Sub-synchronous oscillations with type 3 WT and MMC-HVDC

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Introduction

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Sub-synchronous oscillations (SSO) in power systems

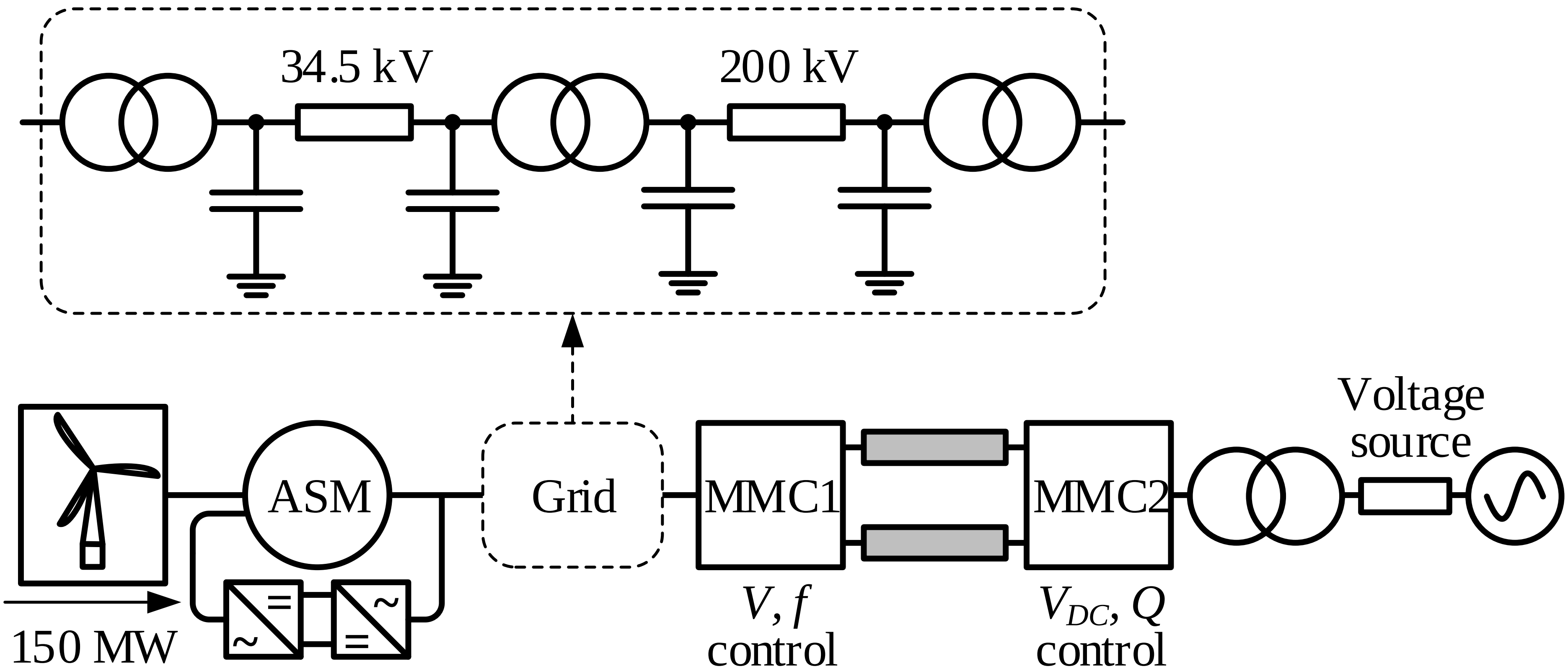
- Energy exchange between different parts of the system happening below grid frequency
- Undesirable phenomenon (overcurrents/overvoltages, equipment damage, protection system operation, …)

Different types of SSO

- Inductance <-> capacitance (compensated network)
- Mechanical <-> electrical (torsional oscillations)
- Control system interaction

System overview

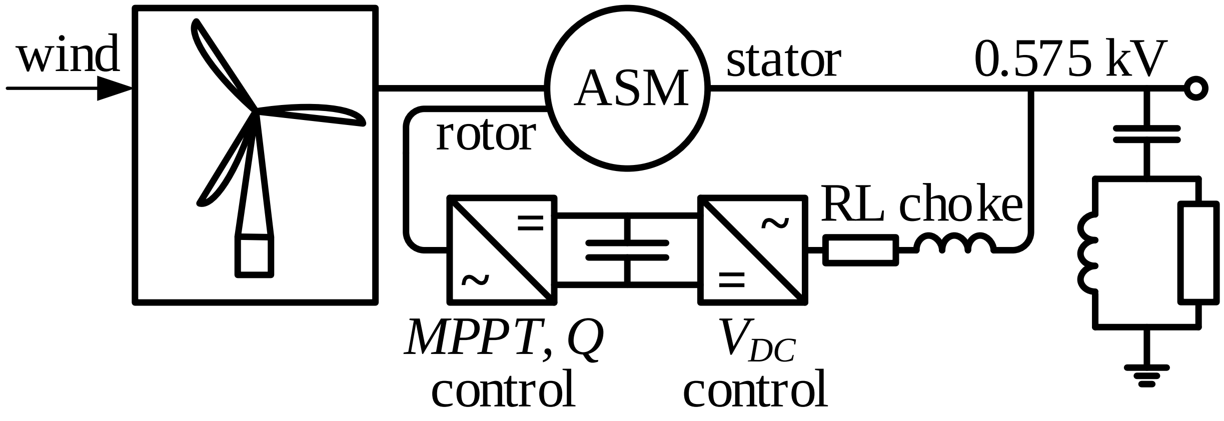
- WT, electrical grid, MMC-HVDC, nominal freq. = 50Hz
- Control system impacts SSO



System overview

Wind turbine:

- Type 3 (DFIG), average value model
- Aggregated model of a wind park (100 x 1.667 MVA)
- Constant wind speed
- 2-mass mechanical model (turbine, generator)
- Cascade control of AC/DC converters (inner loop: decoupled dq frame)

