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Contribution of synchronous compensators to the stability of inverter-based generation

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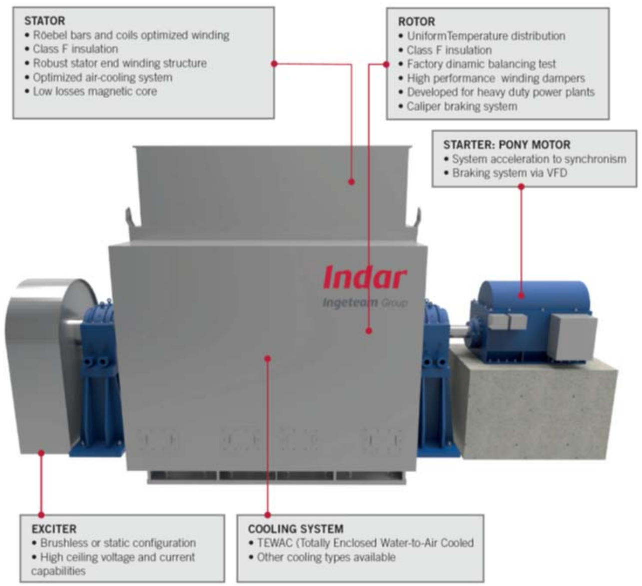
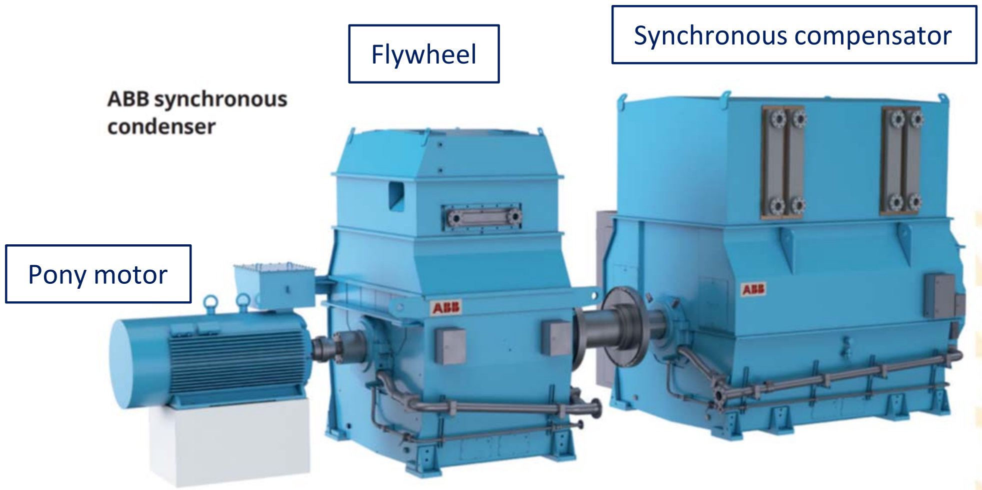
Introduction

- Synchronous compensators
  - are synchronous machines that only supply/consume reactive power
  - do not exchange active power with the grid except for power losses
  - are not driven by a prime mover except by an auxiliary motor during the start-up
  - were used in the past to provide continuous voltage/reactive power control
  - were surpassed by static var compensators because the faster response and lower maintenance costs of the later

Introduction

- Synchronous compensators
  - Two commercial solutions with different features (of course, no comercial interest in any of them)





No need of flywheel because of mechanical design of the rotor

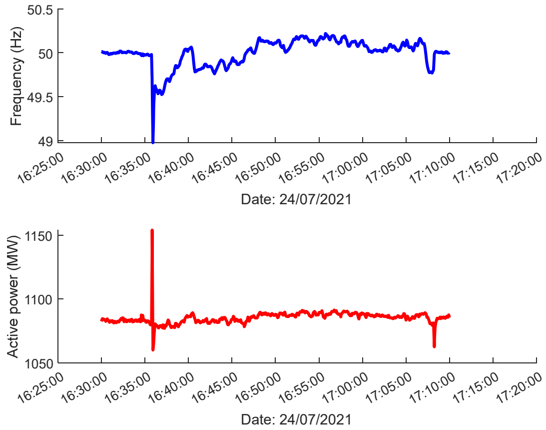
With flywheel

Introduction

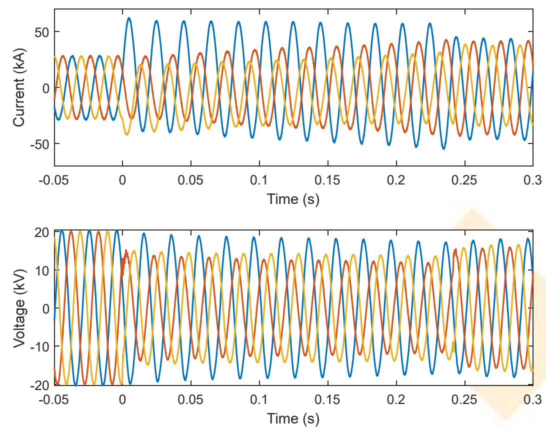
- Application examples
  - Spain
    - Red Eléctrica: Island systems
      - Mallorca: 4x100 MVA
      - Tenerife: 1x25 MVA
      - Gran Canaria: 1x25 MVA
      - Fuerteventura: 1x25 MVA
    - Renewable energy promoters: to increase grid access capacity of asynchronous generation
  - Italy
    - Terna: 16x(+250/-125 Mvar)
  - Ireland
    - Moneypoint: +260/-111 MVar
  - UK
    - Lister Drive: 80 Mvar
  - US
    - Wineyard: +171/-133 Mvar
  - Brazil
    - Marmeleiro 2 and Livramento 3: 2x(+150/-90 Mvar)
  - Australia
    - Buronga and Dinawan: 2x(+100/-50 Mvar)

Introduction

- The transformation of the electric power system from a synchronous machine-based generation to inverter-based generation system will result in the loss of
  - inertia and
  - short circuit current



Inertial response of a large synchronous generator in case the Iberian península sepration from the Continental European system on 24 July 2021



Short circuit response of a large synchronous generator in case of a close-in grid fault

