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APPLICATION OF HARMONIC LOCI-BASED CONTROL DESIGN IN FREQUENCY AND TIME DOMAIN FOR A CONSISTENT DESIGN OF VSC HVDC HARMONIC ACTIVE SOLUTIONS

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Objects of the Investigation

- Application of Loci-Based analysis to evaluate harmonic instability risk in complex AC networks to evaluate the potential risk of harmonic instability in a higher frequency range.

Simple synthetic network models are used as an additional model to test and check harmonic stability and its

Interaction Phenomena and It's Categories

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Multi infeed and interaction between any two power electronic controlled devices (HVDC, FACTS, WTG, etc)

1. **Control Loop Interaction**
    - Near steady–state controls
    - Dynamic controls
2. **Interaction due to non-linear Functions**
    - AC fault performance
    - Transient stress and other non- linear interaction
3. **Harmonic and Resonance interactions**
    - Sub-synchronous resonance
    - Super-synchronous resonance

AC Filter Hunting, Voltage Control

Controller Interaction, Sub-synchronous Control interaction, Controller Stability, and Voltage instability

Commutation Failure LCC performance, Voltage distortion, Phase Imbalance

Transformer saturation, Load Rejection, Voltage Phase Shift, and Filter Trip Scheme

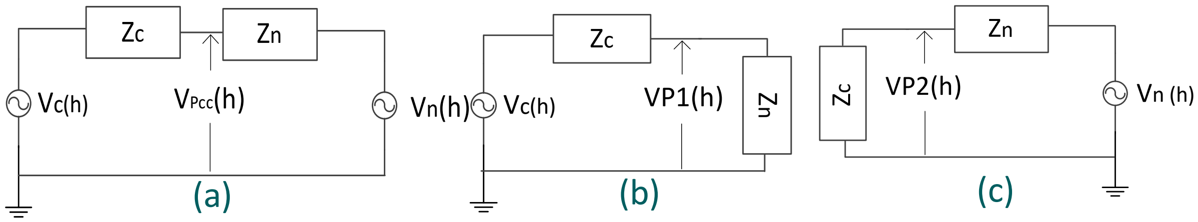
Sub Synchronous Torsional Interaction, Sub Synchronous resonance

Resonance Effects, Harmonic Instability, and Core Saturation instability

HARMONIC STABILITY THEORY AND PROCESS

Methodology

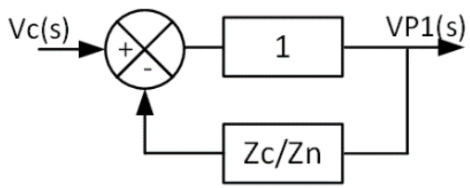
- Instability comes from negative resistance
- Each subsystem represented by impedance in frequency domain.
- If each subsystem is stable, the overall stability of the system is strongly affected by the ratio of Zc/Zn (i.e. H = Open Loop Transfer Function – Nyquist criterion is applied)
- If each subsystem is marginally stable, resonances can occur when the interconnected system is perturbed at resonance frequency.
- Open Loop Transfer Function is stable when:
  - Phase and gain margin positive
  - Simplified Nyquist criterion

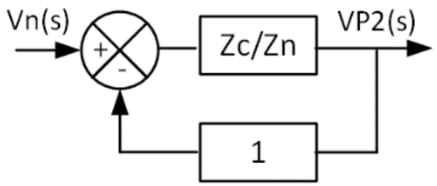


Network (Vn, Zn), HVDC converter (Vc, Zc)
Superposition principle is applied: (a) = (b) + (c)
VP1 & VP2 have same denominators
k1 and k2 : the amplification factor

$$VP1(s) = \frac{Zn}{Zn + Zc} Vc(s) = \frac{1}{1 + Zc/Zn} Vc(s) = \frac{1}{1+H} Vc(s) = k1.Vc(s)$$

$$VP2(s) = \frac{Zc}{Zn + Zc} Vn(s) = \frac{\frac{Zc}{Zn}}{1 + \frac{Zc}{Zn}} Vn(s) = \frac{H}{1+H} Vn(s) = \frac{1}{1 + 1/H} Vn(s) = k2.Vn(s)$$





