Resonance and insertion studies with EMTP: Working with large scale network models

S. Dennetière, A. Parisot, E. Milin, A. Dalmau Pons

Abstract—**In the next few years, the French TSO RTE will install several long EHV cables and HVDC links on its high voltage network. The insertion of these new components requires EMTP studies to detect any potential adverse resonance or interaction with the existing network. Due to the low frequency phenomena involved, the surrounding network must be represented to a far extent, taking into account the various topologies in system operation. This can lead to a very time consuming and error prone EMTP model-building phase in studies, to be repeated for each individual component.**

To limit risk of error from building large networks and to gain time, RTE has decided to develop an interface between system tools and EMTP. This XML based interface enables SCADA data to be automatically imported in EMTP graphical user interface. This approach has been applied to model in EMTP the complete 400 kV network in France.

This paper describes the environment developed in EMTP, imported data from SCADA to EMTP and studies performed with the full models. The results demonstrate the feasibility of this approach and its relevance for insertion studies.

***Keywords*: data portability, EMTP, Electromagnetic transient studies, large scale networks modeling**

I. Introduction

THE French TSO RTE (Réseau de Transport d'Electricité) operates, designs and maintains the largest network in Europe, at the center of the European electricity market. To carry out needed reinforcements in the French grid in a context of dwindling public acceptance for new overhead infrastructure, many installations of long EHV cables, capacitor banks and HVDC links are planned in the next few years. These new components may give rise to unusual electromechanical and electromagnetic phenomena with potential adverse effects on the existing network. Therefore, specific studies have to be conducted, from the earlier planning to final commissioning stages. These studies are commonly referred to as "insertion" studies.

One example of these insertion studies is the detection and mitigation of potential harmonic temporary overvoltages during no-load transformer energization. Long EHV cable installations can lead to harmonic resonances and are therefore susceptible to induce such overvoltages [1]-[2]. Based on the network short circuit power at the cable supply bus bar and the charging reactive power associated to total capacitance seen at cable supply busbar, a preliminary assessment of the risk of resonance can be obtained [2]. This simple expression only provides a quick estimate of the first resonance frequency. More detailed calculations should be carried out for assessing the network harmonic impedance.

When studying such low frequency phenomena, one must determine to which extent the surrounding network must be modeled explicitly as opposed to fundamental frequency multi-port network equivalents [3]. As we will see in part II of this paper, prior work suggests that the use of a large scale model around the study area is recommended to obtain accurate results. However, building such large scale models is time consuming, error prone and also requires accounting for the various network topologies and generation/consumption scenarios in network operation. Therefore, RTE has decided to implement a XML-based link between EMTP-RV [4] and the system tools used in RTE for network operation and system studies. This link will be described in part III of this paper. It has been shown in [8] that with the selection of appropriate simulation methods in both computation and visualization fields, it is feasible to simulate extra large networks in an EMTP type program as EMTP-RV.

Part IV of this paper illustrates the use of this approach in three test cases :

- load flow, frequency scan and time domain calculations for the entire 400 kV network in France, which demonstrates the achieved performance in terms of computation time
- an actual study of insertion of a long EHV cable in the northwest of France, which demonstrates the relevance of large scale network modeling in these studies
- preliminary simulations for the France-Spain HVDC-VSC link, which show a potential application of the model in this context

II. Harmonic impedance assessment on EHV networks

RTE's experience with harmonic temporary overvoltages has been mainly based on power system restoration studies. In such studies, the transmission system topologies are quite different from the well meshed system during normal operation. Due to parallel resonance resulting from the combination of the system impedance and the transmission line

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Paper submitted to the International Conference on Power Systems Transients (IPST2011) in Delft, the Netherlands June 14-17, 2011

capacitance, harmonic distortions caused by the switching of lightly loaded or unloaded transformers are amplified, creating high harmonic overvoltages which may cause catastrophic equipment damages and activation of protective devices. Therefore detailed investigations and studies on the harmonic overvoltage problems during power system restoration are of vital importance. Frequency scan studies enable determination of potential dangerous resonances on the network.