- Synchronous compensators can contribute to both

Contribution to the stability of grid-feeding converters

- Controls of grid-feeding devices are designed assuming a grid short circuit ratio (SCR)

$$SCR = \frac{S_{sc}}{P_n}$$

S_{sc} is the grid short circuit capacity

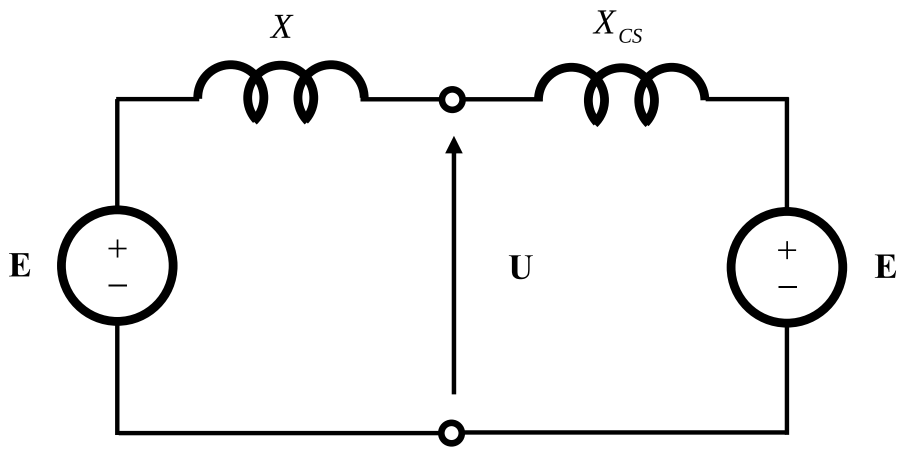
P_n is the nominal active power of the device

- The grid access capacity of renewable energy sources can be increased by increasing the SCR with a synchronous compensator

$$SCR = \frac{\Delta S_{sc}}{\Delta P_n}$$

Contribution to the stability of grid-feeding converters

- The rating of the synchronous compensator can be calculated as

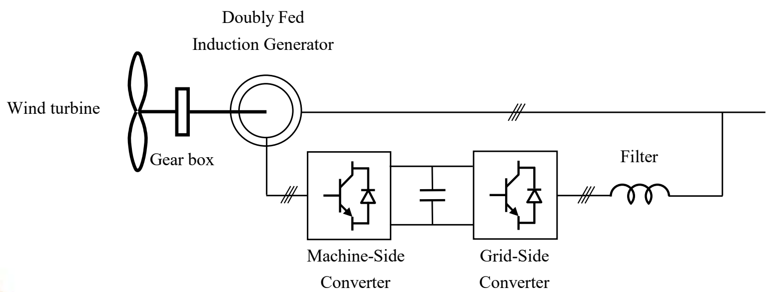


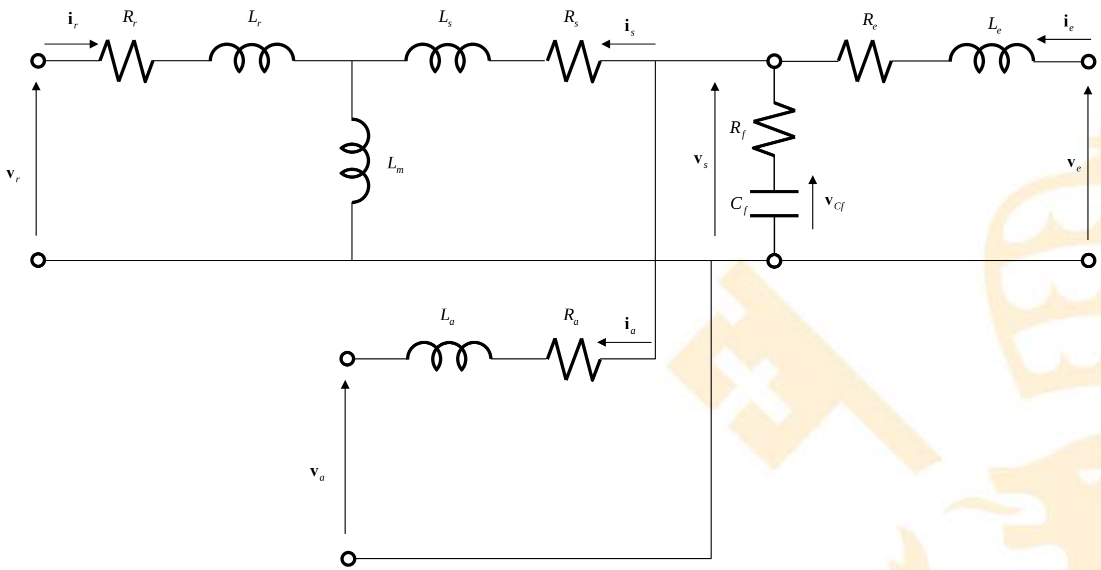
$$\Delta P_n = \frac{\Delta S_{sc}}{SCR} = \frac{\frac{1}{X_{SC}} \cdot S_{nSC}}{SCR}$$

