On resonance instabilities in VSCs connected to weak grids

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Content

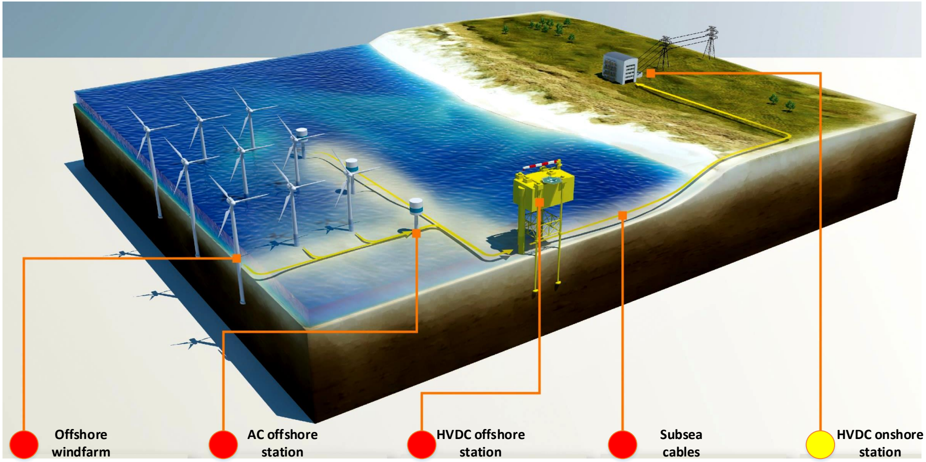
Introduction

- Widely use of power electronic converters on electrical grids.
- Interactions between the converters and electrical networks.
- Oscillations and instabilities might appear.

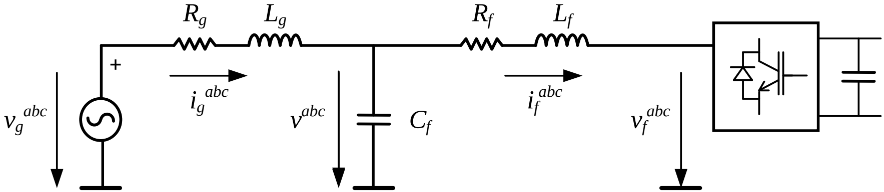
Objectives

- Stability assessment for VSCs connected to weak grids
- Small-signal state-space and impedance-based modelling

Testing network



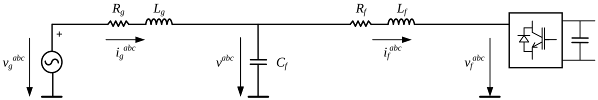
Modelling



Parameter	Symbol	Value	Units
Power	P	1	GW
Voltage	V	400	kVrms
Grid X/R ratio		10	
Resistance	R_f	0.2372	Ω
Inductance	L_f	0.0750	H
Capacitance	C_f	1	μF

