Analysis of Harmonics and Resonances in HVDC-MMC Link Connected to AC grid

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***Abstract* - High-frequency responses of HVDC-MMC links are essential to study because harmonic and resonance phenomena may impact the AC grid. In this paper, EMT-type simulations are used to analyze converter station's frequency response. Several MMC station and AC network parameters are varied to analyze their impact. In addition, an EMT-type test case, based on a recent installed HVDC project, is used to illustrate potential resonances that can occur between converter stations and AC networks.**

***Keywords*: EMTP, Harmonic, Resonance, Impedance Analysis, HVDC, Modular multilevel converter (MMC), Voltage source converter (VSC)**

I. INTRODUCTION

High Voltage Direct Current (HVDC) systems based on the Modular Multilevel Converter (MMC) [1] is the predominant topology used in recent and upcoming HVDC-VSC projects. For instance, several HVDC-MMC projects are currently planned or operated by RTE (French TSO), such as the INELFE, FIL, IFA2, etc.

Harmonic emissions and resonances in a system may reduce the use of power and damage the insulation of the system components if they are not limited properly. Furthermore, a system malfunction may occur if the system has high voltage or current harmonic amplitudes. The harmonics which propagate in the AC network and to power electronic components can cause overheating of equipment and interferences with communication circuits.

Power electronic converters can cause instabilities and/or resonances when interacting with other equipment in a power system. These phenomena can occur in a wide range of frequencies (up to few kHz). Low and high frequency resonances have been registered in several power electronics based projects: in offshore HVDC link high frequency resonances [2] were noted. Instability with converters of a photovoltaic plant [3] and in traction applications [4] are reported. In [5] low frequency oscillations are studied between power electronic and power system devices. Power electronic converters inject harmonics in the grid mainly due to modulation and switching commutations. For a MMC station, the injected harmonics depend mainly on the number of submodules (SMs) per arm and their modulation strategies, which is specific to the manufacturer and/or project.

In HVDC projects, vendors and utilities perform harmonic and resonance studies. These studies are conducted in frequency domain and/or using electromagnetic transient (EMT) tools. Frequency domain studies are used to assess system stability [6] and are convenient for simulating a wide range of configurations and scenarios. To derive the frequency response of a converter, analytical or small signal approaches are commonly used. In [7]-[11] an analytical development of a VSC station is presented. However, during real HVDC and FACTS projects, the EMT-type model provided by the manufacturer is often hidden (or black-boxed) due to intellectual property issue. Therefore, the analytical model derivation is not possible or not sufficiently accurate. In addition, model linearization and derivation are challenging and complex tasks since the MMC includes several variables and complex control structures. In this paper, the derivation of the frequency response of a converter station based on a black-box EMT model, presented in [18], is used. Since this EMT model includes the detailed representation of the converter station with its control system, this approach is more practical than with an analytical model.

This paper is an extended version of [18]. Several test cases are performed to analyze the impact of MMC station parameters (as MMC levels, control system, AC filter, etc.) on the high-frequency response (i.e. harmonics and impedance). In addition, the generic EMT test case where high frequency resonances can occur between the AC network and the converter station presented in [18] is analyzed in this paper. Parametric sensitivity studies of the AC network is conducted in order to assess the impact on system stability.

The paper is structured as follows. Section II recalls harmonics and resonance phenomena. Section III presents the generic MMC-401-Level station and its control structure. Section IV illustrates the derivation of the frequency response based on the EMT-type model. Section V simulation results of the impact of converter station and ac network parameters are presented.

II. MMC STATION OVERVIEW

The generic EMT model includes the detailed representation of the converter station with its control system, see Figure 1 [5]. The equivalent detailed MMC model where each SM is represented, (i.e. Model #2 as defined in [13]) is considered. The control system uses an upper level control including inner/outer controllers and a lower level control to

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regulate MMC internal variables: capacitor balancing algorithm (CBA) to balance SM capacitor voltages in each arm, modulation to convert the reference voltage to a number of inserted SMs and circulating current control (CCC) to regulate converter internal energy. More details can be found in [17].