$$S_{nSC} = X_{SC} \cdot SCR \cdot \Delta P_n$$

Contribution to the stability of grid-feeding converters

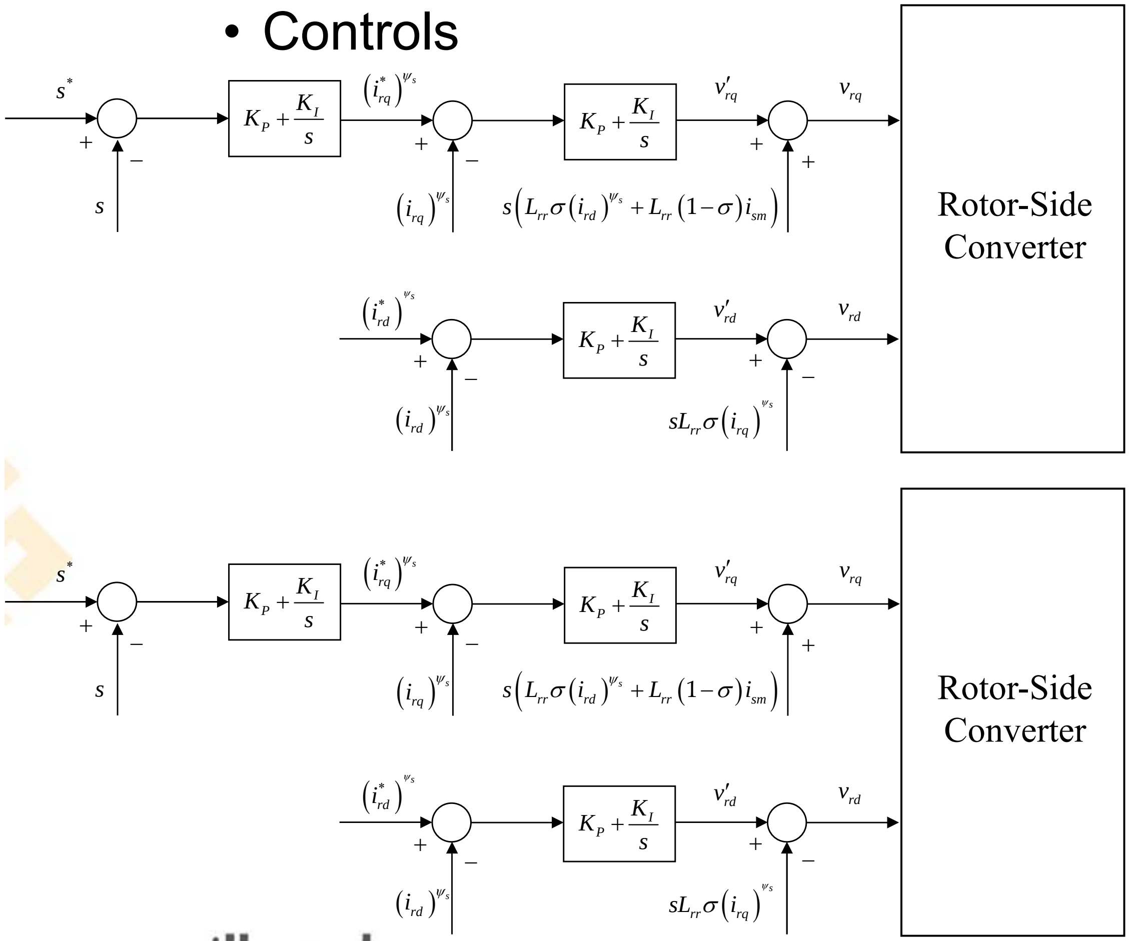
- Type 3 wind generator

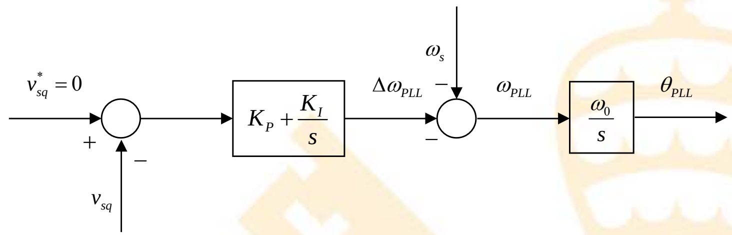




Contribution to the stability of grid-feeding converters

- Type 3 wind generator
  - Controls





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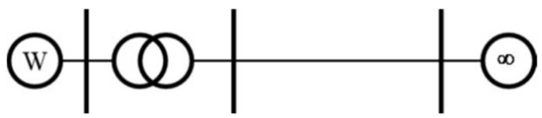
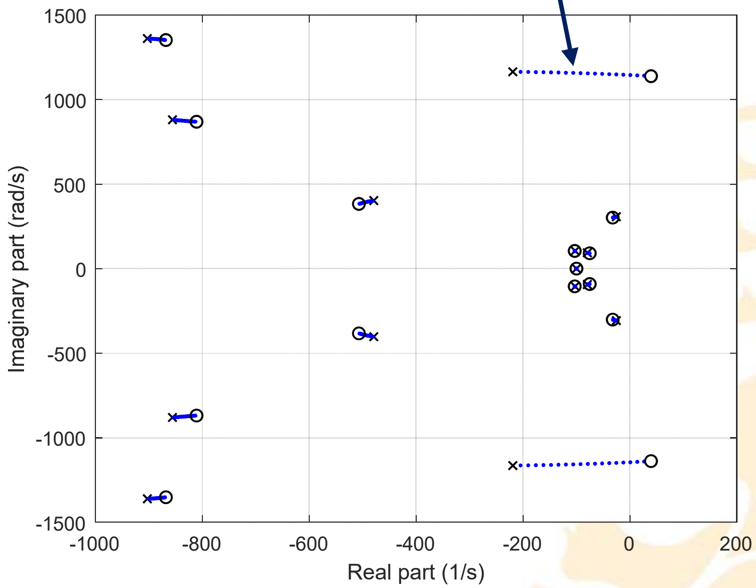
Contribution to the stability of grid-feeding converters

- Type 3 wind generator
  - Stability
    - Root locus as the grid impedance increases

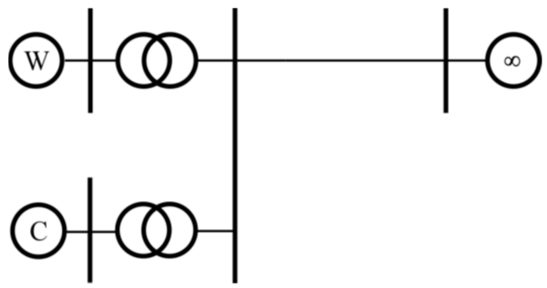


The complex pair associated to the PLL control becomes unstable as the grid impedance increases

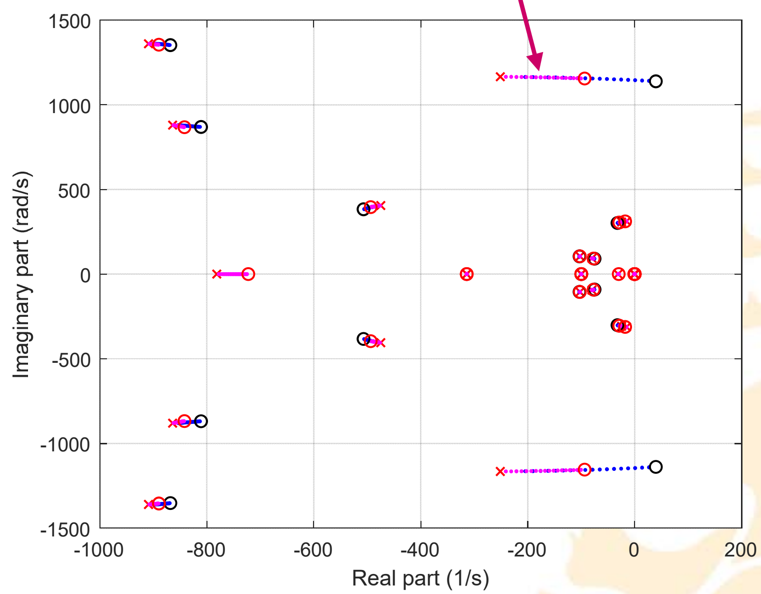


Contribution to the stability of grid-feeding converters

- Type 3 wind generator with synchronous compensator
  - Stability
    - Root locus as the grid impedance increases