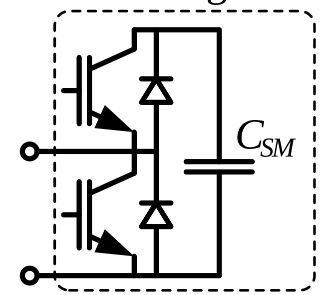


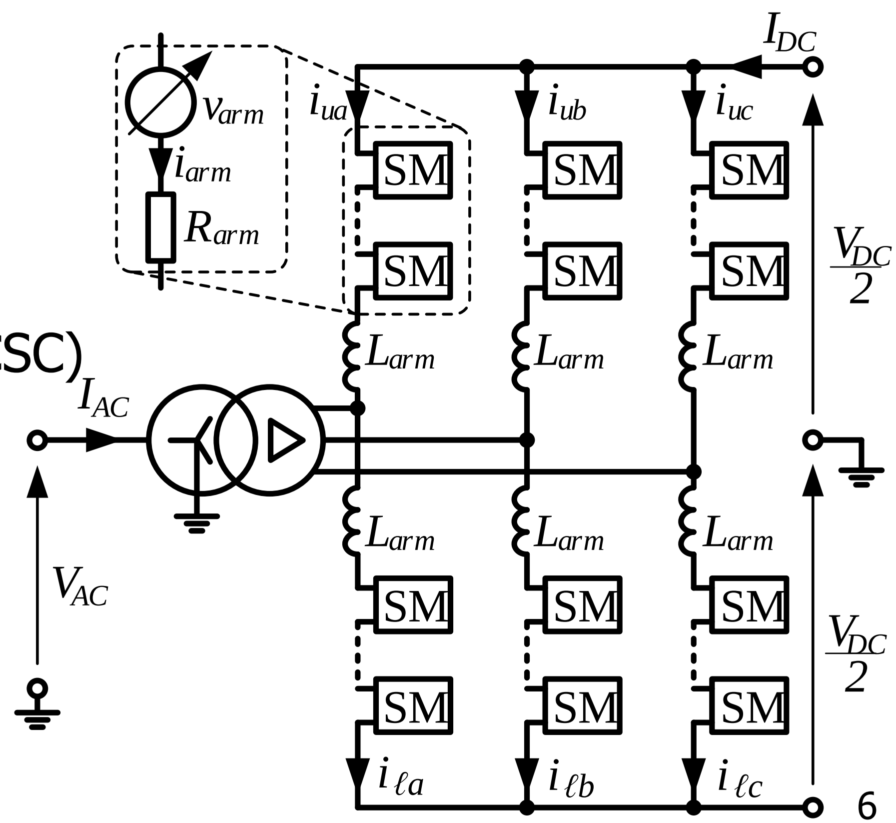
System overview

Modular Multilevel Converter (MMC):

- Lower switching frequency, losses, harmonics
- 200 SMs, arm equivalent model
- 200 MVA
- Cascade control
- Circulating current suppression (CCSC)
  Proportional-Resonant controller

Half-bridge SM

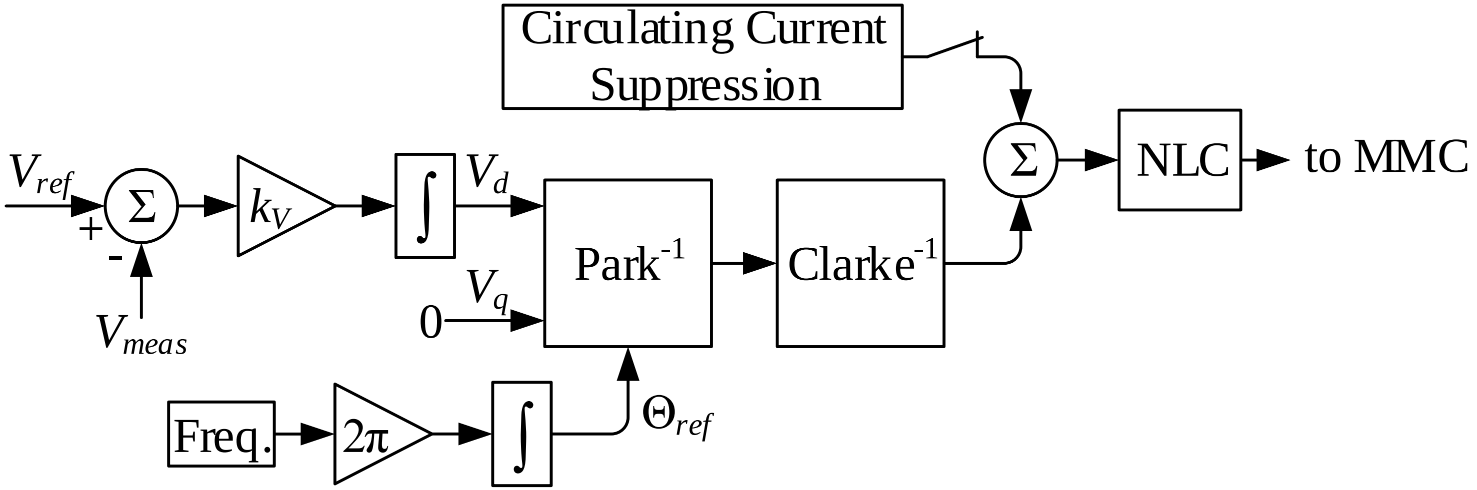




System overview

MMC-HVDC controls:

- AC grid side control: V_{DC}-Q, PR current control
- WF-side control: provides AC voltage reference for the grid
  - *V-f* control
  - CCSC can be deactivated



