# Interactions Studies of HVDC-MMC link embedded in an AC Grid

H. Saad, J. Mahseredjian, S. Dennetière, S. Nguefeu

*Abstract* - HVDC link interconnections under construction or planned in France are part of a highly meshed ac network. This is a relatively new operating condition. The impact of their operation and the risk of abnormal interaction may have an influence on the ac network. The use of voltage source converters (VSCs) with the modular multilevel converter (MMC) topology is becoming more attractive mainly due to their higher performances and cost. This paper analyses the operation and interaction of MMC-HVDC links embedded in an ac grid. First a MMC-HVDC link model suitable for small-signal analysis is presented. This small-signal HVDC model is then validated against an EMT-type model for ac systems having different SCR (Short-Circuit Ratio) values. Modal analysis and parametric studies are performed in order to study the impact of the ac line connected in parallel with HVDC link.

*Keywords*: EMTP, HVDC transmission, MMC, VSC, Interactions, Modal analysis.

# I. INTRODUCTION

Several HVDC-MMC link [1] projects are currently planned or constructed by RTE (French TSO). One of such projects is the INELFE interconnection project, with a capacity of 2,000 MW [2], between France and Spain. HVDC link interconnections in France are part of a highly meshed ac network. This is a relatively new aspect. Such links may have abnormal interaction risks and also impact on the performance of the ac network. In [3] - [5], small-signal analysis of VSC stations and modal studies of a dc grid were presented. In [6], a stability study between two HVDC links and a comparison between VSC and LCC are contributed. Studies on a VSC-HVDC link connected in parallel with an ac line are available in [7] and [8]. In [9], a study of interaction between a VSC-HVDC link and a STATCOM is presented.

In this paper, modal analysis and EMT-type methods are used to study interactions between HVDC links connected in parallel with an ac line. Therefore, unlike previous articles, it provides a complete overview on the abnormal interactions that can occur during small and large disturbances.

There are different simulation tools for assessing the stability of electrical networks. EMT type simulations are used

to evaluate the response of the system subjected to major disturbances. The models required for this type of simulation must be accurate to represent the nonlinearities of the system. EMT-type programs are used to represent accurately the electromagnetic transients; they are also well suited to simulate power electronics devices. For studies related to HVDC links, EMT type models are considered as reference models for validating simplified models. Although EMT type models can be used to study electromechanical transients, it is generally less efficient in terms of computing time and it is possible to apply more simplified methods and models for this type of phenomenon or for slower dynamic behavior in general.

Another approach is based on the small signal type analysis [14]. This approach is based on the linearization of the model around a set point of operation. Therefore, the main advantage is the possibility of using the control theories developed for linear systems. Small perturbations around the operating point can be applied to study the stability of the system. Once these linear state equations are derived, it becomes possible to analyze the system with standard tools such as root locus, participation factor, mode shape, etc. However, since these linearized models are based on simplifications, it is important to validate the results with EMT-type simulations. For example, it has been shown in [15] that the conclusions drawn from quasi-static analysis are not always in agreement with the results of simulations from EMT-type programs.

In this paper, interactions between the VSC-MMC stations embedded in an ac network are studied. This paper begins with the development of the small-signal MMC-HVDC link model. The model is validated by comparing it with an EMT reference model and small signal studies are then developed. Finally, parametric studies using EMTP-RV [16] are presented to evaluate the influence of ac transmission lines connected in parallel with the HVDC link.

#### II. SMALL SIGNAL MODEL

Several types of MMC models were presented in [10]. To achieve small-signal dynamic studies, an average model (AVM) of a VSC-MMC station is used. The AVM model referred to as the MMC Model #4 in [10], is shown in Figure 1.  $C_{dc}$  is the equivalent capacitor of the MMC.  $L_{arm}$  and  $R_{arm}$  refer to the reactor and resistance of each arm.