The complex pair associated to the PLL control becomes stable as the grid impedance increases due to the synchronous compensator action

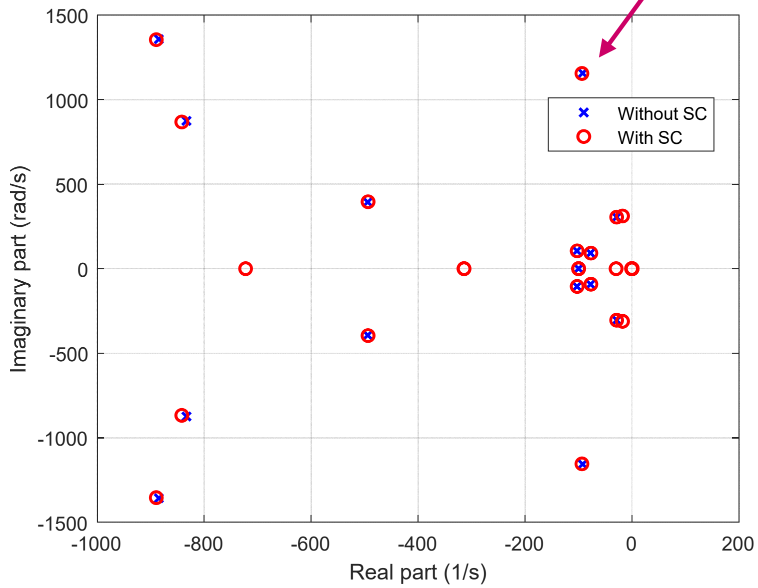


In addition, no adverse interaction with the synchronous compensator controls has been observed

Contribution to the stability of grid-feeding converters

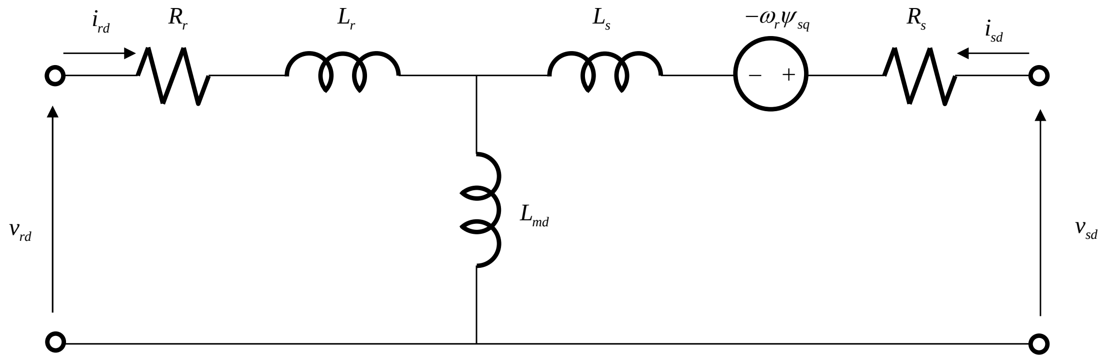
- Type 3 wind generator without and with synchronous compensator for the same equivalent short circuit ratio

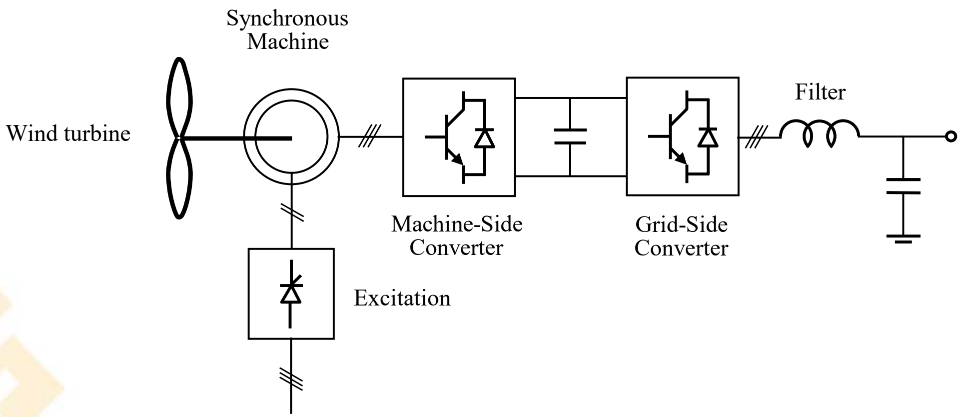
The complex pair associated to the PLL control is accurately provided by the simplified model of the SC

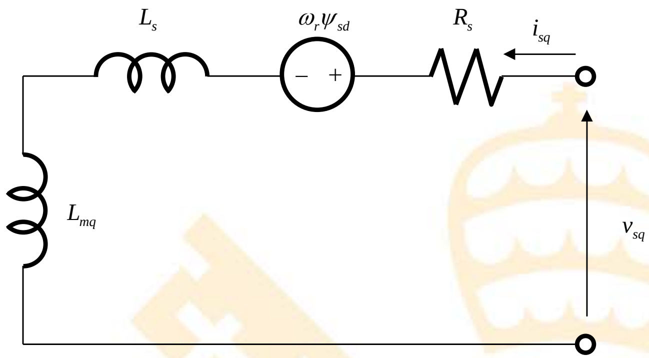


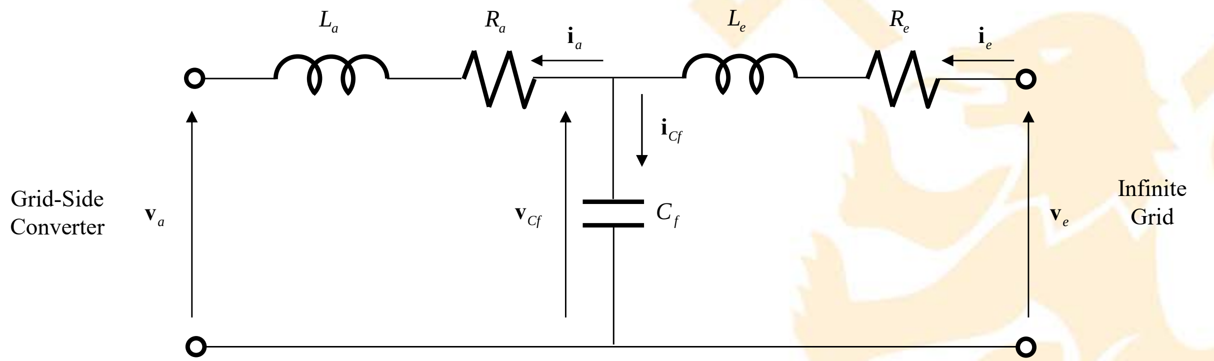
Contribution to the stability of grid-feeding converters

