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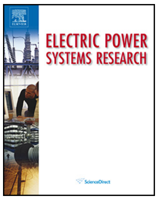

Interactions studies of HVDC–MMC link embedded in an AC grid

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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 lower 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 an ac line connected in parallel with an HVDC link.

1. 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 2000 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 [7,8]. 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

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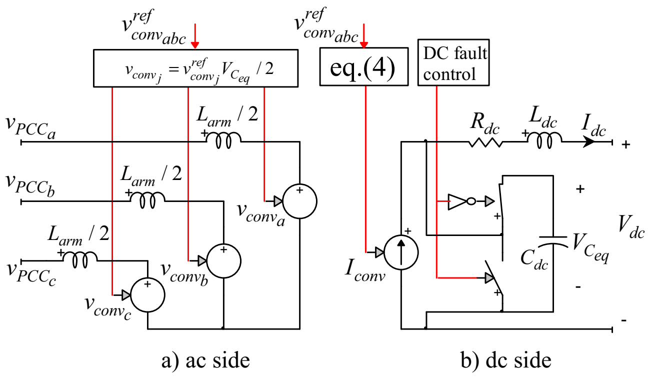

Fig. 1. MMC Model #4 derived in [10].

influence of ac transmission lines connected in parallel with the HVDC link.

2. 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 Fig. 1. C_{dc} is the equivalent capacitor of the MMC. L_{arm} and R_{arm} refer to the reactor and resistance of each arm.

2.1. MMC model

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

$$\begin{aligned}\frac{d\Delta i_d}{dt}&=-\frac{R_{ac}}{L_{ac}}\Delta i_d+\frac{1}{L_{ac}}\Delta v_{PCC_d}-\frac{1}{L_{ac}}\Delta v_{conv_d}+\omega\Delta i_q\\ \frac{d\Delta i_q}{dt}&=-\frac{R_{ac}}{L_{ac}}\Delta i_q+\frac{1}{L_{ac}}\Delta v_{PCC_q}-\frac{1}{L_{ac}}\Delta v_{conv_q}-\omega\Delta i_d\end{aligned}\qquad(1)$$

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 Fig. 1b:

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

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

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

From Fig. 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.

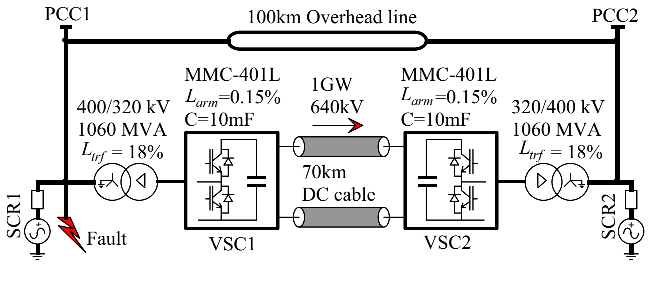

Fig. 2. MMC–HVDC transmission system in parallel with an ac line.

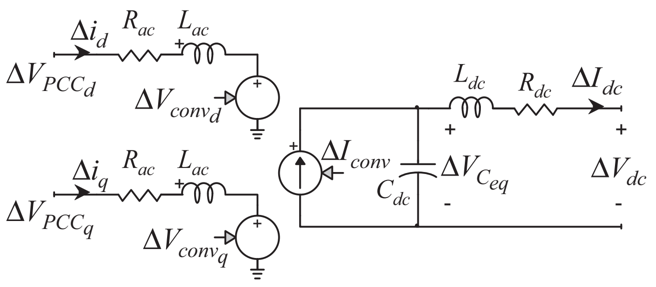

Fig. 3. Small-signal model of MMC station.

Based on energy conversion:

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

in dq reference frame and using Fig. 1b:

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

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

$$\frac{d\Delta V_{C_{eq}}}{dt}=\frac{i_d}{C_{dc}V_{C_{eq_0}}}\Delta v_{conv_d}+\frac{i_q}{C_{dc}V_{C_{eq_0}}}\Delta v_{conv_q}+\frac{v_{PCC_d}}{C_{dc}V_{C_{eq_0}}}\Delta i_d$$
$$+\ldots\frac{v_{PCC_q}}{C_{dc}V_{C_{eq_0}}}\Delta i_q-\left(\frac{v_{conv_{d_0}}i_{d_0}+v_{conv_{q_0}}i_{q_0}}{C_{dc}V^2_{C_{eq_0}}}\right)\Delta V_{C_{eq}}-\frac{1}{C_{dc}}\Delta I_{dc}\qquad(6)$$

where, the subscript 0 denotes initial values

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

2.2. 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 δ_{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].

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

By linearizing Eq. (7), we obtain the RI to dq reference change:

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

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

2.3. Control system

The MMC Model #4 allows neglecting the internal energy balance [10]. Therefore, the circulating currents as well as the balancing capacitor voltages of submodules (SMs) are neglected in this study. Only the inner current loops (i-control) and the outercontrol