H. Saad, S. Dennetiere and S. Nguefeu are with Réseau de Transport d'Electricité (RTE), Paris-La Défense, France (e-mail: <u>hani.saad@rte-</u> france.com).

J. Mahseredjian is with École Polytechnique de Montréal, Campus Université de Montréal, 2900, Édouard-Montpetit, Montréal (Québec), Canada, H3T 1J4.

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Figure 1: MMC Model #4 derived in [10]



Figure 2: MMC-HVDC transmission system in parallel with an ac line

#### A. MMC model

The small signal model can be found from Figure 1 and Figure 2. The equations in dq frame for the ac side are:

$$\frac{d\Delta i_d}{dt} = -\frac{R_{ac}}{L_{ac}}\Delta i_d + \frac{1}{L_{ac}}\Delta v_{PCC_d} - \frac{1}{L_{ac}}\Delta v_{conv_d} + \omega\Delta i_q$$

$$\frac{d\Delta i_q}{dt} = -\frac{R_{ac}}{L_{ac}}\Delta i_q + \frac{1}{L_{ac}}\Delta v_{PCC_q} - \frac{1}{L_{ac}}\Delta v_{conv_q} - \omega\Delta i_d$$
(1)
where  $L_{ac} = L_{trf} + L_{arm}/2$  and  $R_{ac} = R_{trf} + R_{arm}/2$ .

For the dc side, the equations are found from Figure 1.b:

$$\frac{d\Delta I_{dc}}{dt} = \frac{\left(\Delta V_{C_{eq}} - \Delta V_{dc}\right)}{L_{dc}} - \frac{R_{dc}}{L_{dc}}\Delta I_{dc}$$
(2)

$$\frac{d\Delta V_{C_{eq}}}{dt} = \frac{\left(\Delta I_{conv} - \Delta I_{dc}\right)}{C_{dc}}$$
(3)

where  $L_{dc} = 2L_{arm}/3$ ,  $R_{dc} = 2R_{arm}/3$  and  $C_{dc} = 6C/N$ . Based on (1), (2) and (3), the resulting circuit is presented in Figure 3.



Figure 3: small-signal model of MMC station

From Figure 3, the ac side small signal model is similar to a classical VSC-2 or -3 level [11]-[12] design. However, for the dc side, differences are observed between MMC and classical VSC, where an equivalent inductance ( $L_{dc}$ ) and resistance ( $R_{dc}$ ) are included in the MMC model.

Based on energy conversion:

$$P_{dc} = P_{ac} \Leftrightarrow I_{conv} V_{C_{eq}} = \sum_{j=a,b,c} v_{conv_j} i_j$$
(4)

in *dq* reference and using Figure 1.b:

$$\frac{dV_{C_{eq}}}{dt} = \frac{1}{C_{dc}} \left( \frac{v_{conv_{ac_d}} i_d + v_{conv_{ac_q}} i_q}{V_{C_{eq}}} \right) - \frac{I_{dc}}{C_{dc}}$$
(5)

Equation (5) is not linear. Using the first order Taylor series, (5) becomes:

$$\frac{d\Delta V_{C_{eq}}}{dt} = \frac{i_d}{C_{dc}V_{C_{eq0}}} \Delta v_{conv_d} + \frac{i_q}{C_{dc}V_{C_{eq0}}} \Delta v_{conv_q} + \dots$$

$$\frac{v_{PCC_d}}{C_{dc}V_{C_{eq0}}} \Delta i_d + \frac{v_{PCC_q}}{C_{dc}V_{C_{eq0}}} \Delta i_q - \dots$$

$$\left(\frac{v_{conv_{d_0}} i_{d_0} + v_{conv_{q_0}} i_{q_0}}{C_{dc}V_{C_{eq0}}^2}\right) \Delta V_{C_{eq}} - \frac{1}{C_{dc}} \Delta I_{dc}$$
(6)

where the subscript 0 denotes initial values

The small signal MMC model is represented by the linear equations (1), (2) and (6).