An Example of a Renewable Generation Island

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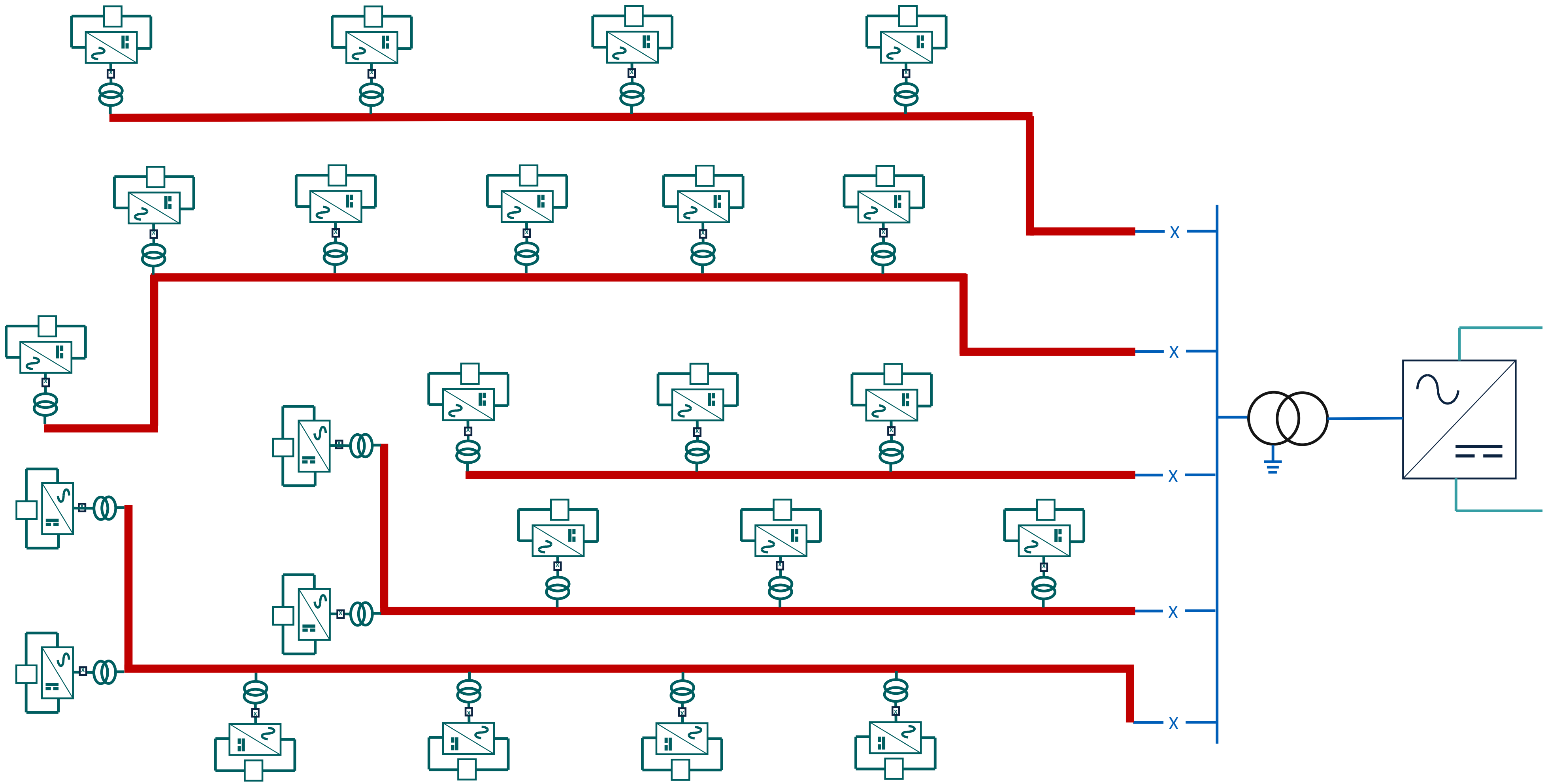