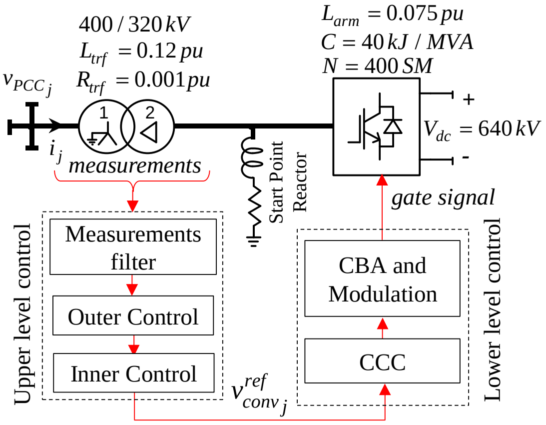


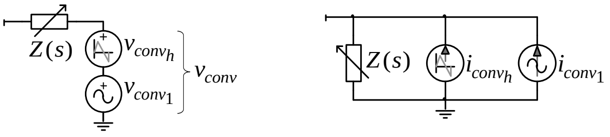
Figure 1: Generic control structure of MMC station

III. HARMONICS AND RESONANCES

We can distinguish two different high frequency phenomena that can take place between power electronics and surrounding AC networks; harmonic emissions and resonances:

- Harmonics emissions are mainly associated with semiconductor switches and therefore continuously transmitted by the system which may affect the wave quality.
- The resonances are mainly related to the control system, filters, delays, etc. Resonances have usually higher order of magnitude than harmonics but their time intervals are shorter since system protection is used to trip network devices.

Figure 2 illustrates these two different aspects. The voltage source (v_{conv_h}) or current source (i_{conv_h}) represents the harmonic emissions and the impedance *Z(f)* (where *f* stands for frequency) depends on control loops and physical equipment which includes system resonances [14]. Since a converter station with its control system, is a nonlinear system, equivalent circuit values depend on the set-point operation of the system and will vary when the converter configuration changes.



a) Equivalent Thevenin circuit

b) Equivalent Norton circuit

Figure 2: Equivalent circuit for frequency response

Determination of *Z(f)* and i_{conv_h} (or v_{conv_h}) is achieved in two ways: by means of an analytical approach or by EMT simulations. The analytical approach offers the capability to use classical modal analysis tools in order to study the converter behavior [6]. However, analytical models may become complex depending on the studied system and must be validated as several approximations are introduced. On the other hand, the EMT simulations include the detailed models of the control system and power equipment. The obtained results are more realistic than with an analytical model, however simulation time constitutes the main drawback.

This article uses the EMT simulation approach to derive Norton equivalent values at each harmonic rank *h*.

IV. FREQUENCY RESPONSE BASED ON EMT SIMULATION

The derivation of the equivalent Norton circuit (Figure 2) based on time domain EMT simulation is briefly described in this section. The circuit setup is shown in Figure 3 and the flow chart computation for each *h* is depicted in Figure 4. The converter station is connected to an equivalent AC grid and a controlled ideal current source i_{inj_h} at the PCC. The injected current i_{inj_h} are varied during time domain simulations in order to compute *Z(f)* and i_{conv_h} (Figure 2.b) [18]. The amplitude of i_{inj_h} should be a fraction of the nominal current of the system to guarantee a small-signal perturbation and to avoid any excitation of the control and protection system. The important feature of this method is that the control system is in normal operation, therefore, a realistic set point can be considered [14]. Norton equivalent values change according to the set point operations.

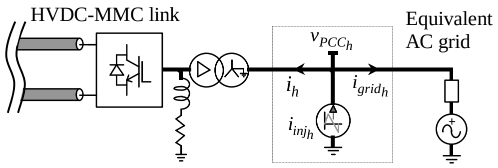


Figure 3: Model setup to derive the equivalent Norton circuit

Figure 4: Block diagram, Norton equivalent computation

The derivation of the Norton equivalent circuit is also useful for frequency domain studies in power grid systems, since the computation time is much faster than with the detailed EMT-model.