# B. Reference change RI to dq

The dq reference frame of the converter station is synchronized with the reference *RI* (Real-imaginary) network frame by means of a PLL. To take into account the PLL dynamics, the variable that represents the phase angle  $\delta_{PLL}$ between the two references must be extracted. It is chosen to align with the axis *q* the imaginary axis *I*. Therefore, the reference change between the ac network and the station can be represented as follows [13].

$$v_d + jv_q = \left(\cos\delta_{PLL} - j\sin\delta_{PLL}\right)\left(v_R + jv_I\right) \tag{7}$$

By linearizing equation (7), we obtain the RI to dq references change:

$$\begin{bmatrix} \Delta v_d \\ \Delta v_q \end{bmatrix} = \begin{bmatrix} \cos \delta_{PLL_0} & \sin \delta_{PLL_0} \\ -\sin \delta_{PLL_0} & \cos \delta_{PLL_0} \end{bmatrix} \begin{bmatrix} \Delta v_R \\ \Delta v_I \end{bmatrix} + \dots \\ \begin{bmatrix} -v_{R0} \sin \delta_{PLL_0} & v_{I0} \cos \delta_{PLL_0} \\ -v_{R0} \cos \delta_{PLL_0} & -v_{I0} \sin \delta_{PLL_0} \end{bmatrix} \Delta \delta_{PLL}$$
(8)

The same procedure can be performed to formulate the conversion from dq to RI references.

# C. Control system

MMC Model #4 allows neglecting the internal energy balance [10]. Therefore, the circulating currents as well as the balancing capacitor voltages of SMs are neglected in this study. Only the inner current loops (*i*-control) and the outer control are modeled. Furthermore, linearization of the model around a steady-state set point, allows considering only the linear part of the controller. The simplifications introduced for the small-signal model are:

- Removal of anti-windup functions in the PI loops
- Limiters and saturations are suppressed
- Linearization and simplification of the PLL (Phase-Locked Loop)
- Removal of abc-dq transformations
- The division by ac voltage (*v*<sub>PCC<sub>d</sub></sub>) to convert power reference into current reference is linearized.

Figure 4 presents the structure of the control system used for small-signal studies. In HVDC links, one station uses a *P*control to regulate the active power of the link and the other one  $V_{dc}$ -control to regulate the dc voltage. Furthermore, each station can independently control the reactive power (*Q*control) or ac voltage ( $V_{ac}$ -control).

To linearize the PLL, some loops and components of the nonlinear EMT model must be neglected: the abc-dq conversion, the average frequency estimation and saturation blocks. These simplifications generate a slight modeling error that will be evaluated in the next section.



Figure 4: Small signal control system

Table 1 and Table 2 present the PI control gains and filters data respectively.

TABLE 1: PI CONTROL VALUES

Control	Variable name	Time constant	Damping ratio ( $\zeta$ )
i-control	$i_{d_{Ctrl}}, i_{q_{Ctrl}}$	10 ms	0.7
$P$ -control $V_{dc}$ -control $Q$ -control $V_{ac}$ -control	$P_{Ctrl}$ $V_{dc_{Ctrl}}$ $Q_{Ctrl}$ $V_{ac_{Ctrl}}$	100 ms	0.7
PLL	PLL	100 ms	1

TABLE 2: FILTER VALUES

Filter	Variable name	Cutoff frequency	Damping ratio $(\zeta)$	
i-control low pass filter	$LP_i_{dqCtrl}$	10 Hz	0.7	
PLL low pass filter	LP_PLL	4.77 Hz	0.7	

The complete small-signal station model is resumed in Figure 5.