SSO demonstration

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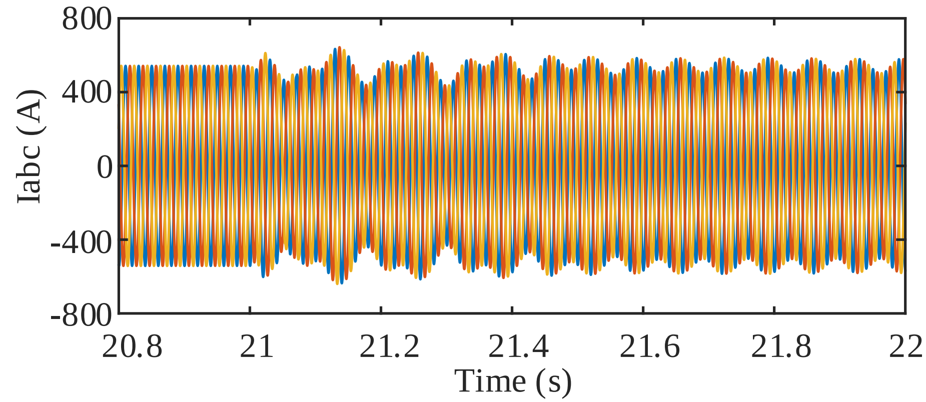
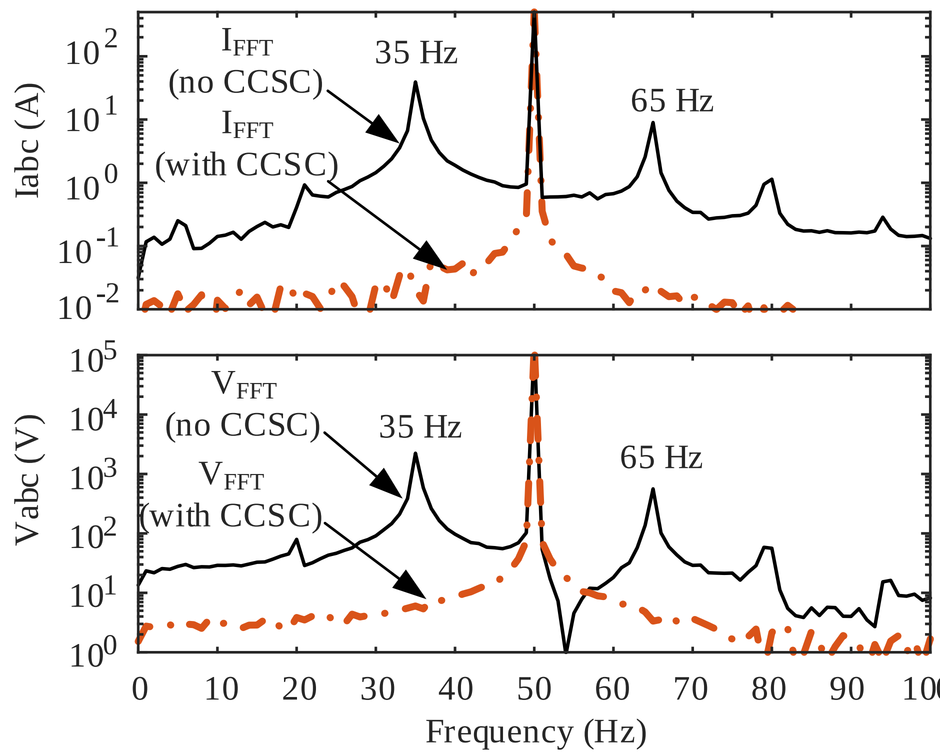
Windfarm side CCSC deactivated at t = 21 s

- No oscillations before 21s
- PCC current and voltage oscillations appear after deactivation of CCSC
- Significant harmonics: 35 Hz, 65 Hz in both current and voltage