It should be highlighted that this approach can be also used in real-time simulators with hardware-in-the-loop simulation including the real-physical control system (or replicas). Such approach can provides faster simulation time and more realistic results since the real and complete control system is used.

V. FREQUENCY RESPONSE STUDIES

In this section, the impact of the converter station parameters on the frequency response is analysed. The test case used is a point-to-point HVDC-MMC 401-Level link with a transmission capacity of 1,000 MW. The AC grid is modeled as an equivalent source with a short-circuit level (SCL) of 20 GVA. Converter station data can be found in Figure 1 and control data is provided in the Appendix. All model developments and simulations are performed using the EMTP-RV software.

A. Harmonic studies

In this sub-section, converter station parameters that impact the harmonic emissions are considered.

1) Impact of MMC levels

Harmonics emitted from the MMC station are known to be low in amplitude. In order to show the impact of MMC levels, the MMC-401-Level is compared with a MMC-11-Level, in this section. Voltage references, harmonic distorsions (i.e. i_{conv_h}) and *Z(f)* are compared in Figure 5. Obviously, harmonic emissions produced from 11-Level MMC are higher than those produced by a 401-Level MMC which are negligible. For such MMC 11-Level, it is expected that an AC filter will be installed at the converter station in order to limit those harmonics. Based on *Z(f)* responses in Figure 5, one can notice that the impedance is not affected by the MMC levels. This was expected since control loops are identical (except the CBA and modulation) between thoses two MMC levels.

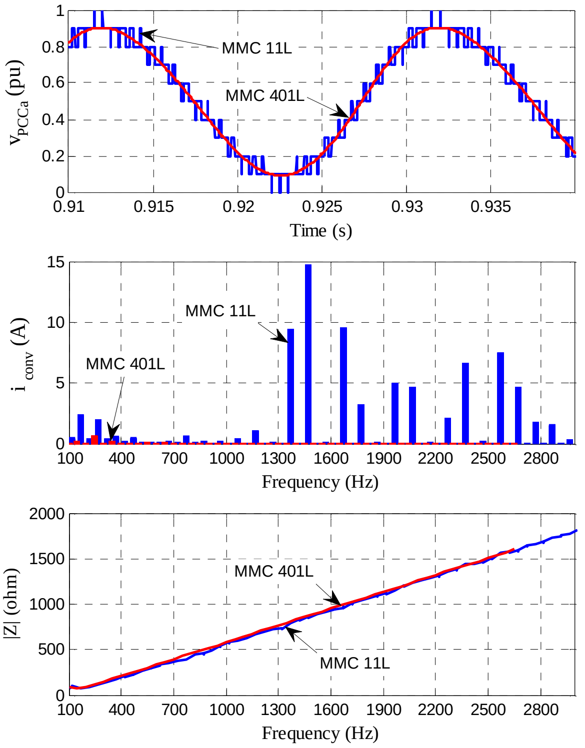


Figure 5: Impact of MMC levels

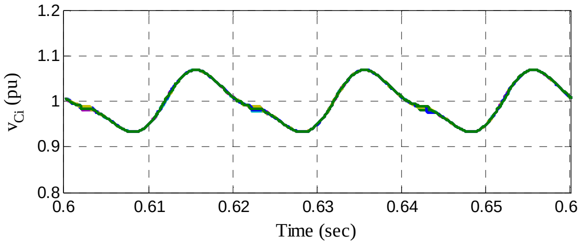
2) CBA impact

In this section, the impact of the CBA over the frequency response is investigated. The capacitor value and the threshold activation [15] of the CBA are varied to get the extreme cases:

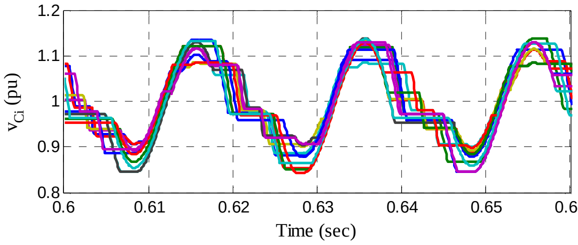
- CBA #1: threshold is set at 1% and *C= 45 kJ/MVA*
- CBA #2: threshold is set at 50% and C =25 kJ/MVA

Similar test case as in [18] has been used, however, a MMC including 401-Level is simulated instead of MMC-11-Level. Figure 6 shows some of the 400 SMs capacitor voltages of phase A upper arm, using CBA #1 and CBA #2. It can be observed that CBA #2 has higher amplitude fluctuation and higher differences between capacitor voltages.

Figure 7 shows the impact of capacitor fluctuations and CBA configurations over the frequency response, i.e. *Z(f)* and i_{conv_h} . It can be observed that these parameters have mainly an impact on the harmonic injection i_{conv_h} rather than on *Z(f).* Note that with CBA #2, high harmonic emissions are noticed at lower frequency (around 250 Hz and 350 Hz). This shows that CBA and capacitor voltage fluctuations have an impact on the harmonic emissions. This results shows also the importance of a detailed EMT model (even for MMC-401 Level) to account for such harmonics.



a) CBA#1 and C=45 kJ/MVA



b) CBA#2 and C=25 kJ/MVA

Figure 6: CBA impact, Capacitor voltages of SMs

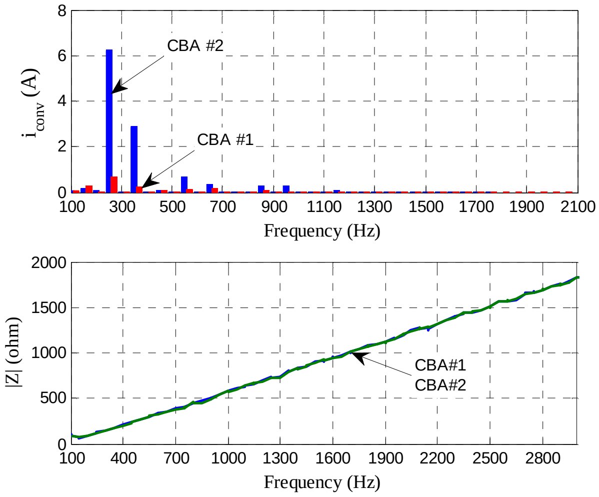


Figure 7: CBA impact, frequency response (i_{conv_h} and *Z*)

3) CCC impact

To analyze the circulating current control impact, the reference value of the second harmonic circulating current control is varied between 0 and 0.1 pu, for CCC #1 and CCC #2 respectively. Similar test case as in [18] has been used, however, a MMC including 401-Level is simulated in this paper, instead of MMC 11-Level. Figure 8 shows the circulating current variation impact. Figure 9 shows the results of i_{conv_h} and *Z(f)*. Since the frequency response of both CCC configurations are close, it can be concluded that the circulating current has a minor impact on the frequency response from the AC side (as highlighted in [16]).