Figure 5: Station converter model

# D. Grid model

The ac grid is modeled using line impedances [14] assuming low frequency perturbation. The general idea is presented as follows:

$$[V] = [Z][I] \tag{9}$$

or using complex numbers:

$$V_R + jV_I = (R + jX)(I_R + jI_I)$$
(10)

the small-signal impedance matrix of an ac network is given by

$$\begin{vmatrix} \Delta v_{R_{1}} \\ \Delta v_{I_{1}} \\ \dots \\ \Delta v_{R_{i}} \\ \Delta v_{R_{i}} \\ \Delta v_{I_{i}} \end{vmatrix} = \begin{bmatrix} R_{11} & -X_{11} & \dots & R_{1i} & -X_{1i} \\ X_{11} & R_{11} & \dots & X_{1i} & R_{1i} \\ \dots & \dots & \dots & \dots & \dots \\ R_{i1} & -X_{i1} & \dots & R_{ii} & -X_{ii} \\ X_{i1} & R_{i1} & \dots & -X_{ii} & R_{ii} \end{bmatrix} \begin{vmatrix} \Delta i_{R_{1}} \\ \Delta i_{I_{1}} \\ \dots \\ \Delta i_{R_{i}} \\ \Delta i_{I_{i}} \end{vmatrix}$$
(11)

# E. DC cable model

One PI section has been used to model the dc cable. It should be noted that, more PI sections will lead to a better representation of the cable. However, in the next section it will be shown that this simplification won't affect the conclusion that will be driven.



Figure 6: dc cable model

From Figure 6, the small signal equations of the cable are deduced:

$$\frac{d\Delta V_{dc_1}}{dt} = \frac{1}{C_{cable}} \left( \Delta I_{dc_1} - \Delta I_{dc_{cable}} \right) - \frac{G_{cable}}{C_{cable}} \Delta V_{dc_1}$$
$$\frac{d\Delta V_{dc_2}}{dt} = \frac{1}{C_{cable}} \left( \Delta I_{dc_2} + \Delta I_{dc_{cable}} \right) - \frac{G_{cable}}{C_{cable}} \Delta V_{dc_2} \quad (12)$$
$$\frac{d\Delta I_l}{dt} = \frac{1}{L_{cable}} \left( \Delta V_{dc_1} - \Delta V_{dc_2} \right) - \frac{R_{cable}}{L_{cable}} \Delta I_{dc_{cable}}$$

#### III. MODEL VERIFICATION

The HVDC link model developed in the previous section must be validated. The nonlinear EMTP-RV MMC Model #4 [10] including the complete control system is used as a reference model. This model was already validated against a more detailed model (see [2]).

In Figure 2, the HVDC link is in parallel with an overhead line. The VSC1 station is in *P*-control and the VSC2 station is in  $V_{dc}$ -control. To create a small disturbance in the system, a step change of -0.1 pu is applied at t=2 s on the active power reference ( $P_{ac}^{ref}$ ) of VSC1.

For all figures, a blue solid line is used for the EMT reference model and a green dotted line for the small-signal model. All simulations were conducted using EMTP-RV software [16].

#### A. Verification with a strong SCR

In this first test, a high SCR is considered for the equivalent Thevenin networks (SCR1 = SCR2 = 10 in Figure 2). The variables of the VSC1 station are compared in Figure 7.

It is observed that there is a difference in the steady state for the majority of variables compared between the smallsignal model and the EMT reference model. The results are slightly shifted because the steady-state set points of the smallsignal model do not match exactly with the set points of the nonlinear EMT model. However, these differences have little influence on the small signal studies and the main objective is to verify that the oscillatory modes of both models are similar (which is the case).



Figure 7: Small-signal model validation for SCRs = 10

#### B. Verification with a weak SCR

For a strong SCR, the PLL control (Figure 4) is undisturbed since the equivalent source of the network imposes the system frequency. Low SCR (SCR1 = SCR2 = 2.5 in Figure 2) contributes to greater disturbances on the phase angle  $\Delta \delta_{PLL}$ and the dynamics of the PLL will be excited. In Figure 8 the results at VSC1 for the same perturbation as above, are presented.