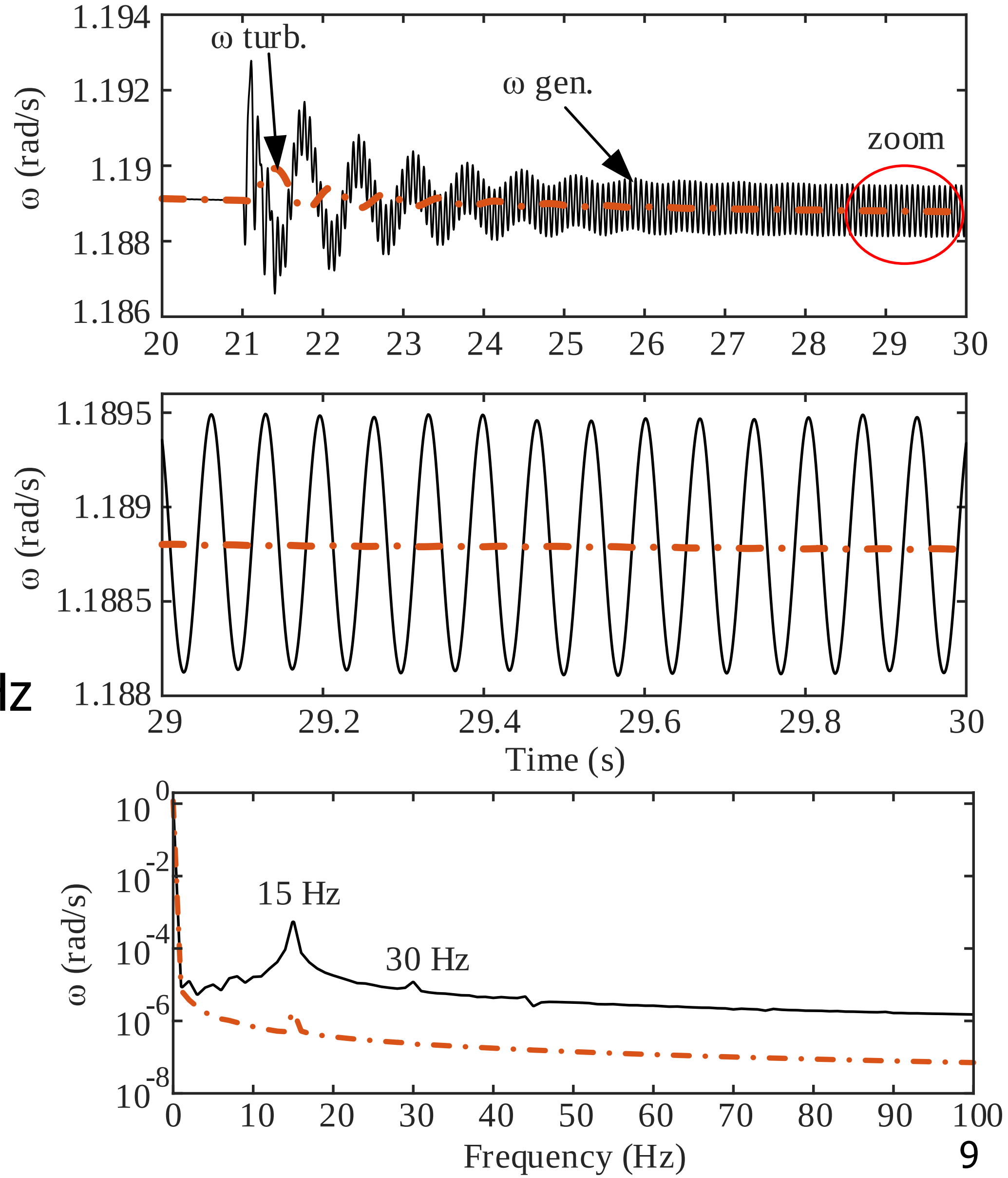




SSO demonstration

Windfarm side CCSC deactivated at t = 21 s

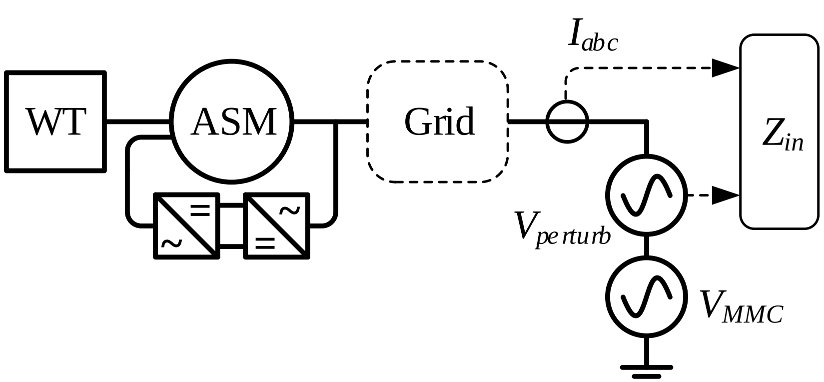
- No oscillations before 21s
- WF turbine speed is stable
- WF generator speed (ASM) after deactivation of CCSC
  - Significant oscillations at 15 Hz
  - Small peaks at 30 and 45 Hz
- 50 Hz – 15 Hz = 35 Hz
  50 Hz + 15 Hz = 65 Hz
  (frequency of AC current and voltage oscillations)

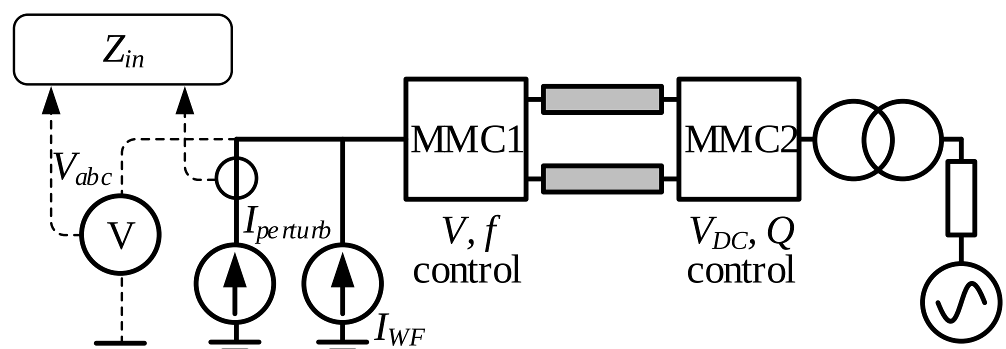


Analysis

Zin analysis:

1. Measure V_{MMC}, I_{WF}: voltage and current at PCC (3-phase, 50 Hz, no SSO)
2. Disconnect WF+grid from MMC
3. Apply V_{MMC} and I_{WF} sources to WF+grid and MMC, respectively
4. Apply small perturbation at different frequencies in time-domain:
    1. MMC with and without CCSC: $Zin(f) = V_{abc}(f) / I_{perturb}(f)$
    2. WF + grid: $Zin(f) = V_{perturb}(f) / I_{abc}(f)$