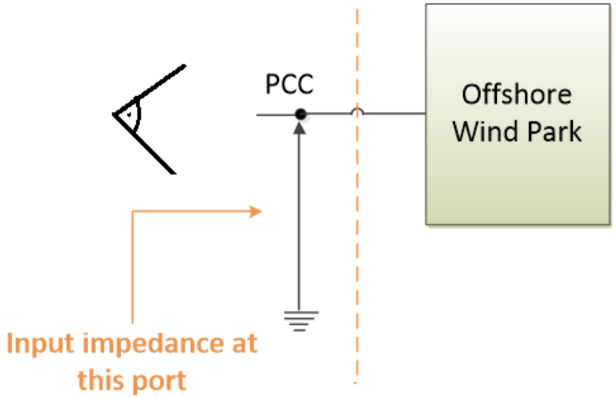
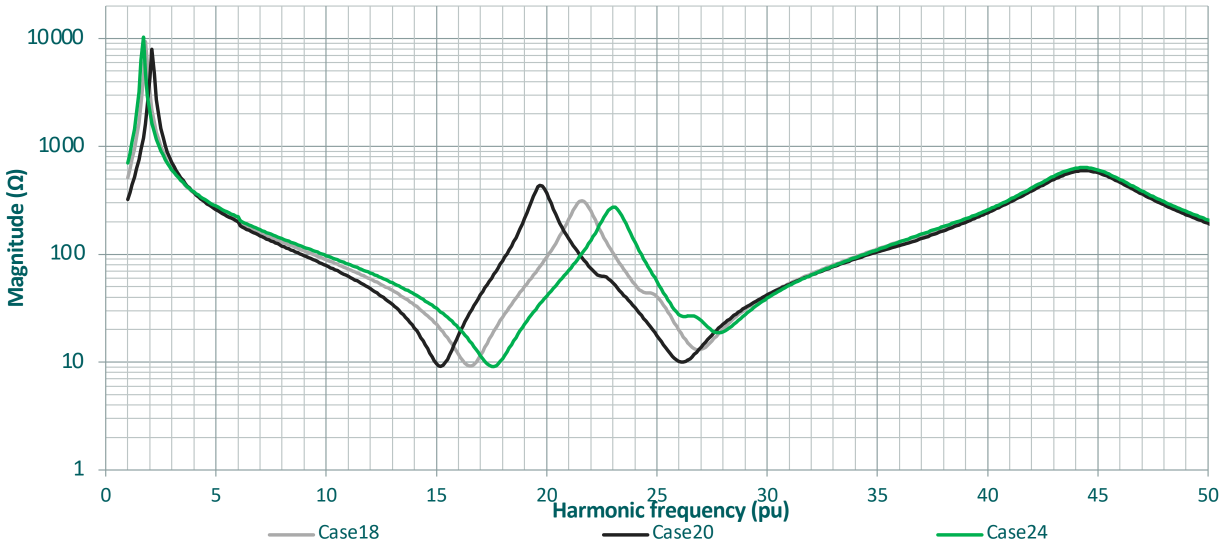
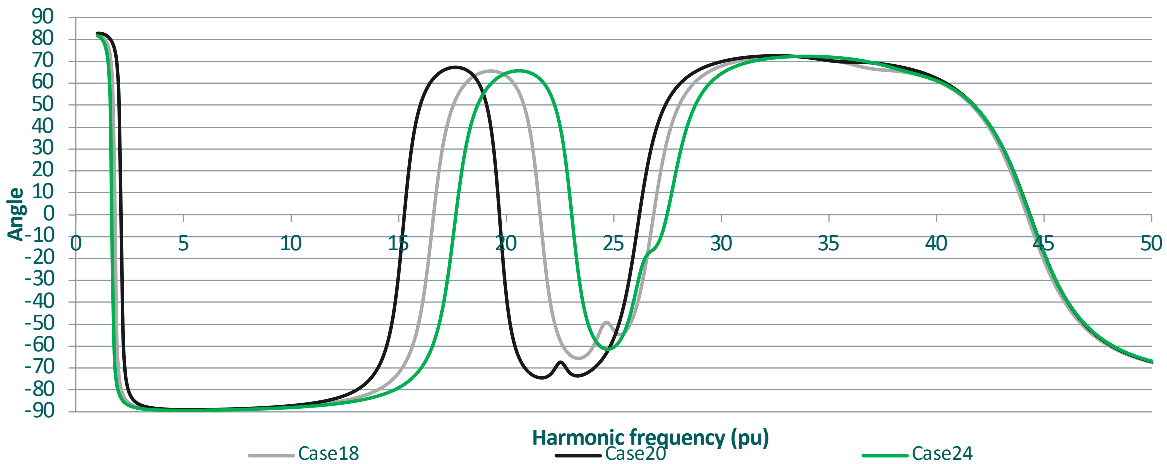