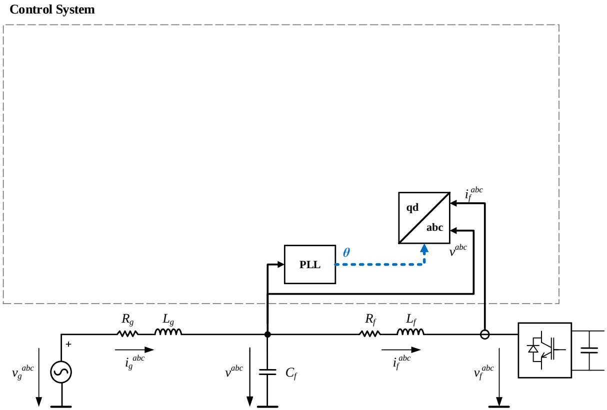
Control Structure

- Grid-connected VSC
- Averaged two-level model



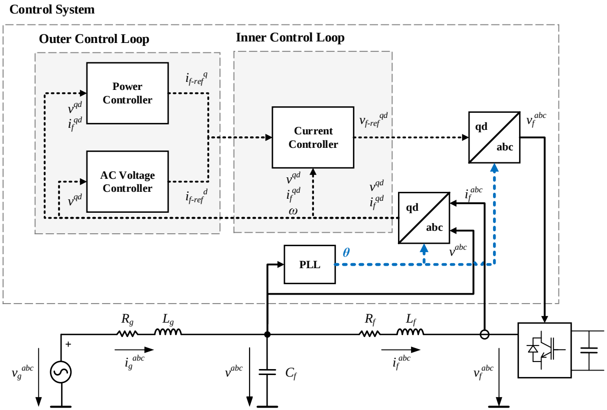
Control Structure

- Grid-connected VSC
- Averaged two-level model
- Vector control strategy



Control Structure

- Grid-connected VSC
- Averaged two-level model
- Vector control strategy
- Two-level cascaded controller
- Active power and AC voltage control
- First order delay and feed-forward voltage



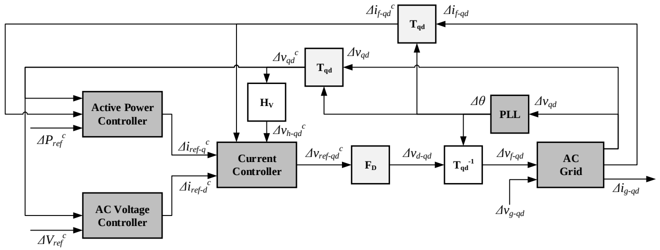
Modelling: State-space

System of linear equations in the time-domain

$\Delta_{in} \rightarrow$

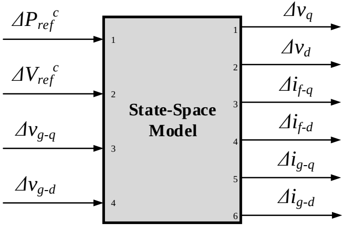
$$\Delta_{\dot{x}} = A\,\Delta_x + B\,\Delta_u$$
$$\Delta_y = C\,\Delta_x + D\,\Delta_u$$

$\rightarrow \Delta_{out}$



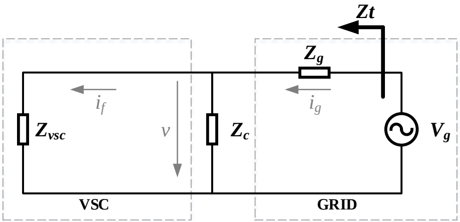
State-space matrix

- 4 inputs and 6 outputs
- 16 states



Modelling: Impedance-based

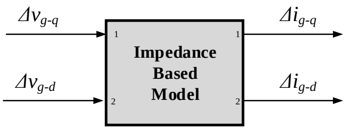
Impedance characterization of the system



$$\Delta V = \mathbf{Z_{vsc}} \Delta I_f$$
$$\Delta V = \mathbf{Z_c}(\Delta I_g - \Delta I_f)$$
$$\Delta V_g = \Delta V + \mathbf{Z_g} \Delta I_g$$

Transfer function in the *s*-domain

- 2 inputs and 2 outputs

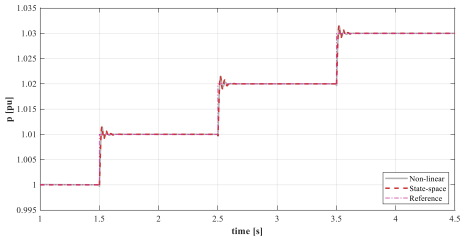


- A matrix of four 16th order transfer functions.

$$\mathbf{Y_T} = \begin{bmatrix} Y_{qq} & Y_{qd} \\ Y_{dq} & Y_{dd} \end{bmatrix}$$

Validation: Non-linear vs state-space

- Non-linear Simulink and linearized state-space model have been compared.
- Time-domain simulation for a $SCR = \mathbf{3}$
- 0.01 pu step variation of active power up to 0.03 pu