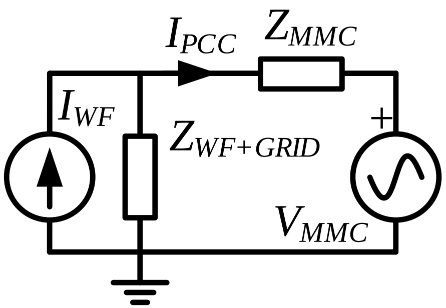


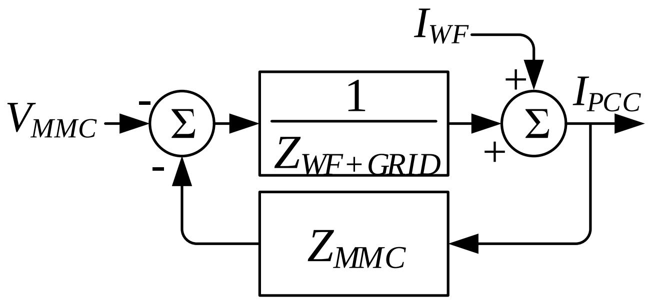


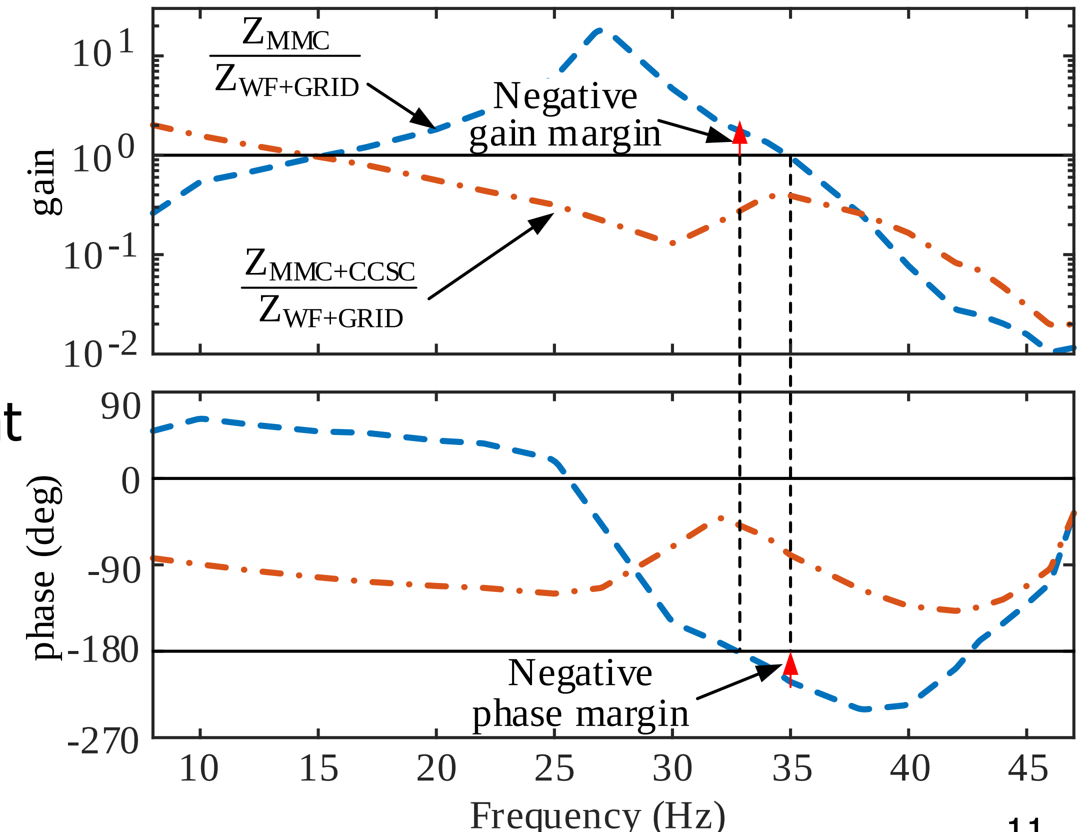
Analysis

Impedance-based stability criterion:

- Zmmc / Zwf+grid
- MMC without CCSC:
  - f = 33 Hz: gain = 2
  - f = 35 Hz: phase = -210°
  - System not stable
  - 35 Hz – frequency of current and voltage oscillations
- Better phase margin in case of MMC with CCSC