Frequency Domain Assessment for Offshore AC System



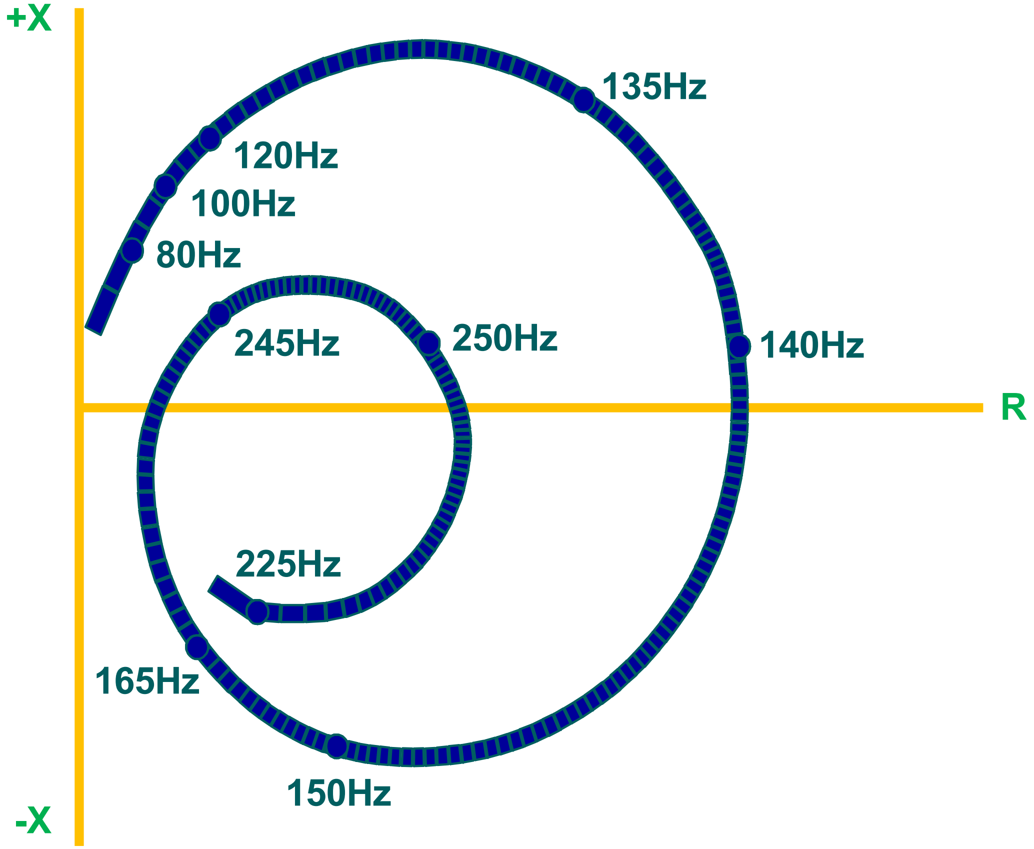
- Different Contingencies



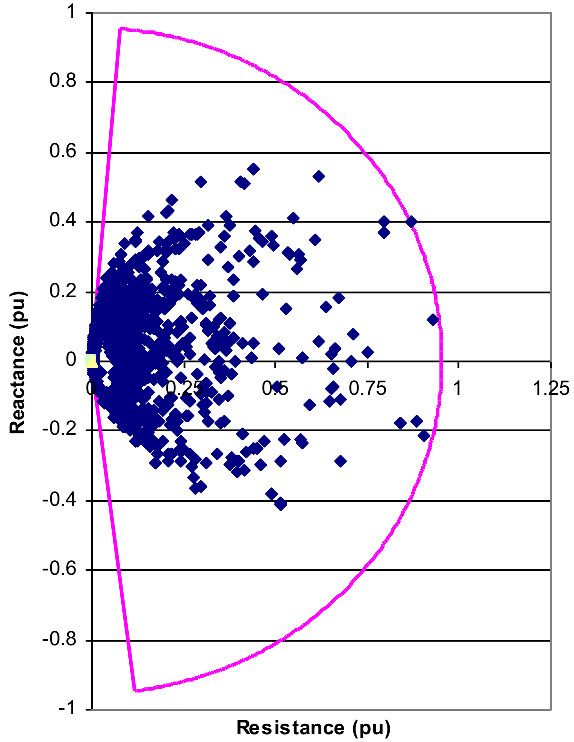


HARMONIC STABILITY BASED ON LOCI

Simplified Supply Network Impedance Diagram



Example of Search Area used for Filter Performance Study



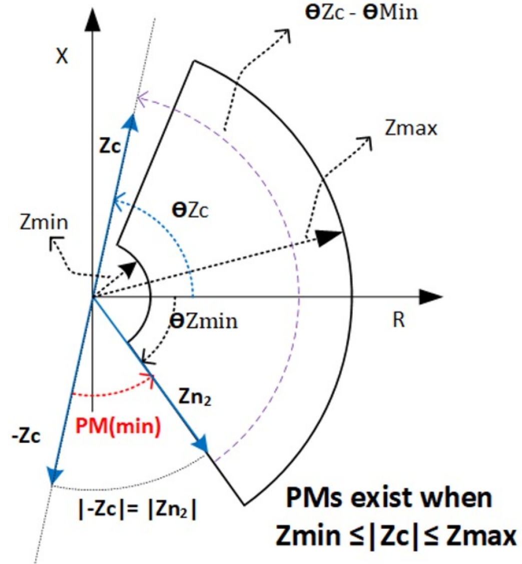
Harmonic range = 8.25 to 13.75

Stability Analysis Based on Loci

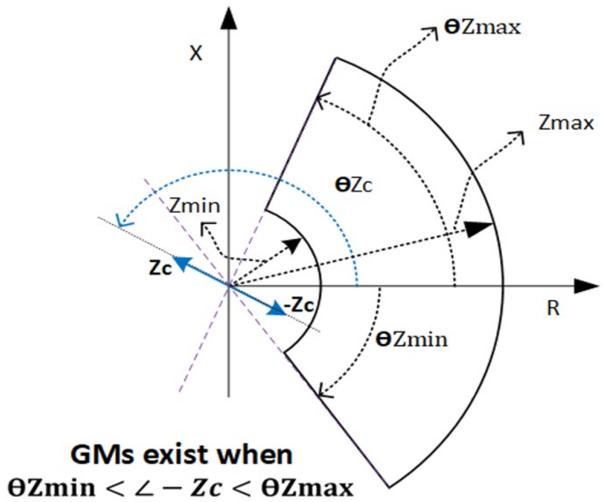
An example of how to calculate PM and GM in locus diagram, it can be determined by using the sector information and calculated converter impedance

$$PM = 180° - (\theta Zc - \theta Zmin)$$

$$GMmin = \frac{Zmin}{|Zc|}$$



Example 1: PM in locus diagram (when Zc inductive)



Example 2: GM in locus diagram

Jose Monteiro, O. Jasim, et al, “*The Harmonic Loci-Based Control Design: Practical Methods in Frequency and Time Domain for a Consistent Design of VSC HVDC Harmonic Active Solution*”, Paper B4-10112, CIGRE Paris, 2022.

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LIFE CYCLE OF HVDC PROJECT

Life cycle of HVDC Project with Different Types of Models and Methodologies for Different Studies