In this case more differences between the two models on all system variables are noticed. As the SCR is lower, the variation on the angle  $\delta_{PLL}$  in Figure 8, is much higher than in Figure 7. We can note that the small-signal model is able to take into account the vast majority of oscillatory modes. However, some high frequency oscillations in  $v_{PCC_{da}}$  (Figure

8) are not represented in the small-signal results. The other difference between small-signal and EMT models lies on system damping rates. The small-signal version underestimates the damping of oscillations due mainly to the simplification made in the PLL model.



Figure 8: Small-signal model validation for SCRs = 2.5

#### IV. MODAL ANALYSIS

In this section, an eigenvalue analysis of the small-signal model is presented. The purpose of this study is to evaluate the impact of a parallel ac network on a HVDC link (Figure 2).

#### A. Analytic study

First, the ac network impedance matrix including the parallel line is found :

$$Z = \begin{bmatrix} \frac{Z_{SCR_1} \left( Z_{ac} + Z_{SCR_2} \right)}{Z_{SCR_1} + Z_{ac} + Z_{SCR_2}} & \frac{Z_{SCR_1} Z_{SCR_2}}{Z_{SCR_1} + Z_{ac} + Z_{SCR_2}} \\ \frac{Z_{SCR_1} Z_{SCR_2}}{Z_{SCR_1} + Z_{ac} + Z_{SCR_2}} & \frac{Z_{SCR_2} \left( Z_{ac} + Z_{SCR_1} \right)}{Z_{SCR_1} + Z_{ac} + Z_{SCR_2}} \end{bmatrix}$$
(13)

where  $Z_{ac}$  is the impedance of the ac line in parallel. The diagonal terms of (13), represent the effective short-circuit impedances seen by the VSC stations. The ac line in parallel contributes to the reduction of short-circuit impedance and

consequently to the increase of the SCR, since :

$$Z_{SCR_{1}} \ge \frac{Z_{SCR_{1}} \left( Z_{ac} + Z_{SCR_{2}} \right)}{Z_{SCR_{1}} + Z_{ac} + Z_{SCR_{2}}}$$
(14)

This implies a better performance of the HVDC link when an ac line is in parallel. However, the off diagonals terms are not equal to zero, indicating a risk of interaction between the two converter stations. Note that when  $Z_{ac}$  tends to infinity, the effect of the parallel line becomes negligible and when  $Z_{ac}$  decreases, the risk of adverse interaction increases.

#### B. Participation factor

To study the influence of the AC line in parallel on the participation factor, a small SCR (i.e, equal to 2.5) is chosen. HVDC link with and without the ac line in parallel are compared. For clarity, modes with a damping rate close to 1 are not presented. The participation factors [14] are presented in Table 3.