During the power system restoration some critical topologies have to be analyzed in details. These topologies usually involve transformer energizing through long unloaded lines. Such a case is presented in Fig. 1 and the 400kV network power restoration is carried out as follow :

- GEN1 generates power required by auxiliary loads (28MW + 15 MVAR),
- LINE1 energizing,
- Transformer TR1 energizing (no-load),
- LINE2 and LINE3 energizing,
- Transformer TR2 energizing (no-load),
- LINE4 and LINE5 energizing,
- Transformer TR3 energizing (no-load).

Transformer TR3 energizing can be critical because LINE5 is long and connected to a lightly loaded network. Frequency scan is used to assess the harmonic impedance at substation F before transformer energizing. In order to evaluate the impact of fundamental frequency network equivalent on harmonic impedance, results obtained with 2 network equivalents are compared against full network modeling. Equivalent networks are defined as follow :

- The first equivalent : entire network except LINE5,
- The second equivalent : GEN1 + TRA + AUX

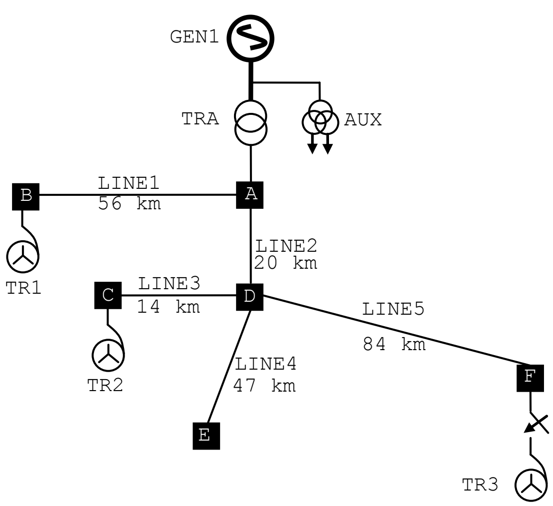

Fig. 1 400 kV network example for power restoration

Harmonic impedances are presented in Fig. 2. 1st equivalent network leads to wrong assessment for resonance frequency and resonance amplitude. 2nd equivalent network gives a good assessment of resonance frequency but resonance amplitude is highly overestimated. As a conclusion full network modeling is the only solution to get harmonic impedances as much accurate as possible.

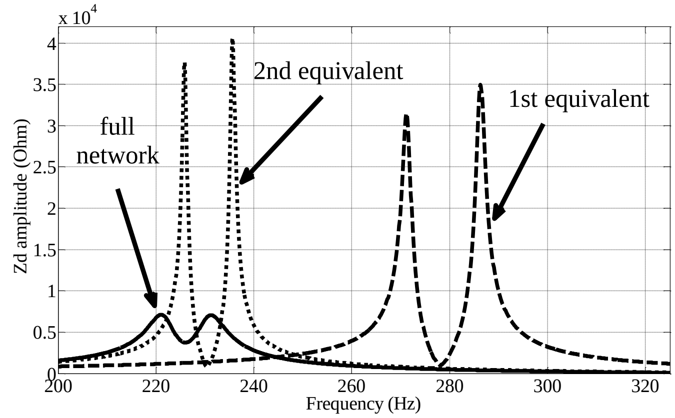

Fig. 2 Harmonic impedance at substation F

In this case full network modeling is the only solution to get the correct solution because loads are neglected by equivalent networks based on short circuit power. For instance 1st equivalent network is calculated from short circuit applied at substation A and auxiliary loads cannot be taken into account by such an equivalent network.

Fig. 3 presents the first resonance amplitude versus the active power consumed by auxiliary loads. The first resonance amplitude for no resistive load is closed to the first resonance amplitude obtained with 2nd equivalent network.