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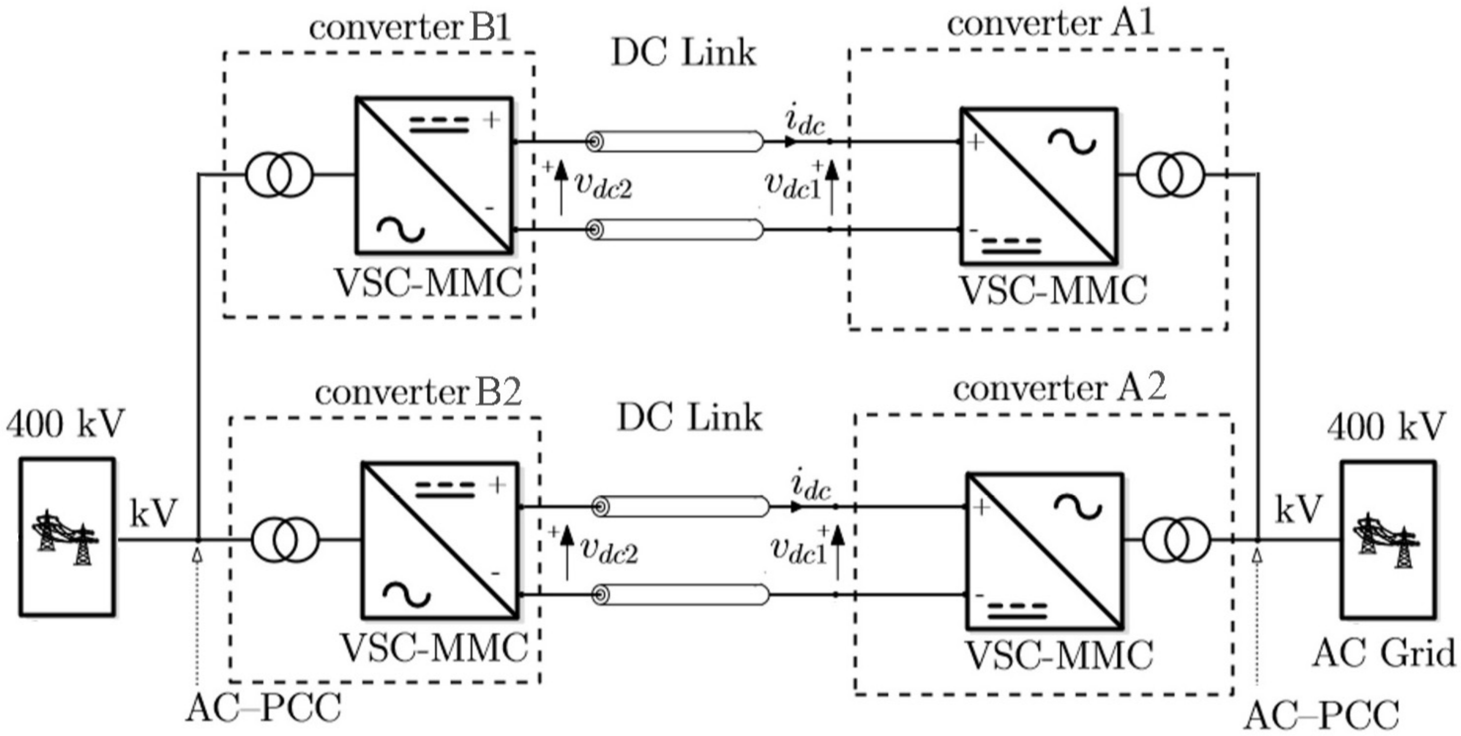
Life cycle of HVDC project after a contract is successfully awarded	*RMS*	*EMT offline*	*EMT Real Time*	*Small Signal*	*A*	*B*	*C*	*D*	*E*	*F*	*G*
Base design	Y	Y			Y	Y	*Y*				
Detailed design	Y	Y	Y	Y	Y	Y	*Y*	*Y*	*Y*	*Y*	
FST/FAT		Y	Y			Y	*Y*	*Y*	*Y*		*Y*
Commissioning		Y	Y			Y	*Y*		*Y*		*Y*
Operation	Y	Y	Y	Y		Y	*Y*		*Y*	*Y*	*Y*

A. Load flow, short-circuit studies, transient stability studies – RMS studies
B. Dynamic performance, C&P design and tuning, TOV and TRV studies – EMT design studies
C. Harmonic analysis, impedance scan – Harmonic studies
D. FST, FAT, replica-based studies – Real-time HIL studies
E. Converter interaction, SSO, SSTI, POD – interaction studies – EMT offline and real time
F. Small-signal analysis – Small-signal stability studies
G. Root-cause analysis of events and fault tracing

EXPERIMENTAL SETUP & TEST RESULTS

Experimental Setup & Test Results

- In the detail design phase, by using C&P software ver.1, Zc for two parallel links reveals a high harmonic converter impedance angle ∠Zc > +90°, for the ranges of (470-540 Hz) and (580-700 Hz).
- By using C&P software ver.2, Zc has been re-shaped where the phase angle of the converter impedance for both positive and negative sequence have been reduced to no greater than 90°.



