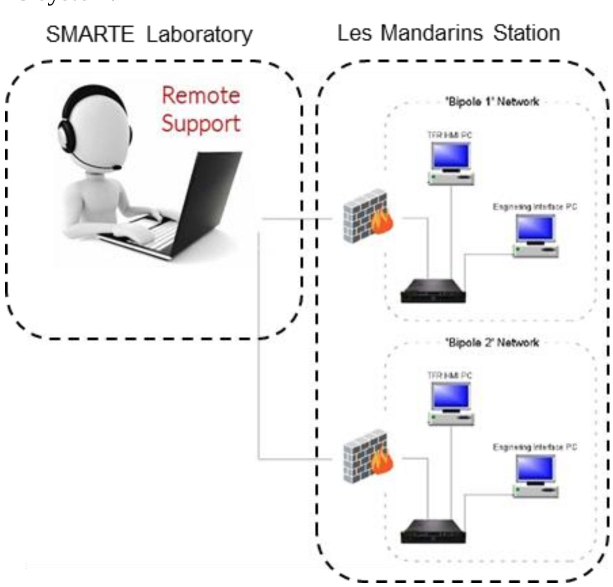

Fig. 14: Remote access architecture for IFA2000 SCADA system

VII. Conclusion

This paper presents the IFA2000 control replica and activities to improve the studies and the maintenance of the HVDC system. This project is part of a global strategy which has been set up at RTE to develop tools and skills on strategic power electronics installations.

Explanations have been provided on the Hypersim modelling to meet real-time simulation requirements and to ensure a good accuracy. A generic HVDC control model has been develop in Matlab-Simulink in order to test the power system model. This model will be used in a second step to model the second link and for offline simulation using EMTP-RV.

Two validations tests have been shown: one from the factory test realized in GE's RTDS laboratory and the other from a recent real site event. A good match have been observed between RTDS and Hypersim results, thus validating the Hypersim model and the installation of the replica. In addition, the comparison with a real cable fault has provided a good comparison giving a high level of confidence in this new installation for the analysis of future events.

Impact of the replica on the maintenance activities has also been discussed for which RTE has ambitious objectives to develop an independent know-how for HVDC and SVC projects.

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