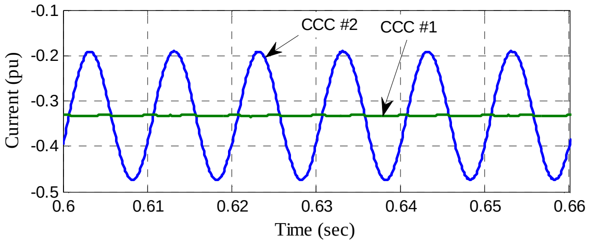


Figure 8: CCC impact, c*irculating current phase A*

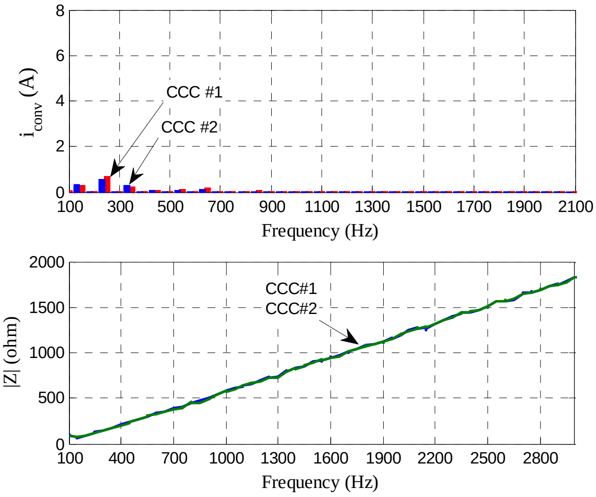


Figure 9: CCC impact, frequency response (i_{conv_h} and Z)

B. *Impedance studies*

In this section, the impact of control system parameters on *Z(f)* is studied.

1) *Inner control loop and time delay*

Inner control loop dynamic and time delay have an impact on *Z(f)*. Results and analysis are provided in [18]: The impact of the inner control is increased when the dynamic response of the control loop is fast.

2) *Impact of AC filter at PCC*

Depending on Manufacturers and project specifications, AC filter equipment can be installed at PCC. To show the impact of this device over the frequency response, in this section a low-pass filter is added at PCC to the MMC station model. Parameters of the low-pass filter are based on [19]. Note, that in practice, this low-pass filter will be tuned according to project specification, however, the scope of this section is only to illustrate the impact of such equipment. Result comparisons between converter station with and without the installation of the AC filter is depicted in Figure 10. It can be noticed that the *Z(f)* is mainly affected by the AC filter installation for frequencies above 400 Hz.

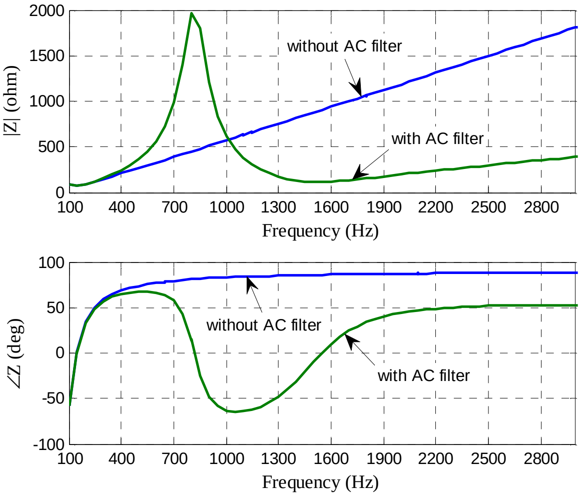


Figure 10: Impact of AC filter at PCC

VI. STABILITY ANALYSIS

In [12] and [18], it has been shown that low-pass filters and delays in converter station control can lead to negative resistance in high frequency range. Therefore, this negative resistance can lead to resonances or instability depending on the AC network configuration and parameters.

To analyze the stability of a system, the considered circuit can be represented as a feedback loop system in the small-signal domain. Therefore, the following Laplace equation can be deduced [3]:

$$i_{PCC}(s) = v_{conv}(s)\frac{Z_{grid}(s)}{1+Z_{grid}(s)/Z(s)} \qquad (1)$$

where $Z_{grid}(s)$ is the equivalent impedance of the AC grid.

From equ. (1), the system is stable if the expression $\left|Z_{grid}(s)/Z(s)\right|$ is lower than one at each frequency. However, if the Nyquist criterion is not met, and in addition, the angle $\angle Z_{grid}(s)/Z(s)$ is higher than $\pm 180^0$, then the system becomes unstable or sustained resonances will occur.

Using the EMT time domain simulation, both $Z(s)$ and $Z_{grid}(s)$ can be computed, and system stability tools can be used.