- Type 4 wind generator



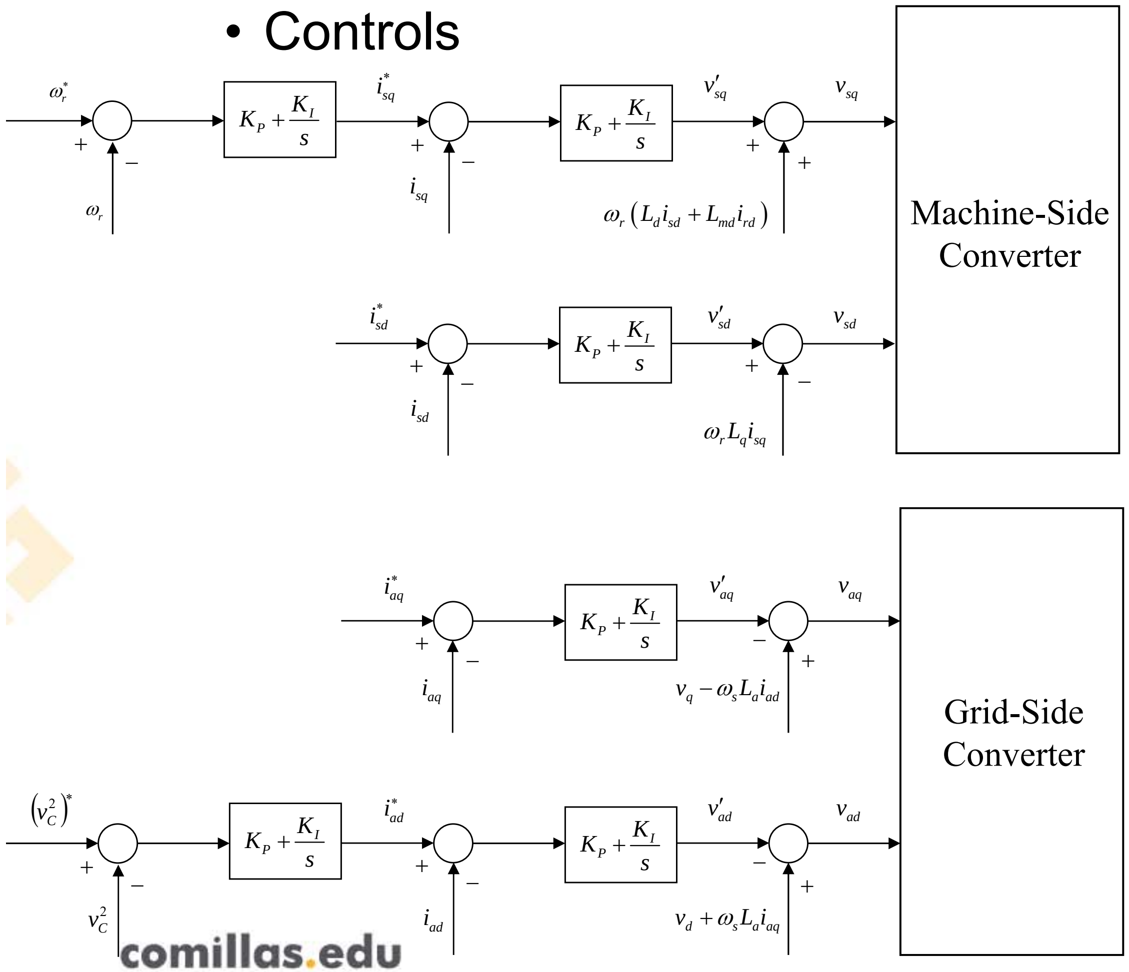


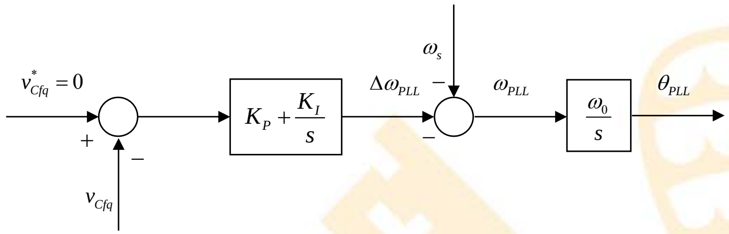




Contribution to the stability of grid-feeding converters

- Type 4 wind generator
  - Controls

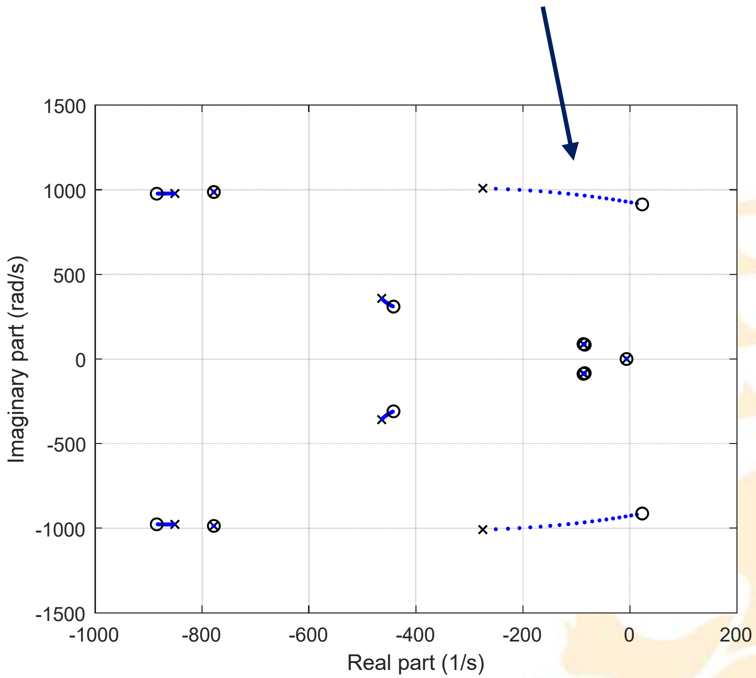




Contribution to the stability of grid-feeding converters

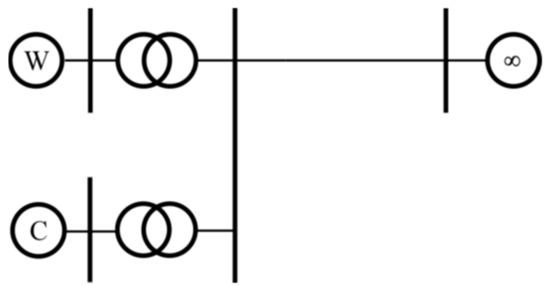
- Type 4 wind generator
  - Stability
    - Root locus as the grid impedance increases