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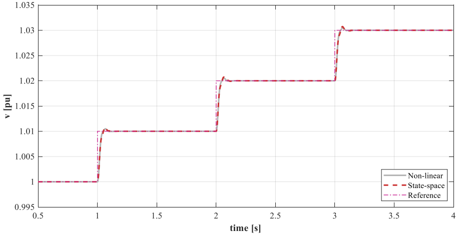
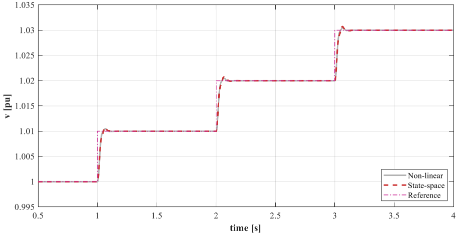
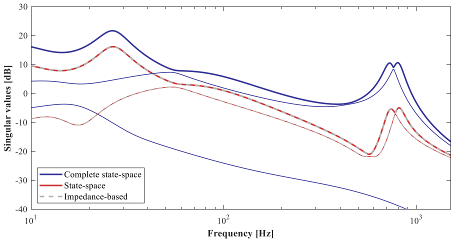
- 0.01 pu step variation of active power up to 0.03 pu
- 0.01 pu step variation of AC voltage up to 0.03 pu

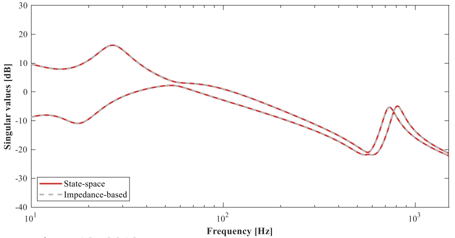




Validation: Impedance-based vs state-space

- The impedance-based transfer function is given by the admittance seen from the grid side : $\frac{i_g}{v_g}$
- State-space model inputs and outputs have been selected for comparison purposes.
- The the singular values of the system frequency response **match**.





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- The impedance-based transfer function is given by the admittance seen from the grid side : $\frac{i_g}{v_g}$
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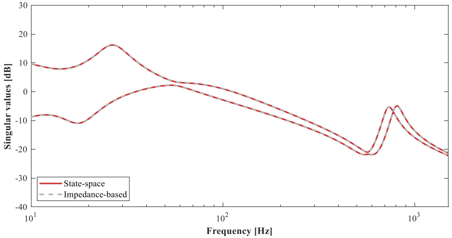
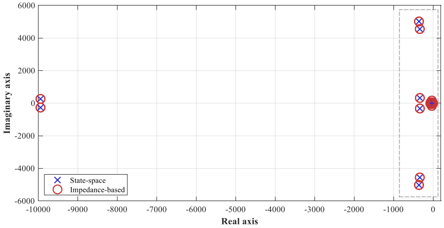
- The the singular values of the system frequency response and eigenvalues **match**.





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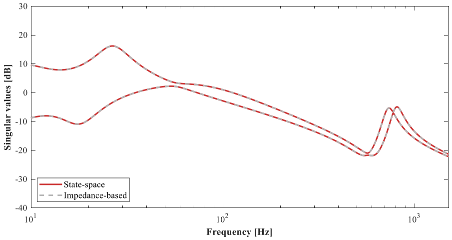
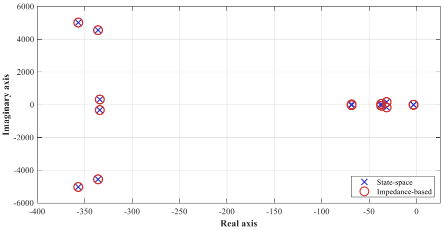
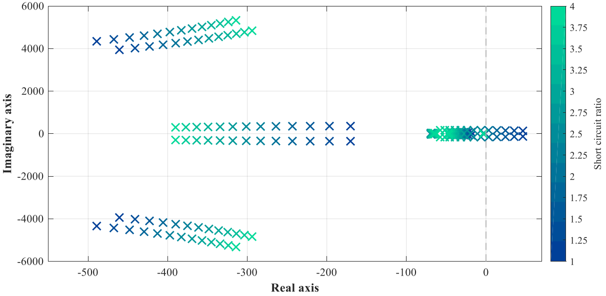