Small Signal Analysis

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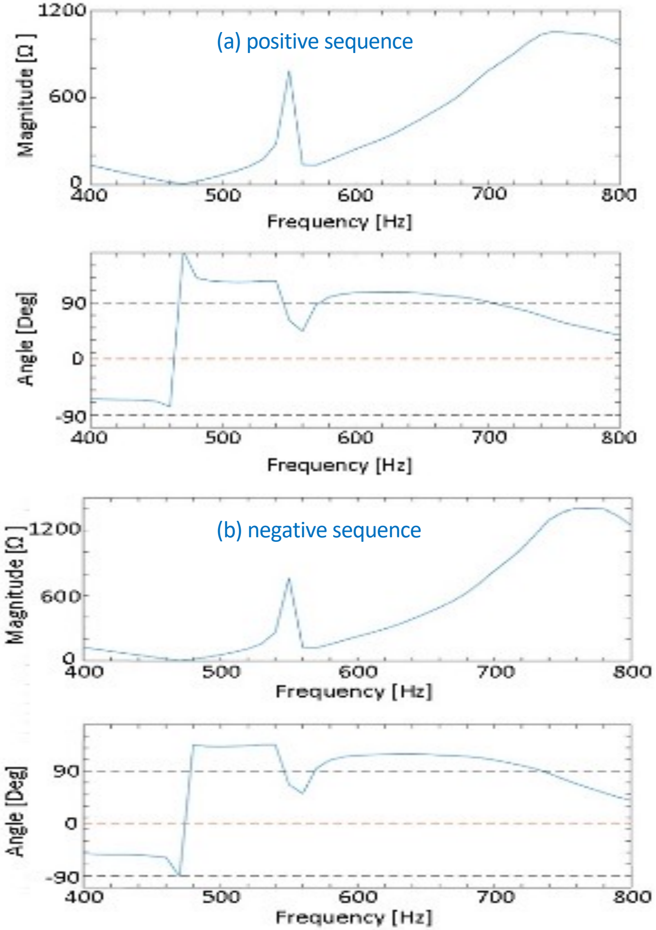
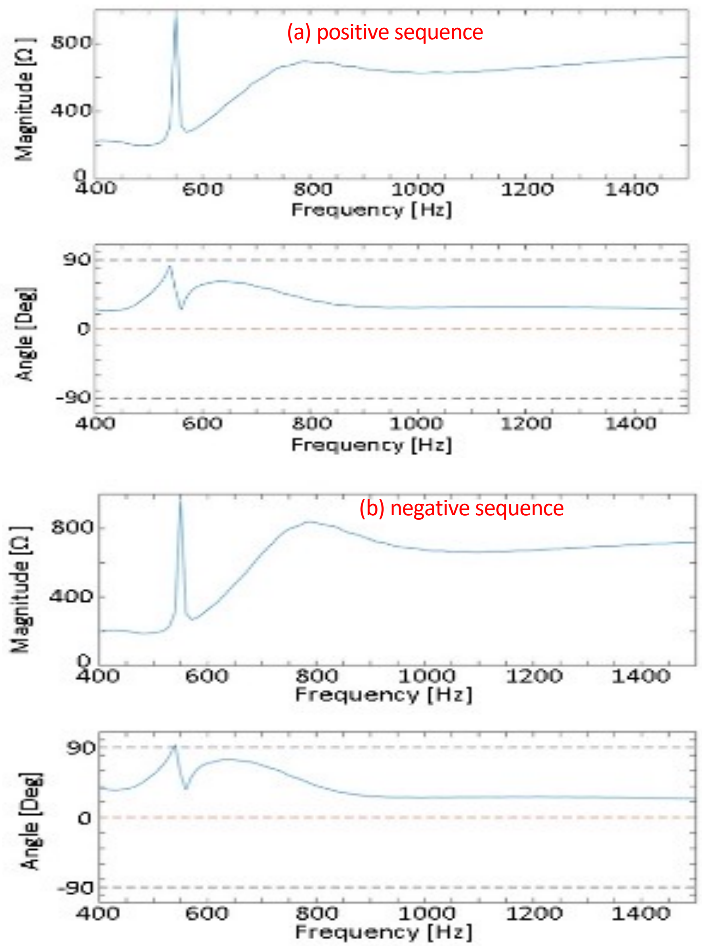
Converter impedance by using software ver.1 before the mitigation action