The complex pair associated to the PLL control becomes unstable as the grid impedance increases

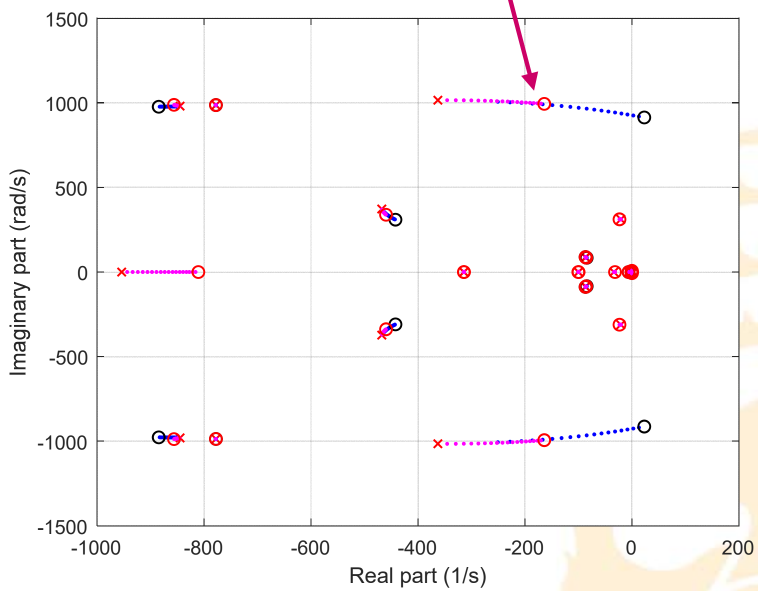


Contribution to the stability of grid-feeding converters

- Type 4 wind generator with synchronous compensator
  - Stability
    - Root locus as the grid impedance increases



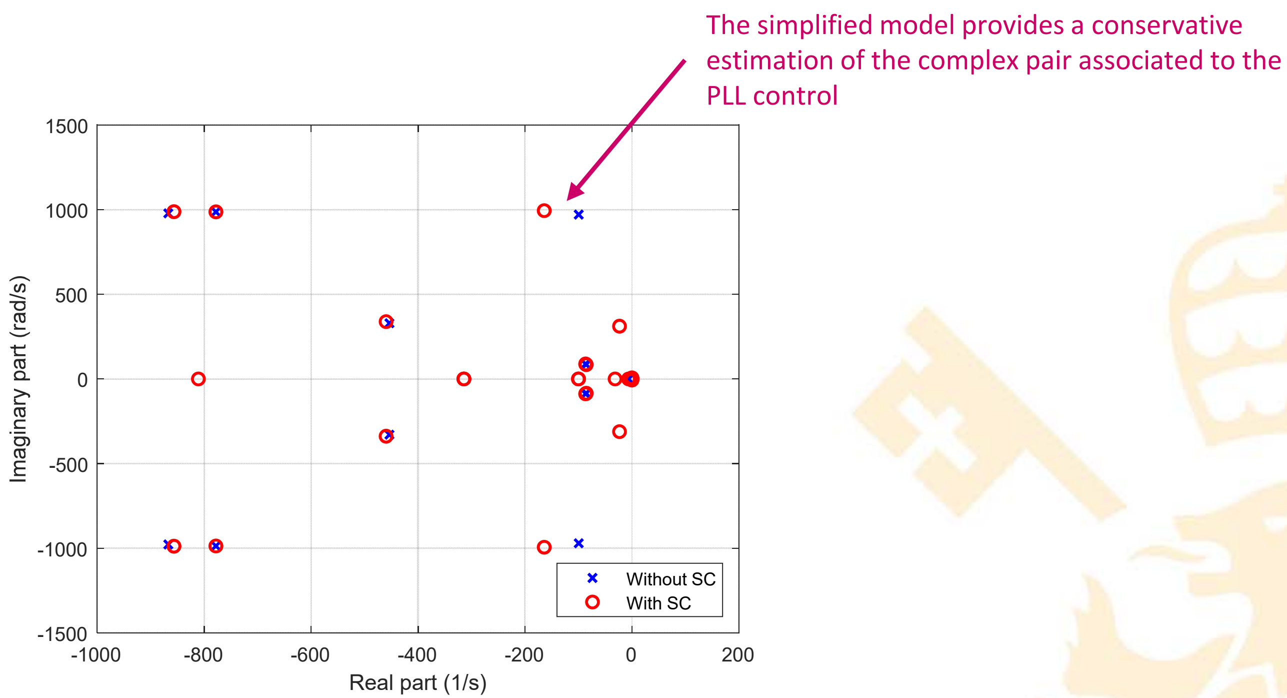
The complex pair associated to the PLL control becomes stable as the grid impedance increases due to the synchronous compensator action



In addition, no adverse interaction with the synchronous compensator controls has been observed

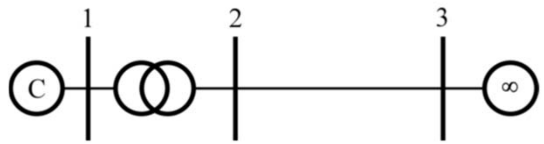
Contribution to the stability of grid-feeding converters

- Type 4 wind generator without and with synchronous compensator for the same equivalent short circuit ratio



Contribution to the damping electromechanical oscillations

- Electromechanical (local) oscillation of a synchronous compensator



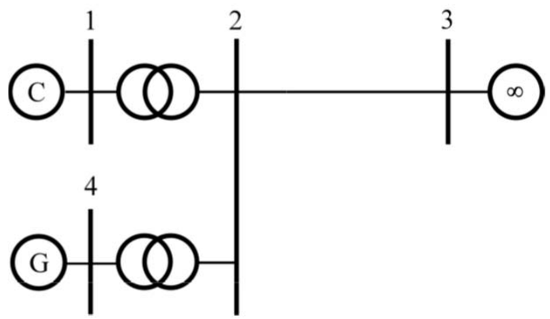
Complex eigenvalues						
					Variable with greatest participation	
No.	Real (1/s)	Imaginary (rad/s)	Damping (%)	Frequency (Hz)	Variable name	Device bus number
1,2	-2.0703	±4.7051	40.274	0.8181	omega	1
3,4	-0.8447	±0.6898	77.4561	0.1736	exc2	1