Table 3 : Impact of  $Z_{ac}$  on participation factors of HVDC

I dole .	$\mathcal{L}_{ac}$ on put	
Mode	without Zac	with $Zac = 0.006$ pu
1	f=780.6 Hz ; $\xi = 0.00867$	f=780.6 Hz ; $\xi = 0.00867$
	$V_{dc_1}, V_{dc_2}, I_{dc_{cable}}$	$V_{dc_1}, V_{dc_2}, I_{dc_{cable}}$
	f= 223.6 Hz; $\xi = 0.0017$	f= 223.6 Hz; $\xi = 0.0017$
2	$V_{dc_1}, V_{dc_2}, I_{dc_1}, I_{dc_2}$	$V_{dc_1}, V_{dc_2}, I_{dc_1}, I_{dc_2}$
3	f= 60.31 Hz ; ξ =0.04642	f= 60.31 Hz ; ξ =0.04642
	$V_{C_{eq_1}}, V_{C_{eq_2}}, I_{dc_1}, I_{dc_2}$	$V_{C_{eq_1}}, V_{C_{eq_2}}, I_{dc_1}, I_{dc_2}$
4	f=120 Hz ; ξ= 0.6034	f=110 Hz ; $\xi = 0.692$
	$i_{d_1}, i_{d_2}, i_{q_1}, i_{q_2}$	$i_{d_1}, i_{d_2}, i_{q_1}, i_{q_2}$
	f= 120 Hz ; $\xi = 0.6102$	$f=37~Hz$ ; $\xi = 0.847$
5	$i_{d_2}, i_{q_2}$	$i_{d_1}, i_{d_2}, i_{q_1}, i_{q_2}$
U	$i_{d_{Ctrl_2}}, i_{q_{Ctrl_2}}$	$i_{d_{Ctrl_1}}, i_{d_{Ctrl_2}}, i_{q_{Ctrl_1}}, i_{q_{Ctrl_2}}$
6	$f=34 Hz$ ; $\xi = 0.3453$	f= 37 Hz ; $\xi = 0.825$
	$i_{d_1}, i_{q_1}$	$i_{d_1}, i_{d_2}, i_{q_1}, i_{q_2}$
	$i_{d_{Ctrl_1}}, i_{q_{Ctrl_1}}$	$i_{d_{Ctrl_1}}, i_{d_{Ctrl_2}}, i_{q_{Ctrl_1}}, i_{q_{Ctrl_2}}$
	f= 32 Hz ; $\xi = 0.3286$	f= 30 Hz ; $\xi = 0.4104$
		$i_{dCtrl_2}$ , $i_{qCtrl_2}$ , $i_{dCtrl_1}$ , $i_{qCtrl_1}$
	$i_{d_{Ctrl_2}}, i_{q_{Ctrl_2}}$	$i_{d_2}, i_{q_2}, i_{d_1}, i_{q_1}$
7	$i_{d_2}, i_{q_2}$	$LP\_i_{d_{Ctrl_2}}, LP\_i_{q_{Ctrl_2}},$
	$LP_{-}i_{d_{Ctrl_2}}$ , $LP_{-}i_{q_{Ctrl_2}}$	$LP_{-}i_{d_{Ctrl_1}}$ , $LP_{-}i_{q_{Ctrl_1}}$
		$\delta_{\it PLL_l}$
8	f= 4.8 Hz ; $\xi = 0.6172$	$f=5.5 \text{ Hz}$ ; $\xi = 0.5172$
	S DI I	$\delta_{PLL_1}, PLL_1, \delta_{PLL_2}, PLL_2$
	$O_{PLL_1}, FLL_1$	$V_{C_{eq_1}}, V_{C_{eq_2}}$
9	$f=4 Hz$ $\xi = 0.3524$	$f=4 Hz$ $\xi = 0.5292$
	$V_{dcCtrl_2}$	$V_{dcCtrl_2}$
	$V_{C_{eq_1}}, V_{C_{eq_2}}$	$V_{C_{eq_1}}, V_{C_{eq_2}}$
	$\delta_{PLL_1}, PLL_1$	$\delta_{PLL_1}$ , $PLL_1$
10	$f=4.3 \text{ Hz}; \xi=0.6916$	$f=5.1 \text{ Hz}; \xi = 0.6798$
	$\delta_{PLL_2}, PLL_2,$	
	$V_{dc_{Ctrl_2}}, Q_{Ctrl_2}$	$\delta_{PLL_1}, PLL_1, \delta_{PLL_2}, PLL_2$

#### 1) DC side modes

The modes 1, 2 and 3, are related with the dc side

eigenvalues. These modes are related to the components of the cable and the MMC dc side (i.e.  $L_{dc}$  and  $C_{dc}$  in Figure 3). First, we note that the frequency and damping factors do not change according to the presence or not of the ac line. Based on the participation factors, we can conclude that mode 1 is related to the LC circuit formed by the cable model. Mode 2 is formed by the interaction between the VSC inductors ( $L_{dc}$ ) with  $C_{cable}$ . Finally, mode 3 is composed of the VSC components  $L_{dc}$  and  $C_{dc}$ .