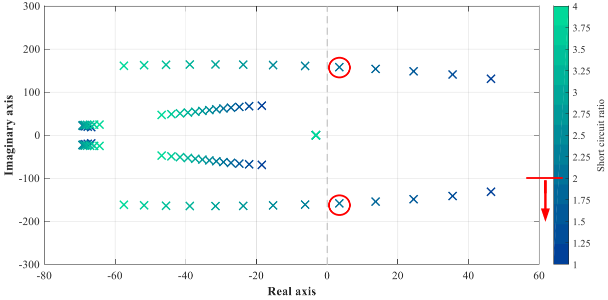
Sensibility analysis of the strength of the grid

- Eigenvalues and singular values for different SCRs.



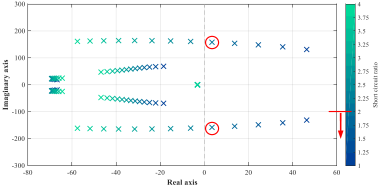
Stability assessment: Eigenvalues

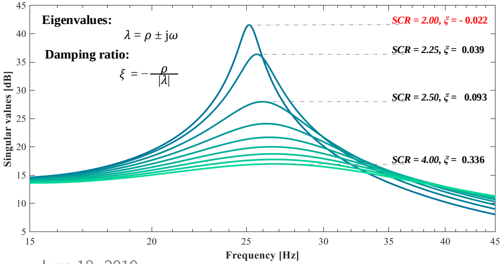
- Eigenvalues and singular values for different SCRs.
- The system becomes unstable for:
  - $SCR = \mathbf{2}$



Stability assessment: Damping

- Eigenvalues and singular values for different SCRs.
- The system becomes unstable for:
  - SCR =**2**
  - ξ =**-0.022**

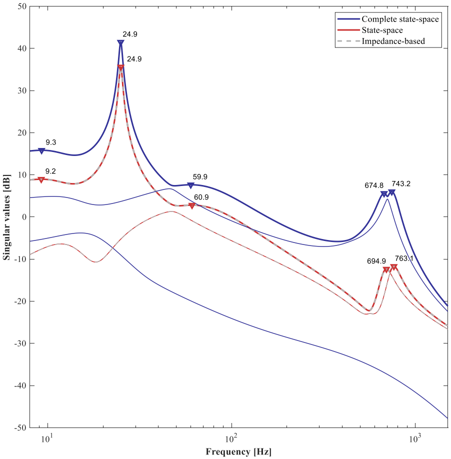




Stability assessment: Singular values

- Oscillations in the sub-synchronous and harmonic range.

Mode	Real	Imaginary	Damping	Frequency [Hz]
9	**3,49**	**156,65**	**-0,022**	**24,93**
10	**3,49**	**-156,65**	**-0,022**	**24,93**
3	**-410,67**	**4691,06**	**0,087**	**746,61**
4	**-410,67**	**-4691,06**	**0,087**	**746,61**
5	-392,36	4256,68	0,092	677,47
6	-392,36	-4256,68	0,092	677,47
13	-28,99	62,18	0,423	9,90
14	-28,99	-62,18	0,423	9,90
7	-264,28	345,50	0,608	54,99
8	-264,28	-345,50	0,608	54,99
11	-69,14	21,97	0,953	3,50
12	-69,14	-21,97	0,953	3,50
1	-9949,47	265,92	1,000	42,32
2	-9949,47	-265,92	1,000	42,32
15	-3,16	0,00	1,000	0,00
16	-3,16	0,00	1,000	0,00



Stability assessment: Participation factors

- The unstable poles, 9 and 10, are related to the second state of the PLL.