Real eigenvalues				
			Variable with greatest participation	
No.	Real (1/s)	Time constant (s)	Variable name	Device bus number
5	-1.5887	6.29E-01	psikq1	1
6	-35.9843	2.78E-02	psikq2	1
7	-36.5797	2.73E-02	psikd	1
8	-99.6694	1.00E-02	exc1	1

Participation factors		
Variable name	Device bus number	Magnitude
delta	1	0.6473
omega	1	0.6473
psifd	1	0
psikd	1	0
psikq1	1	0.2566
psikq2	1	0.1481
exc1	1	0
exc2	1	0

Contribution to the damping electromechanical oscillations

- Electromechanical (local) oscillations of a synchronous compensator in parallel with a synchronous compensator



Contribution to the damping electromechanical oscillations

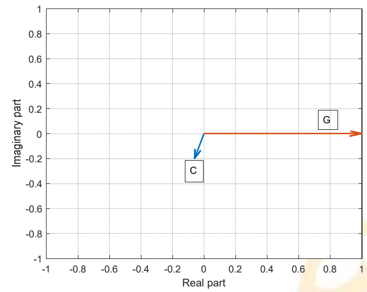
- Electromechanical (local) oscillations of a synchronous compensator in parallel with a synchronous compensator

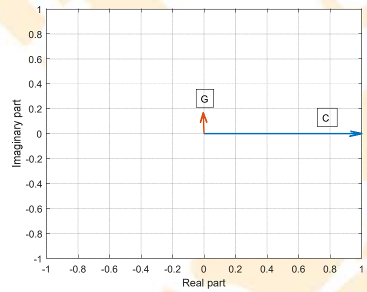
Complex eigenvalues

No.	Real (1/s)	Imaginary (rad/s)	Damping (%)	Frequency (Hz)	Variable with greatest participation: Variable name	Variable with greatest participation: Device bus number
1,2	-0.2134	±5.9316	3.5946	0.9446	omega	4
3,4	-1.9209	±4.6469	38.2014	0.8003	omega	1
5,6	-0.8528	±0.7193	76.4412	0.1776	exc2	1
7,8	-0.3949	±0.6557	51.5954	0.1218	exc2	4
9,10	-35.4866	±0.2513	99.9975	5.648	psikq2	1

Real eigenvalues

No.	Real (1/s)	Time constant (s)	Variable with greatest participation: Variable name	Variable with greatest participation: Device bus number
11	-0.1424	7.02E+00	gov3	4
12	-1.8103	5.52E-01	psikq1	1
13	-3.1985	3.13E-01	gov2	4
14	-5.4702	1.83E-01	psikq1	4
15	-10.1618	9.84E-02	gov1	4
16	-37.8119	2.64E-02	psikd	1
17	-38.1773	2.62E-02	psikq2	4
18	-99.6802	1.00E-02	exc1	1
19	-99.8816	1.00E-02	exc1	4



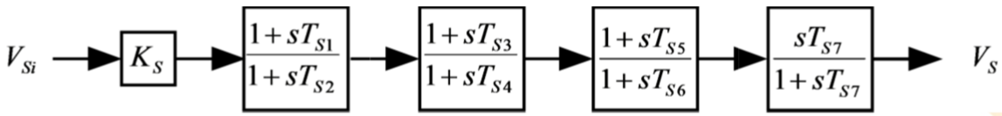


Mode shapes

Contribution to the damping electromechanical oscillations

- Electromechanical (local) oscillations of a synchronous compensator in parallel with a synchronous compensator

Residues		
Device bus number	Magnitude (pu)	Angle (º)
1	0.000657	16.46
4	0.030104	84.07



KS (pu)	TS1=TS3=TS5 (s)	TS2=TS4=TS6 (s)	TS7 (s)
35.7603	0.5172	0.055	5

Contribution to the damping electromechanical oscillations

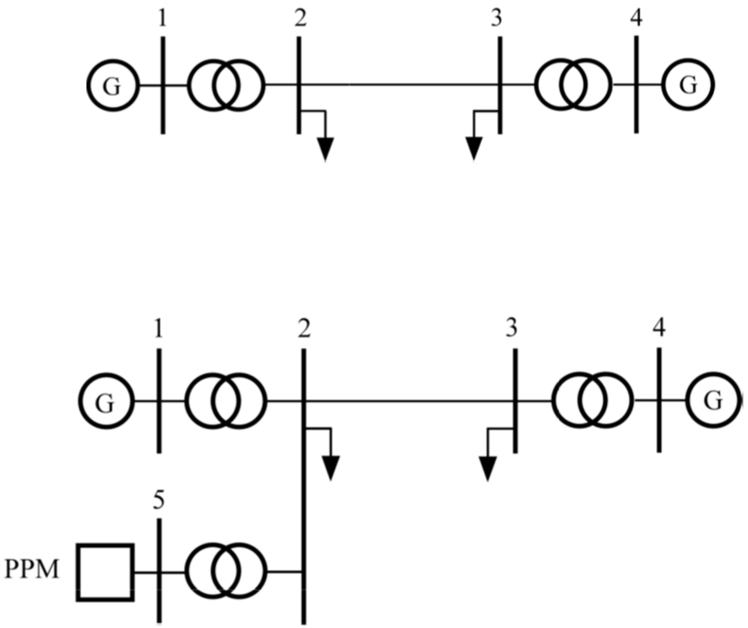
- Electromechanical (local) oscillations of a synchronous compensator (with power system stabilizer) in parallel with a synchronous compensator