Converter impedance by using C&P software ver.2 after the mitigation action



Testing - EMT Offline and Online Study

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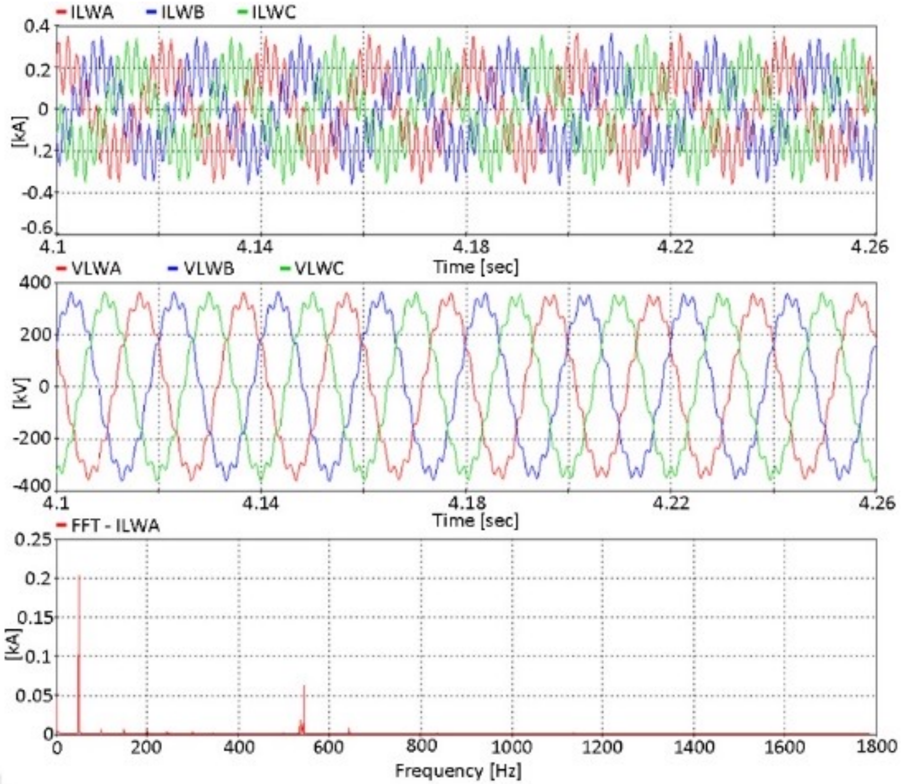
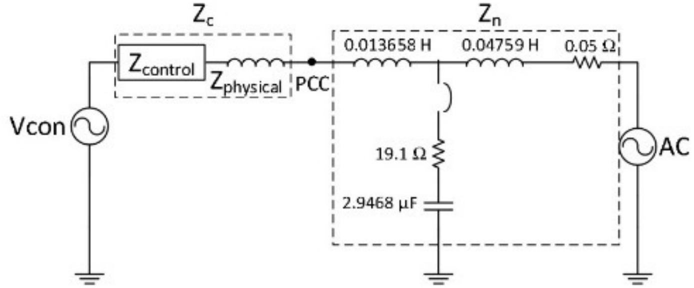
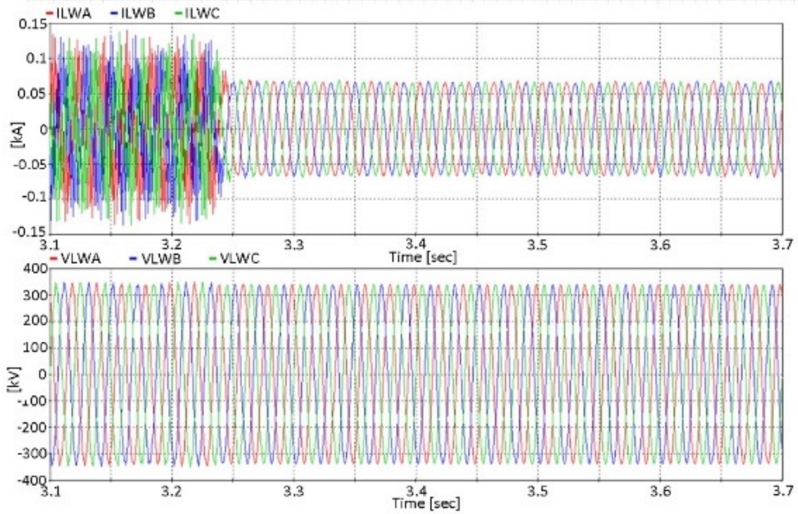
Time domain simulations assuming AC network resonating at 540 Hz, using Software Ver. 1



Synthetic model for time domain simulation



Time domain simulations before and after re-shaping the converter impedance (at 3.25 sec Software Ver. 2 is enabled)



Lifetime Operation: Resonances Under Non-Specified Conditions

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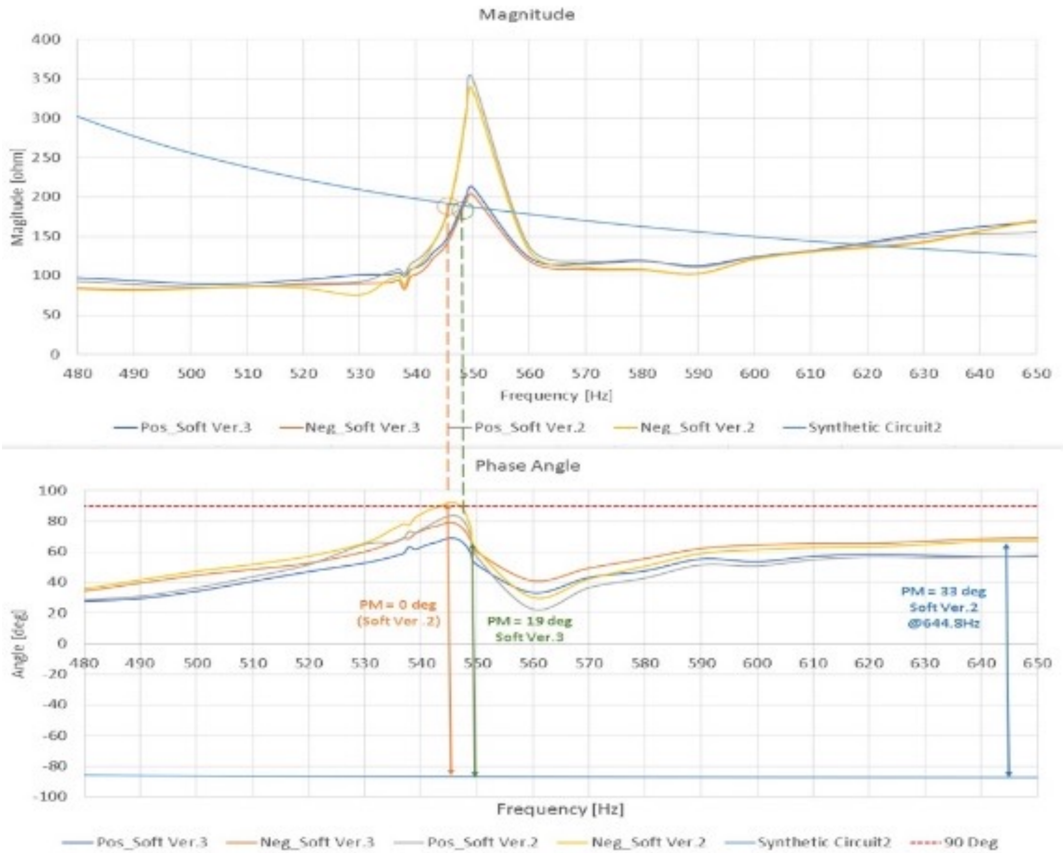
- Unplanned operating conditions in AC networks can lead to conditions outside Loci impedance limits, potentially causing trips due to harmonic resonances.