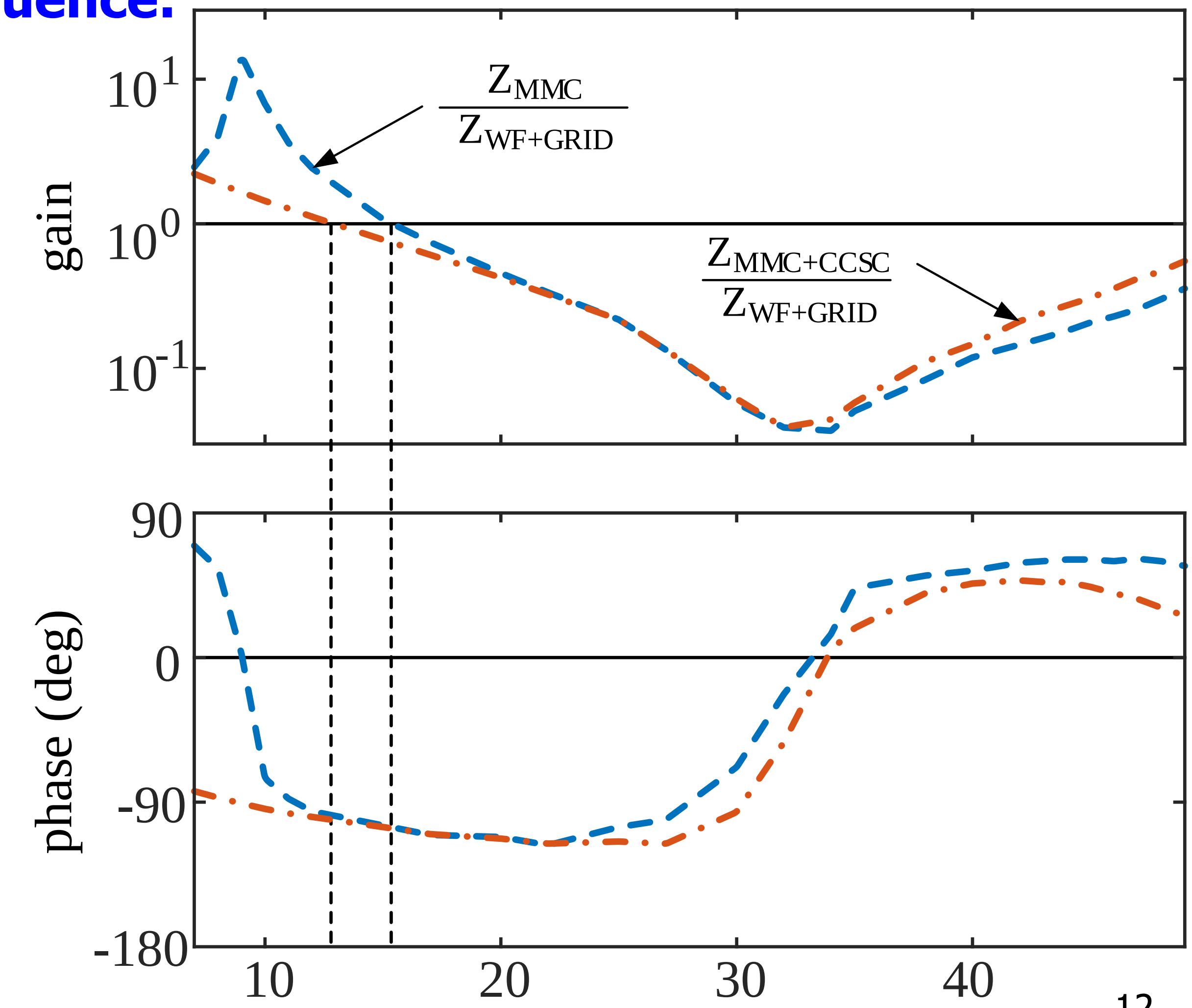




Analysis

Impedance-based stability criterion, negative sequence:

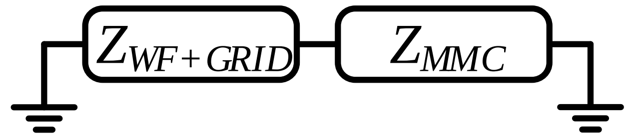
- MMC without CCSC:
  - f = 9 Hz: pole
  - f = 15 Hz: unity gain
  - safe phase margin
- MMC with CCSC:
  - f = 13 Hz: unity gain
  - safe phase margin
- Stable system

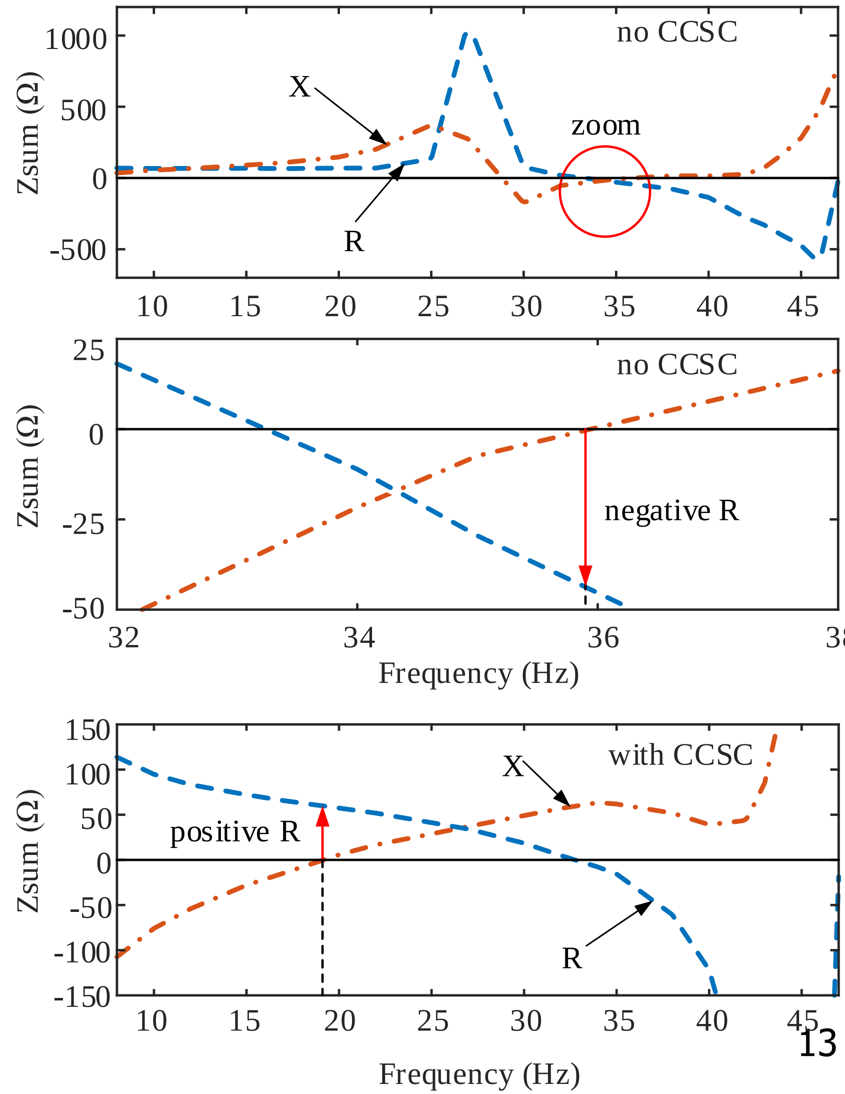


Analysis

R-X analysis:

- Zsum = Zwf+grid + Zmmc
- Oscillations if negative R when X=0
- MMC without CCSC, f = 35.9 Hz:
  - X = 0, R = -45 Ω
  - System not stable
  - 35 Hz – frequency of current and voltage oscillations
- MMC with CCSC, f = 19 Hz:
  - X = 0, R = 60 Ω