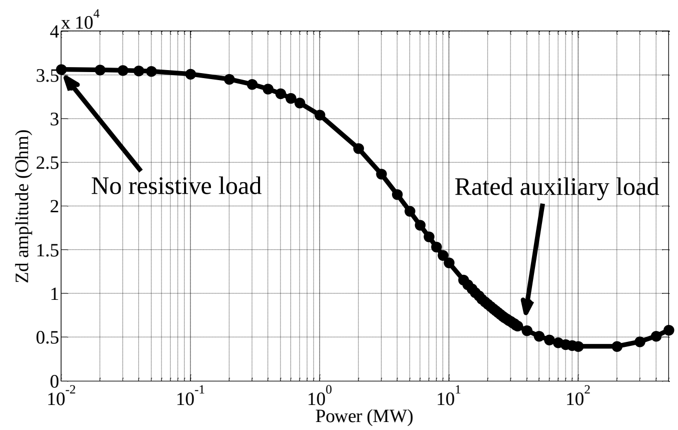

Fig. 3 First resonance amplitude versus active power auxiliary load

This basic example based on a power restoration study suggests that large scale network modeling is mandatory for accurate harmonic impedance assessment on EHV networks. This is coherent with a joint CIGRE/CIRED WG CC02 document [6], which recommended (without justification) to model accurately at least all the primary transmission network in such studies. The WG also deemed it appropriate to consider the loads on the secondary transmission network in order to decide whether these should be modeled explicitly or as an equivalent circuit. If these loads are placed directly on the secondary side of the transformer, the damping they cause can be overestimated when using too simple equivalents. According to this WG the entire 400 kV French grid at least should be modeled to accurately assess the harmonic impedance close to EHV cable new installation.

III. Interface Description

A. CONVERGENCE platform

Many years ago RTE identified the need of a platform gathering network data and tools for static simulations. As of now, a first version of this platform has been developed and provides the following features :

- Description of the entire RTE network from 400 kV to 63 kV : sequence impedances of lines (direct and zero-sequence), transformers parameters (impedances, tap changer positions,…), generators (sequence impedance, voltage and power references), loads, substations configurations
- Network data in real time : RTE network snapshots are available every 5 minutes.
- Network data for planning studies
- Load-flow and short-circuit calculations in the same platform.

From CONVERGENCE platform (see Fig. 4) network data and load-flow results can be exported into an XML file.

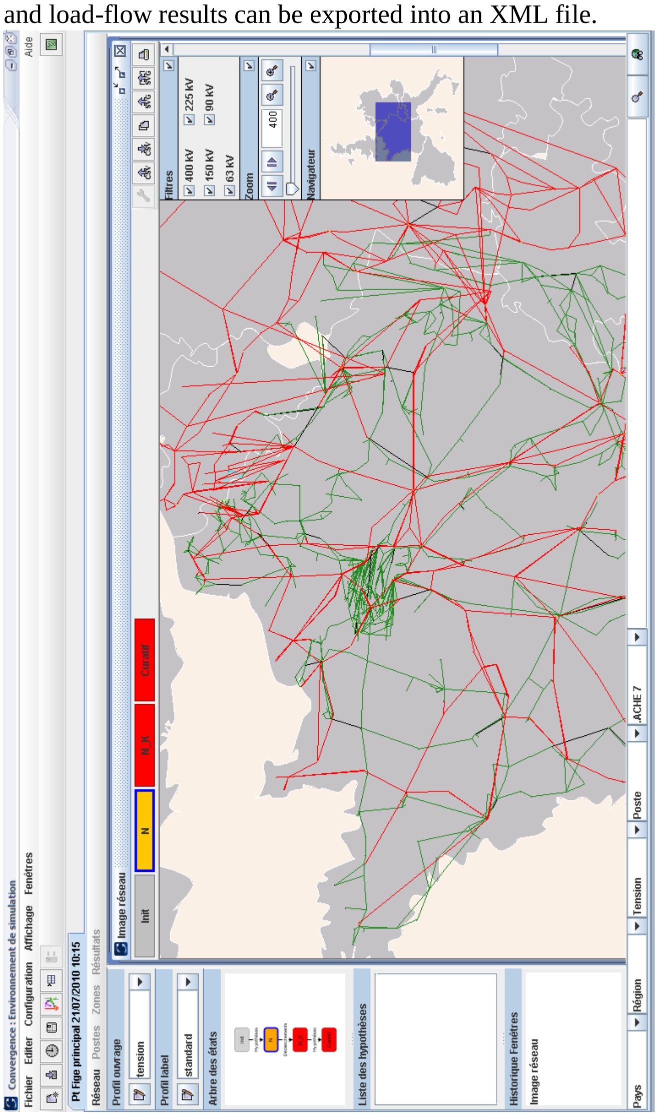

Fig. 4. CONVERGENCE platform showing a part of the RTE network

B. EMTP-RV graphical user interface

The Graphical User Interface of EMTP-RV is named EMTPWorks. As explained in [4] almost all the aspects of this GUI are scriptable and modifiable by the user. Data input is based on web pages. It provides quasi unlimited capabilities in the development of data forms through dynamic HTML programming. Users can create their own user interface. Forms, device drawings, simulation options can be controlled through JavaScript language. The scripting language is JavaScript with EMTPWorks extensions.

