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Question 1.7: *Harmonic interactions between the active and passive components of HVDC, FACTS and AC grids are of concern. During the past years several major incidents have been reported due to harmonic interactions between the PEs or PEs and the AC grid components.*

- *Are there methodologies and approaches to analyse the possible harmonic interactions and predict the scenarios with harmonic interactions?*

Generally, there are different methodologies and tools available in the literature to analyse the possible harmonic interactions. These can be listed as:

1. Frequency domain Phasor Mode-based simulations (RMS) and Electro-Magnetic Transients (EMT)-type simulations
2. Small Signal Analysis
3. Control hardware in the loop with real time simulators

VSC harmonic converter modelling considers the impact of control and is presently the subject of intense international research and is focused around better understanding the HVDC converter behaviour itself. The other side of the problem is the detailed analysis of the impact of the AC network uncertainties in the harmonic converter design process which is the core of the CIGRE paper 10112 from the Paris Session 2022, Ref. [1].

The harmonic performance in VSC schemes is typically analysed using the same classical approach of AC network representation used in LCC design: the network Loci representations. The harmonic stability analysis in VSC can be done in either frequency or time domain. Existing methods can be summarised in three types: Impedance based stability analysis, Modal analysis and Time domain analysis by using (EMT) simulations. All these methods assume that it will be possible to define a representative set of individual AC harmonic impedances for all operating conditions. By knowing the precise frequency response of each configuration, it would be possible to define the precise harmonic transient behaviour of a system and design the controllers accordingly.

For converters connected to complex AC networks, to know in detail the frequency response of such networks is a very challenging task, but there is 50 years industry experience of using the classical loci approach in designing AC filters for LCC converters to compensate such uncertainties.

Ref. [1] proposes a method to deal with both issues (performance and stability) in a unified manner by using the well-known loci-based analysis extended to the stability issues using Nyquist Analysis.

Another important issue is the time domain testability for frequency resonances higher than 2nd harmonic. The lack of simple time domain models to cover this part of the design is a concern at the time the final controllers are fully tested at the manufacturer's test facilities.

Ref. [1] also presents simple synthetic network models to be used in time domain analysis able to reproduce single and double resonances based on network envelopes.

The proposed method covers different design issues as further explained below:

- Control design considering an extended frequency range (kHz) is a complex and a relatively new problem for the 60 years old HVDC power industry. Simple test procedures are essential to ensure that the final design is as per specifications.
- Factory System Test system procedures at the end of control design are mostly dealing with the performance around and below the fundamental frequency range. There are no simple procedures widely available to verify the control design in the harmonic range.
- The principle of independence between high voltage equipment and control can become 'blurry'. We cannot guarantee a sequential design approach as in LCC design.

- The design processes described until now have identified some of the main issues related to the harmonic design of VSC systems, however, they did not revisit the process of the complete converter design itself. Mainly the deadlock between the necessity to specify high voltage equipment at very earlier stages of the design and critical dependencies to a control that will only be completely known at the very end of the converter design.
- The available harmonic stability analytical processes, used today, require the detailed knowledge of all relevant network configurations in the complete frequency range for them to be effective.
- In the case of harmonic problems, it is not easy to detect the source of problem. Where to fix or target values since typically the detailed network circumstances are not known and a verification process is not pre-agreed (i.e., today sector information is not used for harmonic stability evaluation).

Summary of Proposed method in [1]

To solve these main design issues as detailed above, ref. [1], is proposing a method. The main aspects of this method are:

- Lack of harmonic data**:** It extends the Loci representation of AC network into harmonic stability area to allow for the design of virtual AC filters using the control functions.
- Synthetic networks to replace detailed AC networks: The Loci representation allows the use of synthetic networks for time domain tests of any control version in the frequency range in time domain.
- Final control tests in time and frequency domain: At the manufacturer test facilities it will be possible to fully test the controls (using frequency and time domain methods) in the complete frequency range. The converter could be declared "stable by design" at very end of the design based on the Loci supplied by the client.
- Use of converter impedance Zc as a key control parameter design: The key part of the process is to derive the equivalent impedance of the converter Zc (this includes the converter control functions) and use this information to fine tune the controls functions when compared with the network Loci impedance.
- Create a consistent agreement between client and Owner: The use of harmonic Loci-Based Control Design would allow a consistent agreement between manufacturer and clients during all stages of harmonic design processes including a harmonic test at the final stages of the control delivery.
- Further studies developed using more complex tools: The methodology recognises the full complexity of transient responses considering non-linearities, interaction between controllers, etc., and the necessity to perform extensive analysis in complex hardware-in the-loop platforms; however, by using such a simple methodology, GE expects to make the harmonic control design targets more transparent despite the uncertainties existing in the design of VSC HVDC converters.

[1] J. A. R. Monteiro, O. F. Jasim, E. Lavopa, H. Saad, S. Wijesinghe, "The Harmonic Loci-Based Control Design: Practical Methods in Frequency and Time Domain for a Consistent Design of VSC HVDC Harmonic Active Solutions", CIGRE Paris Session, August 2022.