Mode	Real	Imaginary	Damping	Frequency [Hz]
9	3,49	156,65	-0,022	24,93
10	3,49	-156,65	-0,022	24,93
3	-410,67	4691,06	0,087	746,61
4	-410,67	-4691,06	0,087	746,61
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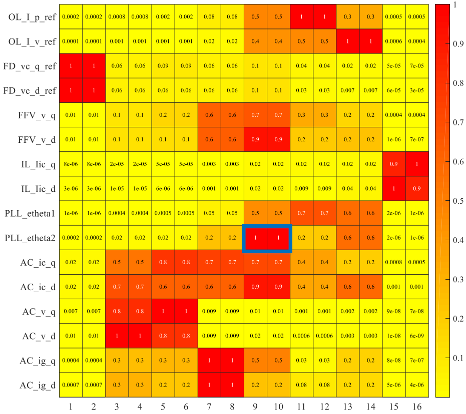

Stability assessment: Participation factors

- Poles 3, 4, 5 and 6 are related to the states of the AC grid.

Mode	Real	Imaginary	Damping	Frequency [Hz]
9	3,49	156,65	-0,022	24,93
10	3,49	-156,65	-0,022	24,93
3	-410,67	4691,06	0,087	746,61
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5	-392,36	4256,68	0,092	677,47
6	-392,36	-4256,68	0,092	677,47
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14	-28,99	-62,18	0,423	9,90
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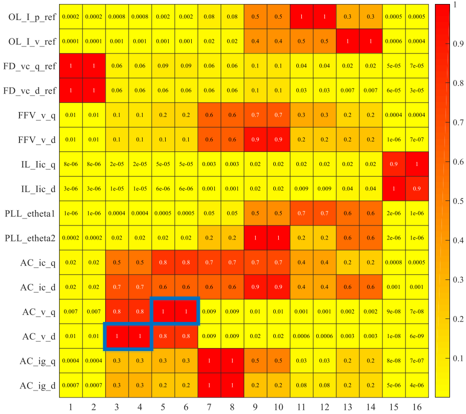
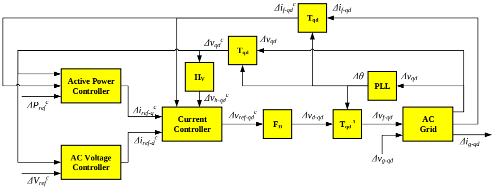
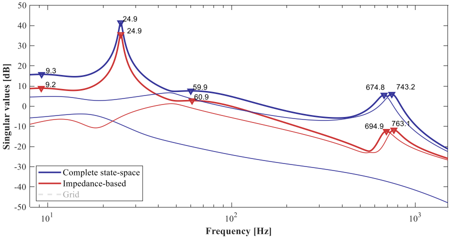
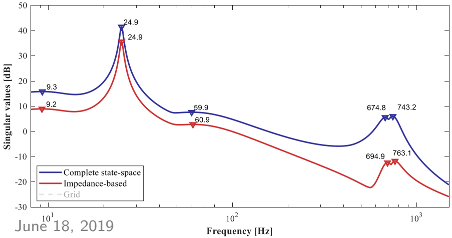
8	-264,28	-345,50	0,608	54,99
11	-69,14	21,97	0,953	3,50
12	-69,14	-21,97	0,953	3,50
1	-9949,47	265,92	1,000	42,32
2	-9949,47	-265,92	1,000	42,32
15	-3,16	0,00	1,000	0,00
16	-3,16	0,00	1,000	0,00



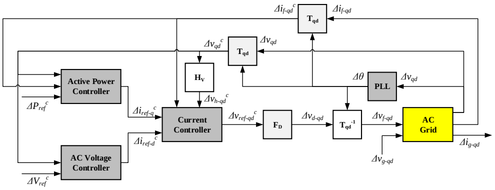
Stability assessment: Complete state-space model of the system