To build a network in EMTP that looks system representations of the network a set of standard devices has been developed as presented in Fig. 5. The network in EMTP is built manually by user based on the standard devices.

Parameters of these devices can be modified through custom made forms as presented in Fig. 5. Busbar connections are updated on the drawing depending on data available in forms.

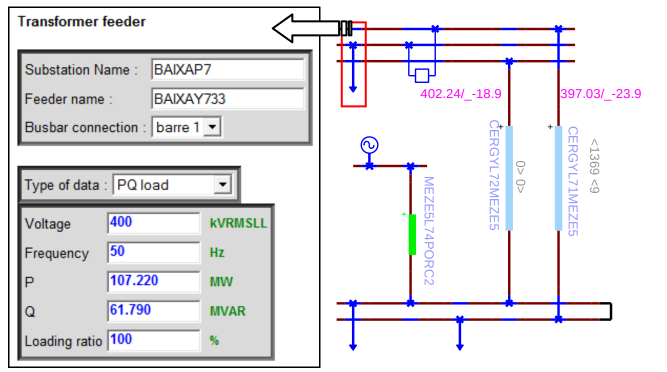

Fig. 5. Part of the 400 kV network schematic based on specific devices and transformer feeder form

These standard devices (for instance an outgoing line feeder connected to a 3 busbar substation) are used many times in the drawing. As explained in [8] a mechanism is available in EMTPWorks for updating all subcircuit contents by modifying the internal details of only one instance. This object oriented mechanism is called unique type definition. A unique type definition can be maintained for contents, but mask data can vary independently.

C. From SCADA data to EMTP GUI

As explained in previous section, data of the entire RTE network can be exported in XML file through CONVERGENCE platform. A part of the XML tree view used for data export is presented below.

```
<SUBSTATIONS>
    <NAME>
    <COUNTY>
    <NOMINAL VOLTAGE>
    <SWITCHING DEVICES>
    <FEEDERS>
<LINES>
    <NAME>
    <SUBSTATION IN>
    <SUBSTATION OUT>
    <SEQUENCE IMPEDANCE>
<TRANSFORMERS>
    <NAME>
    <SUBSTATION IN>
```

```
    <SUBSTATION OUT>
    <SEQUENCE IMPEDANCE>
    <NOMINAL VOLTAGE>
    <TAP CHANGER PARAMETERS>
<GENERATORS>
    <NAME>
    <SUBSTATION>
    <REGULATION PARAMETERS>
    <SEQUENCE IMPEDANCE>
<LOADS>
    <NAME>
    <SUBSTATION>
    <ACTIVE POWER>
    <REACTIVE POWER>
<REACTIVE COMPENSATION>
    <NAME>
    <SUBSTATION>
    <RATED MVAR>
    <MAX MVAR>
```

To import the XML data into EMTPWorks the Microsoft COM implementation of the XML Document Object Model (DOM) has been used. The XML DOM provides a navigable set of classes that directly reflect the W3C Document Object Model Level 1 specification. This DOM implementation provides JavaScript interfaces and thus can be used in EMTPWorks. XML DOM is activated through the JavaScript COM interface. The XML file exported from CONVERGENCE platform is read by EMTPWorks JavaScript functions and converted in string format in less than 1s. This string contains the entire XML document. To locate parameters of specific equipment, path expressions are used to select nodes in the xml document.