The generic EMT test case where resonances can occur between the AC network and the converter station presented in [18] is analyzed in this section. Parametric sensitivity studies of the AC network is conducted, in order to assess the impact on system stability. The HVDC-MMC 401 Level link is connected to an AC network (Figure 11). Network 1 includes: AC overhead lines, AC breaker “BRK”, shunt compensator of 400 MVar and an equivalent Thevenin source with SCL equal to 20 GVA. Active power of 1,000 MW is transmitted from Grid 1 to 2. The outer control strategy considers a DC voltage/reactive power control on Station 2 and active/reactive power control on Station 1.

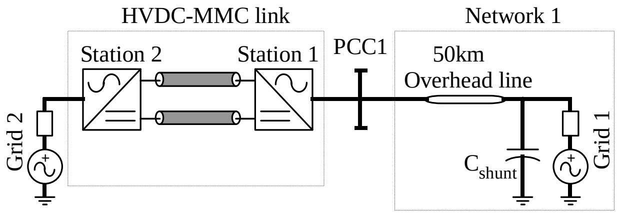


Figure 11: EMT test case

In the following subsections, the impact of AC network parameters is elaborated.

A. Impact of AC line length

The impact of the line length parameter on the system stability is analyzed. AC overhead line length is varied ±10% from the initial 50km value. Figure 12 shows the EMT simulation results of the $Z_{grid}(s)/Z(s)$ amplitude and angle.

Line length has mainly an impact on the frequency resonance value. However, the frequency bandwidth that exceeds the amplitude of one (threshold that guaranties the stability) is the same. In addition, the phase margin $\angle Z_{grid}(s)/Z(s)$ is close (and even slightly higher) to -180^0, which shows that resonances can occur in this specific frequency range. Indeed, in [18], time domain waveforms illustrate such resonances.

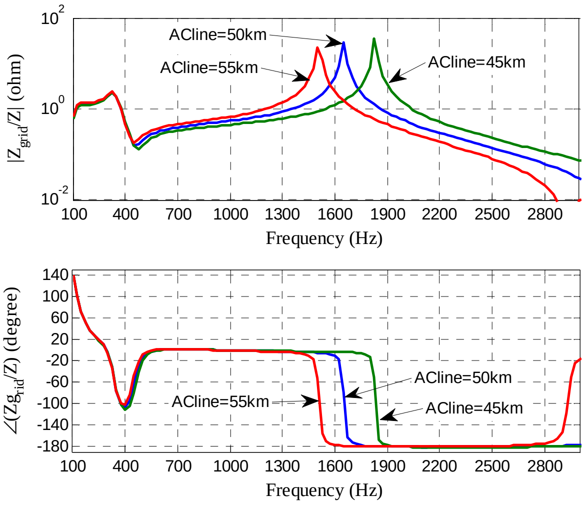


Figure 12: Impact of AC line length

B. Impact of shunt compensator

Shunt capacitors have also an impact on the stability of the system. In Figure 13, the impact of the capacitor value on $Z_{grid}(s)/Z(s)$ is depicted. Capacitor values of 800MVar, 400MVar, 100MVar and 0MVar are considered. It is noticed that when no shunt capacitor is included in the system, the system is stable since the phase margin $\angle Z_{grid}(s)/Z(s)$ is lower than ±180^0. When the capacitor value increases, $\left|Z_{grid}(s)/Z(s)\right|$ amplitude increases and $\angle Z_{grid}(s)/Z(s)$ tends to -180^0 which makes the system unstable.