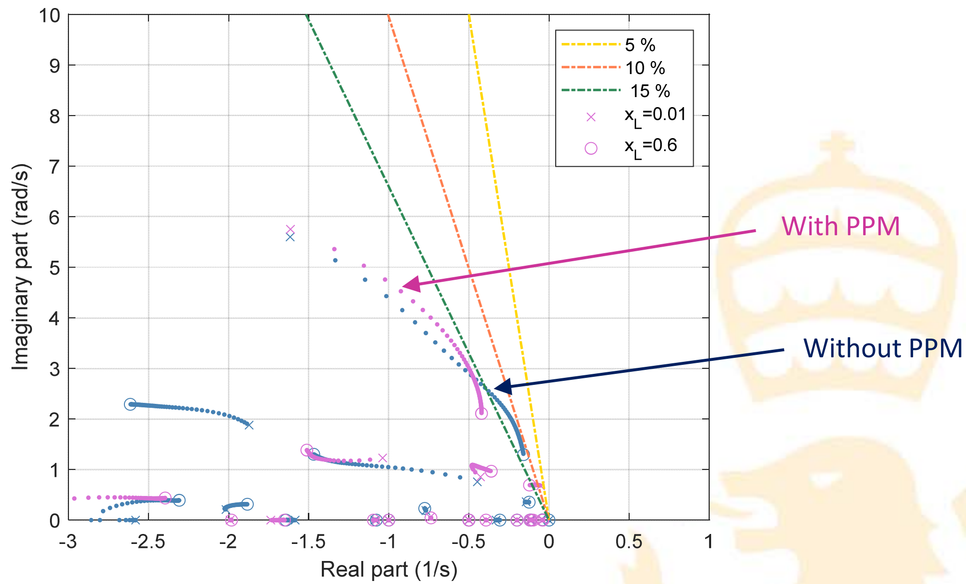
Complex eigenvalues						
					Variable with greatest participation	
No.	Real (1/s)	Imaginary (rad/s)	Damping (%)	Frequency (Hz)	Variable name	Device bus number
1,2	-1.1846	±5.9703	19.4623	0.9687	omega	4
3,4	-41.5098	±4.9514	99.2961	6.6533	psikq2	4
	-1.3017	±4.8365	25.9884	0.7971	omega	1
	-14.4952	±4.7523	95.0234	2.4278	sta3	1
5,6	-32.3268	±4.4619	99.0608	5.1937	psikd	4
7,8	-0.8521	±0.7207	76.3506	0.1776	exc2	1
9,10	-0.3954	±0.6559	51.6295	0.1219	exc2	4

Real eigenvalues				
			Variable with greatest participation	
No.	Real (1/s)	Time constant (s)	Variable name	Device bus number
15	-1.42E-01	7.02E+00	gov3	4
16	-2.00E-01	5.00E+00	sta4	1
17	-1.81E+00	5.52E-01	psikq1	1
18	-3.20E+00	3.13E-01	gov2	4
19	-5.43E+00	1.84E-01	psikq1	4
20	-10.243	9.76E-02	gov1	4
21	-24.1029	4.15E-02	psikd	4
22	-99.6699	1.00E-02	exc1	1
23	-99.8852	1.00E-02	exc1	4

Contribution to the damping electromechanical oscillations

- Inter-area oscillations in presence of inverter-based generation





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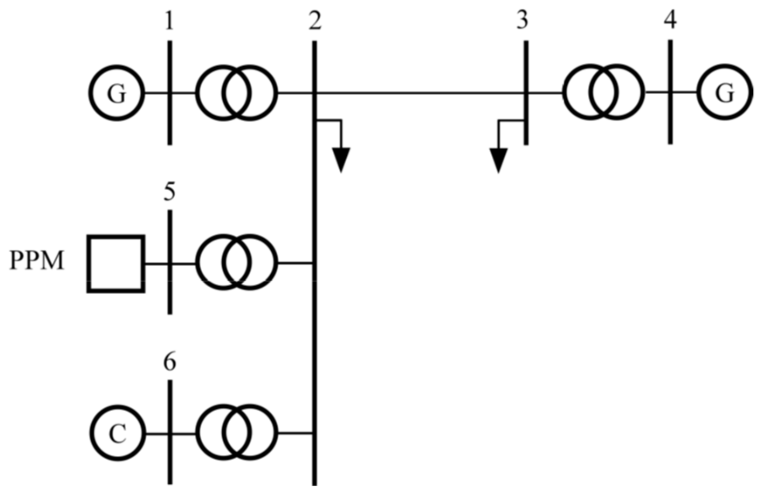
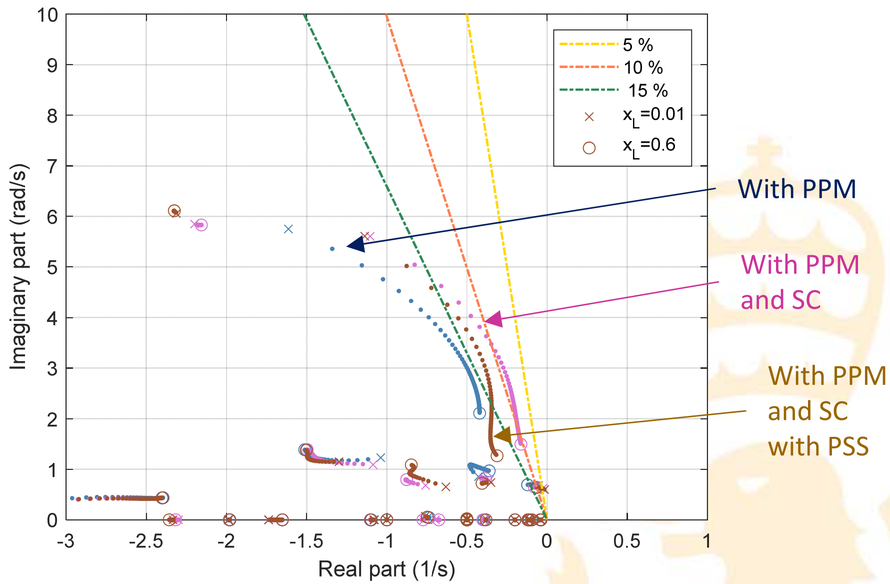
Contribution to the damping electromechanical oscillations

- Inter-area oscillations in presence of inverter-based generation





Conclusions

- Contribution to the stability of grid-feeding converters
  - The synchronous compensator contributes to the stability of the PLL eigenvalue pair without imparing the overall system stability
  - The contribution is robust with respect to the type of wind generator (either type 3 or type 4 wind generators)

Conclusions

- Contribution to the damping electromechanical oscillations
  - A synchronous compensator connected to an infinite bus exhibits a rotor oscillation that is well-damped but cannot be further damped with a power system stabilizer.
  - The installation of a power system stabilizer in a synchronous compensator can damp out the local oscillation of a synchronous compensator in parallel with a synchronous generator connected to an infinite bus.
  - Synchronous compensators can affect the damping of inter-area oscillations in the presence of inverter-based generation. Hence, they have to be equipped with power system stabilizers.

Acknowledgments

- Many thanks to my doctoral student Mr. Jorge Suárez Porras for providing the numerical results.