- These conditions are typically temporary operating conditions that may be not foreseen during the characterization of the Loci AC network. In the example given, the harmonic network damping at the resonant point was temporally reduced to zero (i.e. -90 deg).

Converter impedance before (i.e. software ver.2) and after the final converter impedance re-shaping (i.e. software ver.3) to withstand a temporary capacitive operating condition



Lifetime Operation: Resonances Under Non-Specified Conditions

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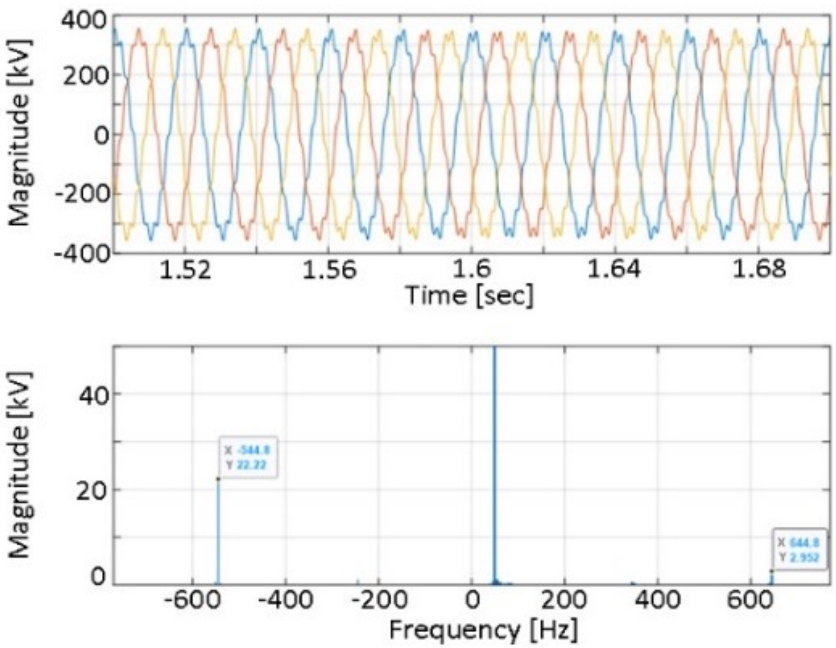
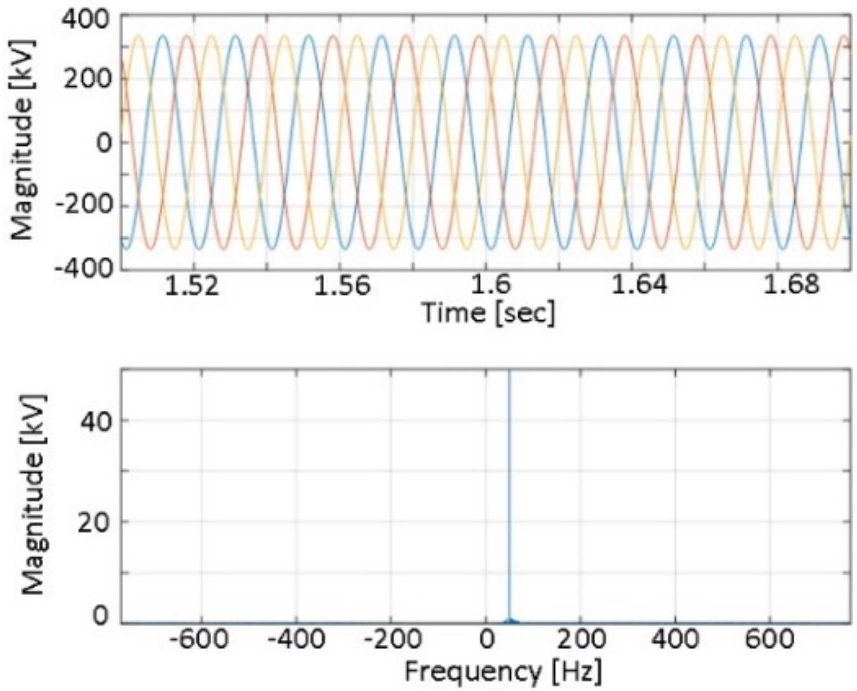
VLW at the AC-PCC & two dimensional FFT for positive and negative sequence component software Ver.2



VLW at the AC-PCC & two dimensional FFT for positive and negative sequence component software Ver.2



Conclusion

- The process of stability analysis using Loci is simple to follow and powerful.

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Q+A

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