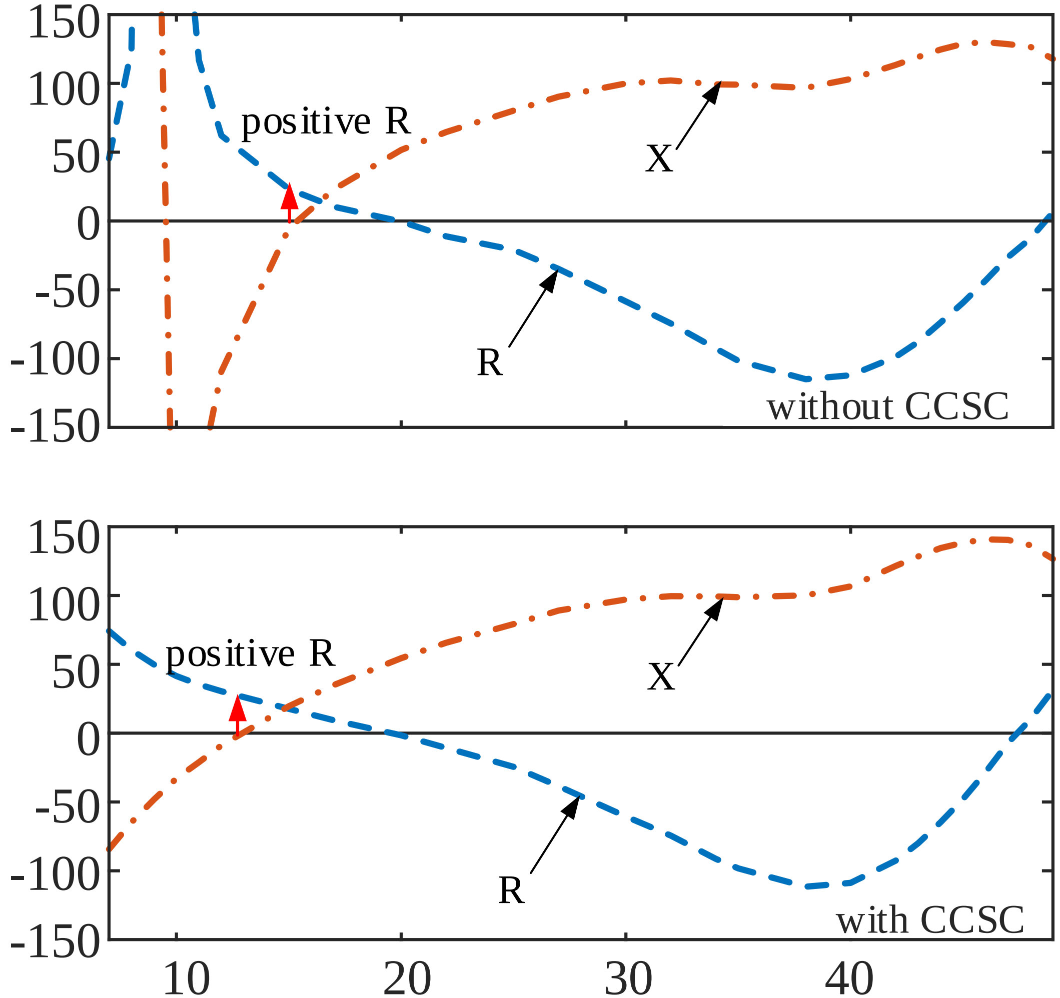




Analysis

R-X analysis, negative sequence:

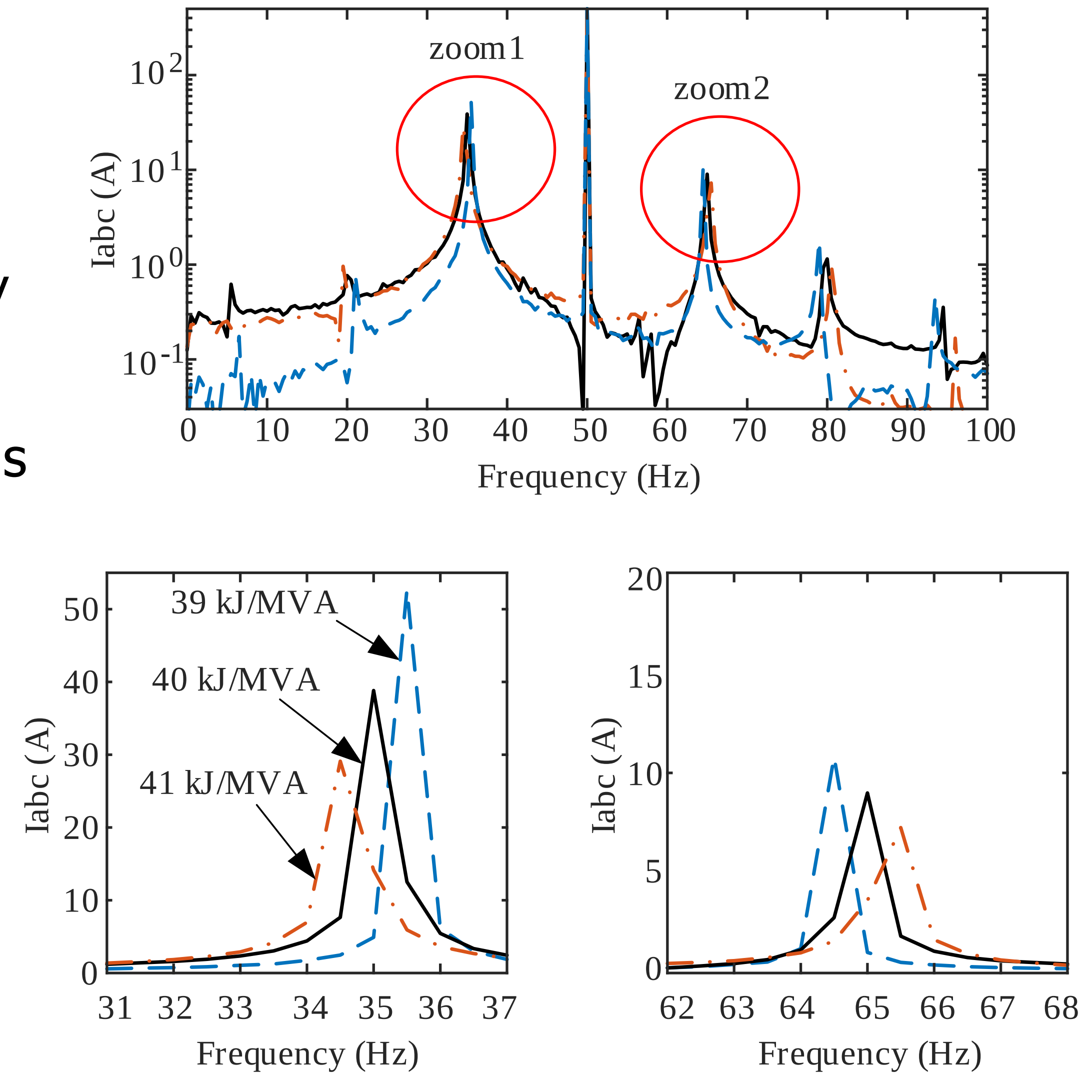
- MMC without CCSC:
  - f = 15 Hz
  - X = 0
  - R = 20 Ω
- MMC with CCSC:
  - f = 13 Hz
  - X = 0
  - R = 27 Ω
- Stable system