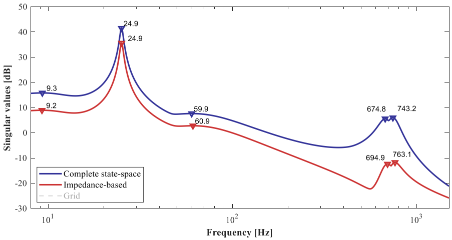




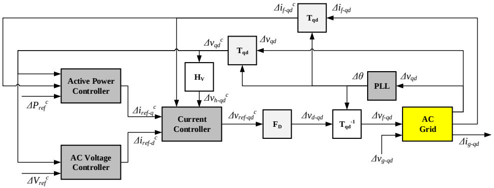


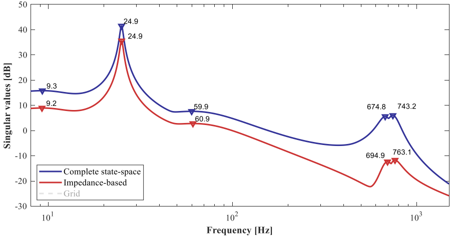
Stability assessment: Passive elements of the network

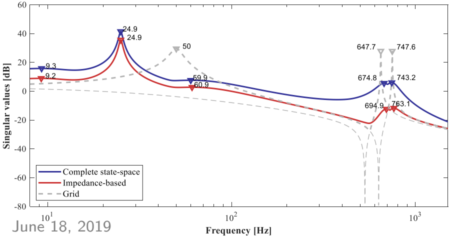




Stability assessment: Passive elements of the network

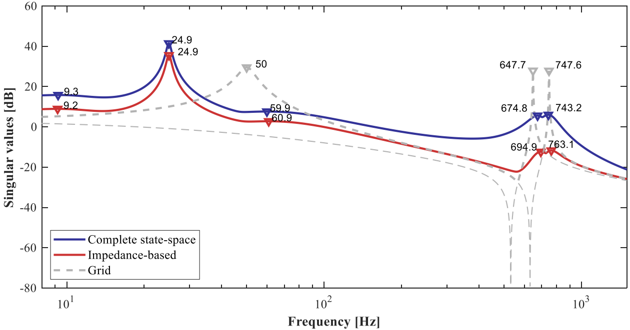




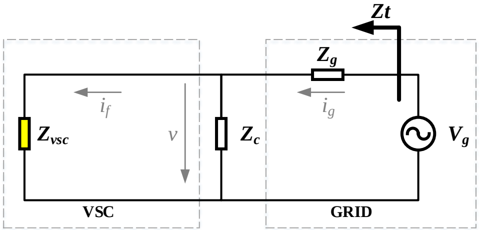


Stability assessment: Control interaction with passive elements of the network

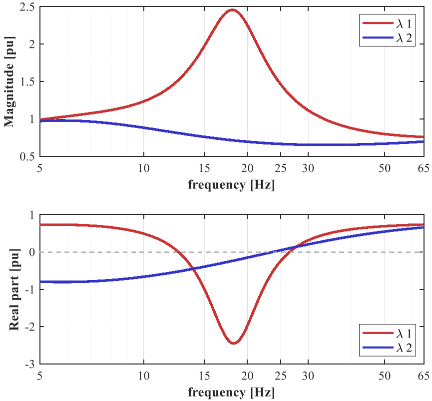
- Existing resonances of the passive elements of the network in the synchronous and harmonic range.