Note that no variables from the ac side are participating in the three modes of the dc side. However, the opposite is not necessarily true; the perturbation from the dc side can still interact with the ac side. This can be viewed in mode 9 which is connected with the variable  $V_{dcCtrl_2}$  ( $V_{dc}$ -control of VSC2, Figure 2). Therefore, for the station in  $V_{dc}$ -control, the three

resonance frequencies from dc side should be filtered or blocked by the PI controller to avoid the inclusion of these oscillations in the control loop. It is therefore important to choose the gains of the PI controller adequately in order to reject these resonances. This is already the case, since the time constant of  $V_{dc}$ -control is set to 100 ms.

# 2) AC side modes

The eigenvalues related to modes 4, 5, 6 and 7 (Table 3) are dominated by the variables related to ac current:  $i_{dq_{1,2}}$  and  $i_{dqCtrh_2}$ . The modes 8 and 10 are dominated by  $\delta_{PLL_{1,2}}$  and  $PLL_{1,2}$ . Note that for each of these modes, when  $Z_{ac}$  is connected in parallel with the HVDC link (Table 3, third column), the variables of the two stations have relatively high participation factors. When the impedance of the ac line decreases, the participation factors from the other stations increase. This implies, therefore, a coupling between the two VSC stations. As a result, a disturbance from one of the two stations may have an impact on the other VSC station. However, a coupling between two stations variables (i.e. inclusion of variables of the two stations in the same modes) does not necessarily imply negative interactions. To measure the risk of this negative interaction, the mode shape tool is used.

#### C. Mode shape

The mode shape evaluates the phase shift angle between the vectors of the complex variables contributing to the same mode. The compared vectors of the complex variables must have the same physical meaning to derive conclusions [14]. When the phase angle between the vectors is close to  $180^{\circ}$ , the risk of oscillation is high.

The dominant variables of the modes 4  $(i_{dq_{1,2}})$ , 5  $(i_{dq_{Ctrl_{1,2}}})$ and 8  $(\delta_{PLL_{1,2}}, PLL_{1,2})$  including  $Z_{ac}$  (Table 3, third column) are shown in Figure 9, Figure 10 and Figure 11 respectively. For modes 4 and 5, we see that the phase angles between the vectors of the two stations are either in phase or the amplitude of one vector is negligible compared to the other one. As a result, the risk of interaction between these variables appears to be negligible. For mode 8 which is the  $PLL_{1,2}$  and  $\delta_{PLL_{1,2}}$ , phase differences are noticeable between the two VSC stations. However, in the case of  $\delta_{PLL_{1,2}}$  the angle is less than 90<sup>0</sup> and for the  $PLL_{1,2}$ , the ratio between the two amplitudes is relatively small, therefore the risk of interaction seems to be quite limited.



Figure 9: Mode 4 - Table 3 with  $Z_{ac} = 0.0065$  pu



Figure 10: Mode 5 - Table 3 with  $Z_{ac} = 0.0065$  pu



Figure 11: Mode 8 - Table 3 with  $Z_{ac} = 0.0065$  pu

# V. PARAMTERIC STUDY IN EMTP-RV

To validate the above small-signal analysis, a parametric study is performed using EMTP-RV. The parameter variations of the ac line and the HVDC link configurations are summarized in Table 4.

Table 4: Setup configuration for parametric study

Parameter	Number of configurations
Z <sub>ac</sub>	4 configurations : 0.001, 0.01, 0.1 et
Transit of active power	2 configurations : +1000 MW
Station VSC1 in <i>P</i> -control or in	2 configurations : $P$ -control or $V_{dr}$ -
$V_{dc}$ –control	control
Station VSC1 : choice between	2 configurations : $Q$ -control or $V_{ac}$ -
$Q$ - and $V_{ac}$ -control	control
Station VSC2 : choice between	2 configurations : $Q$ -control or $V_{ac}$ -
$Q$ - and $V_{ac}$ -control	control

# A. Small perturbations

A small perturbation at the PCC1 (Figure 2) is made at t = 1 s by applying a high resistive (1 k $\Omega$ ) three phase to ground fault. A low SCRs = 2.5 is considered. Active power results at VSC1 are plotted in Figure 12.