Following the XML document loading, scripts are used to update the network parameters: lines parameters, generators voltage and power references, circuit breakers / disconnect switch positions, etc. When network parameters are updated, the discrepancies between network schematic in EMTP and network data in XML document are output in a log file. Additional functions are also implemented to:

- Locate a substation based on its name
- Apply a ratio on loads for selected load devices.
- Replace CP line models with propagation delays smaller than integration time step by π-line sections with their corresponding sequence impedances

A CIM/EMTP-RV interface has already been developed in the past [9]. This interface has not been used by RTE because it is based on bus-branch topology description.

IV. Test Cases

A. 400 kV French grid

Data of the entire RTE network and a limited part of ENTSO-E network is available in CONVERGENCE platform. The listing of main devices in XML document is :

- 4731 transmission lines
- 557 generators
- 880 power transformers
- 4482 loads

The XML document is loaded in less than 1s. The network schematic developed in EMTP includes the entire 400 kV French grid. The total system model is composed of 419 transmission lines operating at 400 kV and 91 synchronous generators. The total number of electrical nodes is 1,211 (around 400 3-phase buses). Transmission lines are modeled using the CP model where lines with propagation delays smaller than integration time step are automatically replaced by π-line sections with their corresponding sequence impedances. A partial view of the EMTP network model is presented in Fig. 6.

Computer speed for simulation of the 400 kV French grid are given in TABLE I. CPU timings are given for an Intel i5/640 processor and a fast (7200 rpm) hard disk.

TABLE I
400 kV French Grid Simulations- CPU timings

	Parameters	Computer Time (Sec)
Load-flow	6 iterations	4.1
Frequency-Scan	[0 → 1000 Hz] $\Delta f = 1$Hz	3.8
Time-domain	tmax = 1s; $\Delta t = 200\mu s$	5.2

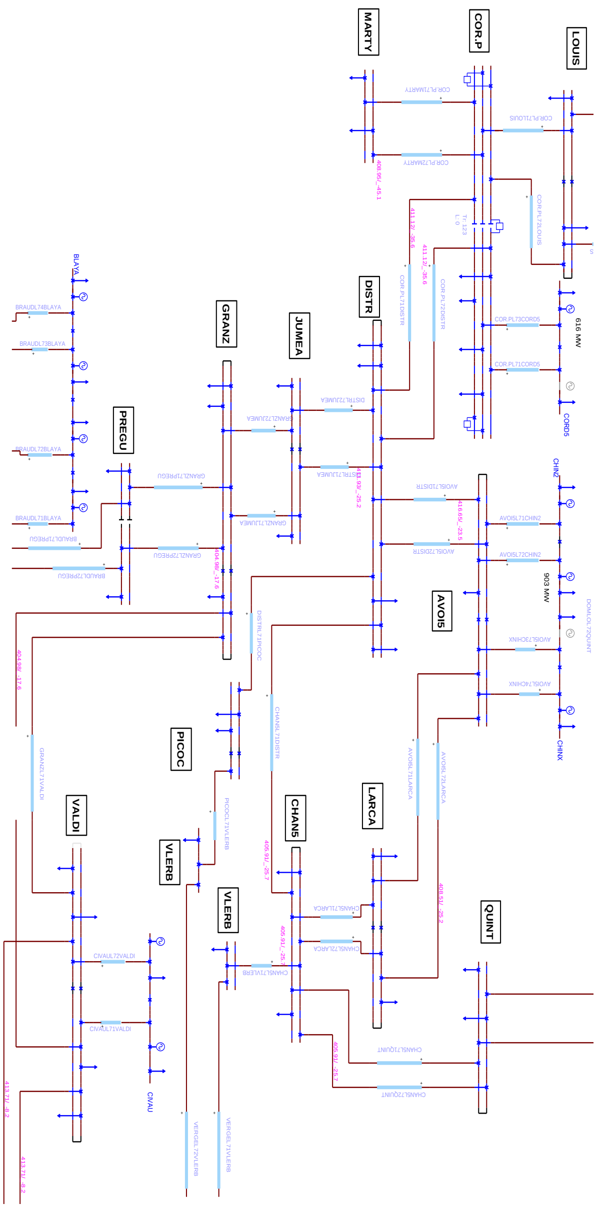

Fig. 6. Partial of the RTE network in EMTP

B. Frequency scan studies for long EHV cable installations

The 400 kV network presented in the previous section has been used to analyze the relevant study area for frequency scan studies. Frequency scan studies are performed in RTE as part of projects for long EHV cable installations. In these cases the local 225 kV network is added as well.