Stability assessment: Impedance of the converter



$$\mathbf{Z_{VSC}} = \begin{bmatrix} Z_{qq} & Z_{qd} \\ Z_{dq} & Z_{dd} \end{bmatrix}$$



Stability assessment: Mitigation

- PLL bandwidth is 0.05 sec.
- The damping poles of 9 and 10 is -0.022.
- **Unstable**

Mode	Real	Imaginary	Damping	Frequency [Hz]
9	**3,49**	**156,65**	**-0,022**	**24,93**
10	**3,49**	**-156,65**	**-0,022**	**24,93**
3	**-410,67**	**4691,06**	**0,087**	**746,61**
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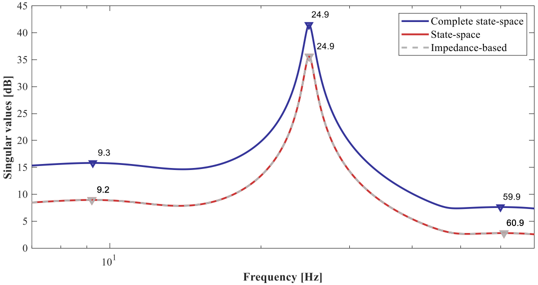
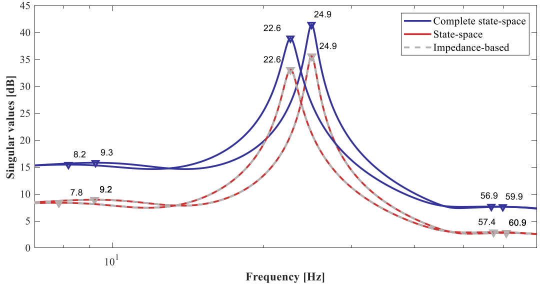


Stability assessment: Mitigation

- PLL bandwidth is 0.07 sec.
- The damping poles of 9 and 10 is -0.031.
- **Unstable**

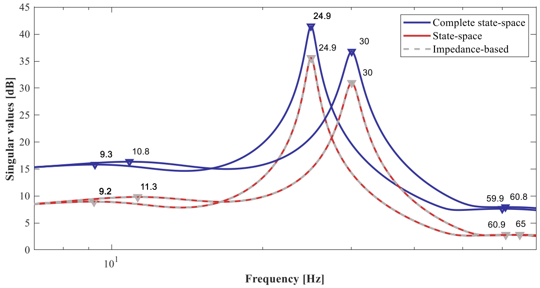
Mode	Real	Imaginary	Damping	Frequency [Hz]
9	4,45	142,17	-0,031	22,63
10	4,45	-142,17	-0,031	22,63
3	-402,70	4690,79	0,086	746,56
4	-402,70	-4690,79	0,086	746,56
5	-384,36	4256,80	0,090	677,49
6	-384,36	-4256,80	0,090	677,49



Stability assessment: Mitigation

- PLL bandwidth is 0.03 sec.
- The damping poles of 9 and 10 is 0.034.
- **Stable**

Mode	Real	Imaginary	Damping	Frequency [Hz]
9	**-6,35**	**188,78**	**0,034**	**30,05**
10	**-6,35**	**-188,78**	**0,034**	**30,05**
3	**-429,38**	**4690,57**	**0,091**	**746,53**
4	**-429,38**	**-4690,57**	**0,091**	**746,53**
5	-410,99	4257,56	0,096	677,61
6	-410,99	-4257,56	0,096	677,61



Conclusion

- Both methodologies can determine the oscillatory resonances of a system.
- The linearized state-space model closely reproduces the dynamics of a non-linear Simulink model.
- The effect of reducing the strength of the network reduces the damping, increasing the amplitude of the oscillations till the system becomes unstable.
- It is well-known that state-space models can be converted to transfer functions, but this is not possible in the opposite way. Detailed information of the system becomes inaccessible in this process.

Conclusion

- It is possible to identify the states which are causing oscillatory phenomena by using participation factors with state-space modelling.
- By re-tuning the controllers, the negative interaction of the converter with the passive elements on the network can be shifted to a different frequency and reduce the amplitude of oscillation.

Thanks for your attention!

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