In the results presented in this section, the curves with thick lines represent the HVDC link simulation cases without the presence of the parallel ac line. As for the other configurations (i.e. with ac line), they are represented by thin curves.

It is apparent that the highest perturbation amplitudes are obtained without the presence of the ac line connected in parallel (i.e. without  $Z_{ac}$ ). This confirms the modal analysis presented in section IV.A; adding an ac line in parallel increases the SCR for each station and hence the performance of the HVDC link is improved. On the other hand, the negative interactions between the two stations remain negligible even when the ac line impedance is low.



#### B. Large disruptions

However, these findings are valid only for small perturbations. Indeed, during major disruptions nonlinear phenomena may exist; for example, when ac faults occur, the limiters of control systems may operate and the protection system can trigger a station. To assess the impact of the ac connection in parallel with the HVDC link during major disruptions, a solid three phase to ground fault at t=1 s lasting 200 ms is applied at PCC1 (Figure 2). The same configurations previously presented in Table 4, are considered. The results of active power for VSC1 are shown in Figure 13.



It is noticed that several cases of the configuration including the ac line in parallel cause more oscillations and larger disturbances compared to the case without the ac line in parallel. This shows that for large transients, the ac line in parallel can cause deterioration of the dynamic performance and negative interactions of the HVDC link unlike for the cases involving small perturbations.

To evaluate the impact of these major disturbances on ac overvoltage after fault extinction (around t=1.2 s), the results of the subgroup in which the station is in *P*-control and rectifier mode are shown in Figure 14. Similar results can be obtained for the other 3 subgroups.



Figure 14: Parametric study for large perturbation on  $V_{PCC}$ 

The oscillations including the ac line in parallel have smaller damping factors than the cases without ac line in parallel. In addition, in some configurations, the maximum peak reaches higher values than in the case without the ac line in parallel. These peaks can therefore exceed the threshold overvoltage of the protection system, which can cause the blocking and/or tripping of the HVDC link.

The increase in the amplitude of ac voltage after fault extinction is mainly due to the reactive contribution from the other station. Indeed, the inclusion of the parallel ac line allows the transmission of reactive power from VSC2 to VSC1 and vice-versa. This means that when a fault occurs close to one station, reactive power will flow between the two stations. Just after fault clearance, a greater transient occurs because of the response time of the control loops that will maintain, for a few tens of ms, the supply of reactive power. These large disturbances can depend on several nonlinear factors, such as the link operation mode, the saturation of the control systems, fault ride through capability, the thresholds of the protection system, etc. Unfortunately, all these complex factors cannot be taken into account through small-signal analysis studies.

#### VI. CONCLUSIONS

A HVDC-MMC link connected in parallel with an ac line was evaluated in this study. A complete overview on the abnormal interactions that can occur during small and large disturbances was presented. A small-signal analysis model was used to study interactions in this system. This model was verified using non-linear time-domain simulations in EMTP-RV and the impact of SCR was evaluated. The analysis of eigenvalues and mode shapes was used to assess interactions between different variables of the system.

It was found, that during small perturbations, the parallel ac line can improve the dynamic performance of the HVDC link and that the risk of negative interaction between both HVDC stations is negligible.

The parametric studies conducted under EMTP-RV have confirmed the small-signal studies for small perturbations, but it was found that for large disturbances, negative interactions can occur when an ac line is in parallel with the HVDC link. Therefore, it is important to perform parametric studies using EMT-type models in order to cope with negative interactions.

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