To analyze the impact of the study area, various network reductions are compared. Network is modeled up to 1, 2 and 3 nodes away from the study points. Study points are the cable connections to the EHV grid. Links between successive nodes are lines as well as transformers. Networks beyond the border nodes are represented by short-circuit impedances calculated at power frequency.

Frequency-scan studies are carried out with reduced and complete networks. Harmonic impedances amplitude at connection points are presented in Fig. 7. Network reduction based on short-circuit impedance leads to overestimate the magnitude of resonances. As a consequence RTE decided to use the approach proposed in the paper to model the entire 400 kV network and the local 225 kV network for EHV cables installation studies. This conclusion is consistent with that of the CIGRE/CIRED working group CC02 and the basic intuition based on power restoration studies and presented in section II. However, in the first case, the recommendation was given without justification, and in the second case, the network size was quite limited.

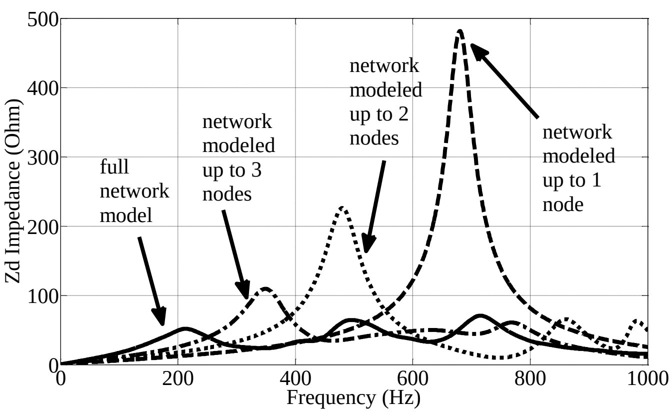

Fig. 7. Harmonic impedance at connection point depending on study area

C. Large System Test: France-Spain Interconnection

1) Project background

An underground HVDC link interconnecting the 400 kV systems of France (Baixas) and Spain (Santa Llogaia) across the Pyrenees will be commissioned by 2013. The interconnection is composed of 2 links with a rated transmission capacity of 1,000 MW each. A geographic map of the 400 kV and 225 kV grids, including the future DC interconnection, is presented in Fig. 8.

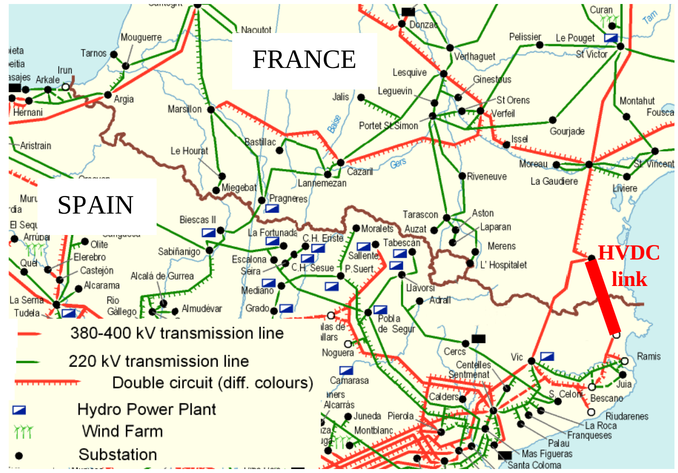

Fig. 8. France-Spain VSC-HVDC interconnection

RTE France has conducted transient studies using EMTP-RV to help with the preparation of technical specifications and to study system's transient behavior. The detailed and AVM of the VSC-HVDC system presented in this paper are tested for this interconnection. Details of the models as well as the results of the simulations are discussed in this section.

2) AC System Model and Initialization

The AC model includes the entire 400 kV French grid presented in the previous section plus a dynamic equivalent system of the 400 kV Spanish grid.