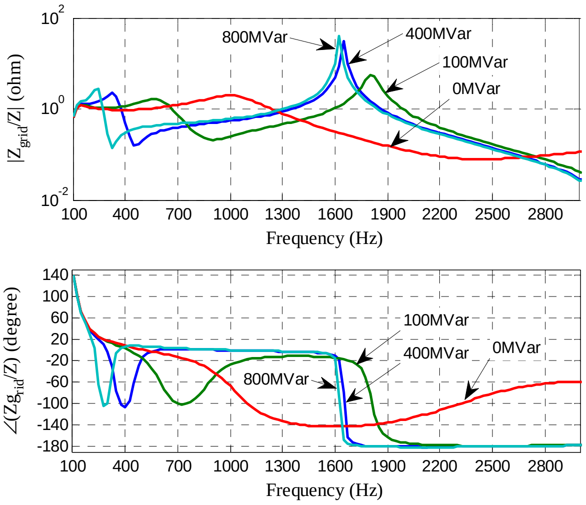


Figure 13: Impact of *Cshunt*

C. Impact of short-circuit level

Short-circuit level (SCL) of the Thevenin source (Grid 1) is varied in this subsection. Figure 14 shows the result of $Z_{grid}(s)/Z(s)$ for three different values: 50, 20 and 5 GVA. Based on this result, it can be concluded that for high frequency resonances (>1 kHz), the short circuit level has a minor impact on the stability of the system.

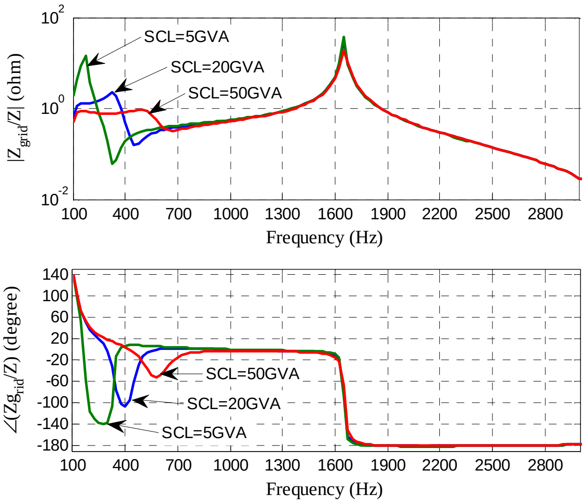


Figure 14: Impact of SCL

D. Impact AC lines in parallel

The impact of the number of AC lines connected in parallel is depicted in Figure 15: one line to three lines in parallel has been considered. It is noticed, that when the number of AC lines connected in parallel increases, the stability of the system increases. In fact, with one AC line is connected, the frequency range that leads to instability is as large as 100 Hz (1750 to 1850 Hz), however when three AC lines are in parallel, the frequency range of instabilities tend to zero.

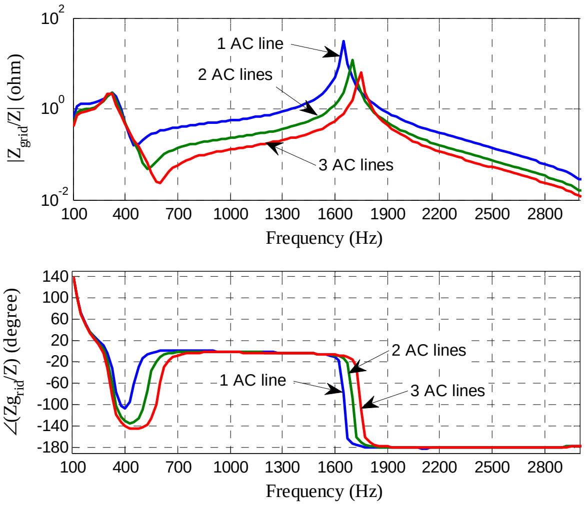


Figure 15: Impact of AC lines in parallel

VII. CONCLUSIONS

This paper presents the impact of MMC station parameters on the frequency response (Z and i_{conv_h}) of the converter on the AC side. It uses the EMT simulations approach and a detailed MMC-401 Level model to derive these results.

Several parameters were considered to analyze their impact on the frequency response: MMC levels, CBA, circulating current, AC filter installation. Based on the presented results, it can be concluded that MMC levels and CBA have the main impact on the harmonic emissions. The circulating current impact seems negligible on the frequency response at the AC side. On the other hand, the paper showed that AC filters have an impact on the impedance *Z(f)*.

Parametric sensitivity studies have been also presented to shows the impact of the AC network on the stability of the system: AC line length, shunt capacitor and the number of AC lines in parallel play a role on the stability of the system. However, the short circuit level does not seem to affect such high frequency resonances.

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