Analysis

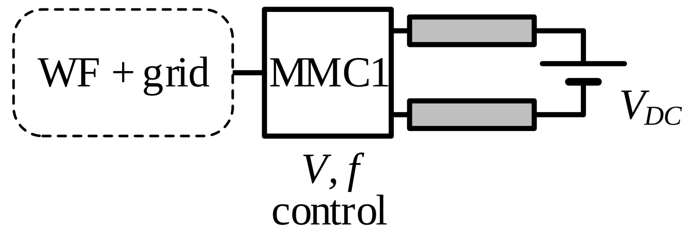
SM capacitance effect:

- Energy: 39, 40, 41 kJ/MVA
- With lower capacitor energy (i.e. smaller capacitances):
  - Higher amplitude oscillations
  - SSO frequency peaks shift closer to 50 Hz

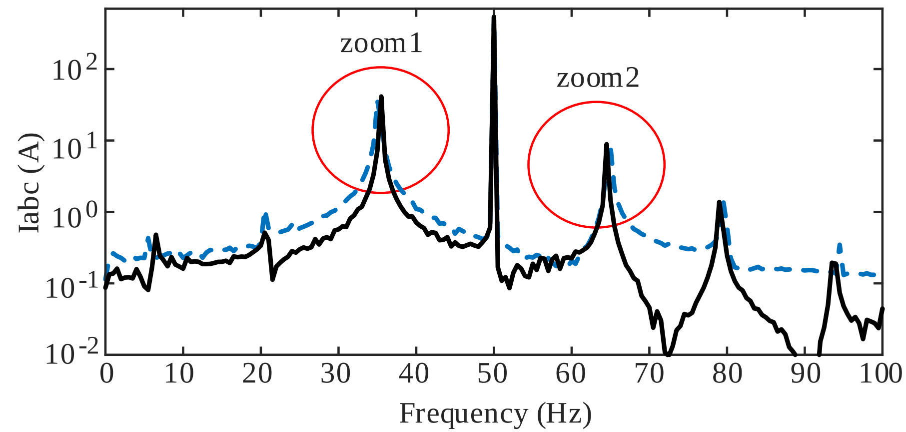


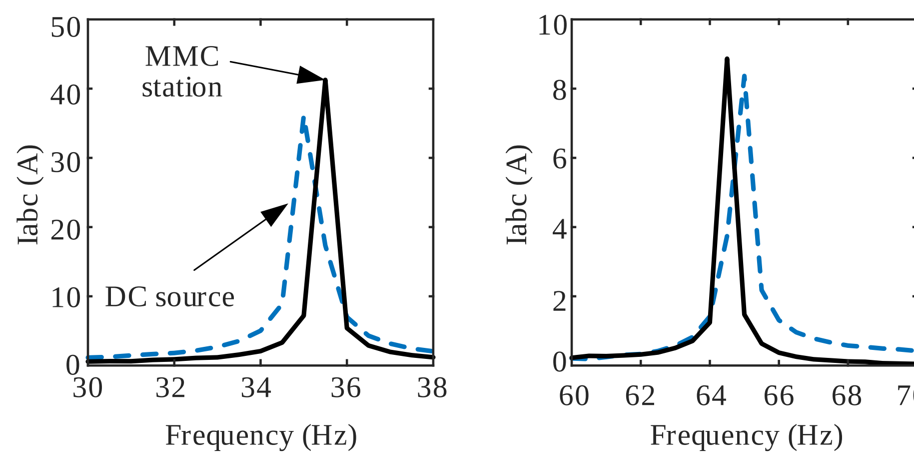
Analysis

Vdc-control station modeling:



- Ideal DC voltage source
  - Smaller oscillations in AC currents and voltages
  - SSO frequency peaks shift further from 50 Hz
- MMC station
  - Larger oscillations in AC currents and voltages
  - Oscillations in DC voltage and DC current





Analysis

MMC model effect:

- AEM:
  - All SMs aggregated into one equivalent variable C_{eq}
  - Sustained SSO (demonstrated in the presentation)
- DEM:
  - Each SM available, IGBT switches represented by R_{ON}, R_{OFF}
  - Sustained SSO (results similar to AEM)
- AVM:
  - Controlled voltage sources
  - No oscillations
  - Circulating current does not exist in this model

Conclusions

- Sub-synchronous oscillations can occur between DFIG-WF and MMC-HVDC
- Cause: MMC input impedance characteristics in absence of CCSC (pole at 27 Hz)
- Negative sequence impedance has negligible impact on SSO
- Submodule capacitance impacts the amplitude of the oscillations
- Smaller amplitude oscillations if ideal DC voltage source is used at the other end of HVDC transmission
- Average value MMC model insufficient to see sub-synchronous oscillations

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THANK YOU!

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