Initialization of large networks including HVDC systems is a key issue for EMT-type analysis. The VSC-HVDC model presented in section V does not include automatic initialization of control system variables. To deal with this limitation in a large power system, the VSC-HVDC link is connected to ideal voltage sources during start-up and is synchronized to the AC grid when the reference power is reached. The voltage magnitude and angle of the ideal sources are automatically calculated from the load-flow solution. As shown in Fig. 9 the AC network simulation starts in perfect steady-state and disturbances, such as AC or DC faults, can be applied after the VSC-HVDC system reaches the power reference ($T_{start-up}$=600ms).

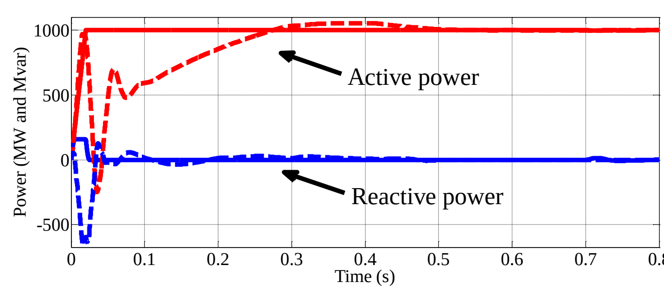

Fig. 9. Active and reactive power initialization at the rectifier VSC (Solid line: AC initialization, Dashed line: VSC-HVDC initialization)

3) Preliminary Dynamic Performance Studies

The VSC-HVDC system modeled for the France-Spain interconnection has the following characteristics:

- Capacity: 1,000 MW (for each VSC link)
- DC voltage: ±320 kV
- AC networks voltage: 400 kV @50Hz (both ends)
- DC cables: 2x70 km single core cables

To accurately model and simulate both steady-state and transients in the DC cables, a wideband frequency model is used [5]. This frequency-dependent model allows representing the behavior of the cable in a wide range of frequencies from DC to a few kHz.

Transient stability and electromagnetic transient simulations are conducted in order to test the dynamic behavior of the HVDC when integrated to a large power system. VSC-HVDC systems have power-reversal capabilities. In case of a large contingency in the AC network, power-flow could be reversed in a few hundred milliseconds to avoid a major system disturbance. Power reversal is tested by changing the power reference at t=1.2s from 1.0pu to -1.0pu using a 200ms ramp reference. The VSC-HVDC link initially transmits rated power of 1,000 MW. The active power on the rectifier VSC is presented in Fig. 10. Power oscillations are observed at the end of power reversal event which are induced by generators close to the VSC-HVDC link

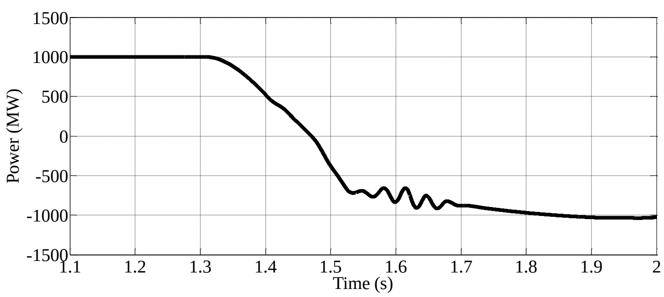

Fig. 10. Active Power on Rectifier Side during power reversal

V. Conclusions

In this paper, we report on RTE's recent experience with modeling large scale networks in the context of insertion studies. Past experience with power system restoration studies and prior work in CIGRE/CIRED suggested that modeling a large share of the network explicitly in EMT software was necessary to accurately compute the harmonic response of the network and assess the risk of harmonic temporary overvoltages when energizing transformers. Based on this intuition an XML-based interface has been developed to automatically import data from system tools into EMTP-RV. This approach has been used to model in EMTP-RV the entire 400 kV network in France, with the possibility to adjust the network topology and load/generation data from SCADA snapshots or system planning studies.

The presented test cases demonstrate that the feasibility, robustness and relevance of this approach for studies of low frequency phenomena when inserting new components in electrical networks. The achieved computation time with the obtained model for full 400 kV network in France is compatible with a direct utilization in actual insertion studies. Application of the approach to insertion studies for long EHV cables confirmed the necessity of representing the entire network in these studies in order to accurately compute the harmonic response of the network. The XML-based link can also be used in other studies, as illustrated in the case of the France-Spain HVDC-VSC project.

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