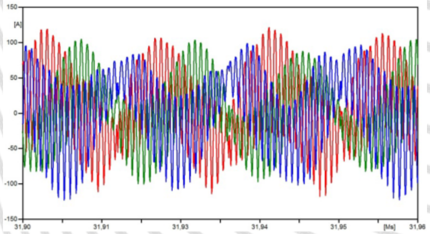

Harmonic Stability Analysis in Wind Farms

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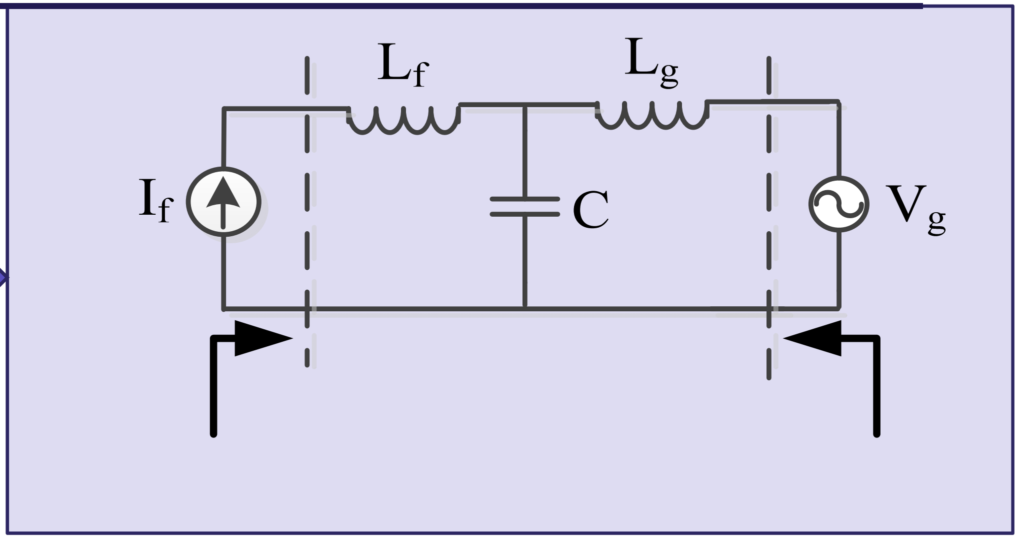
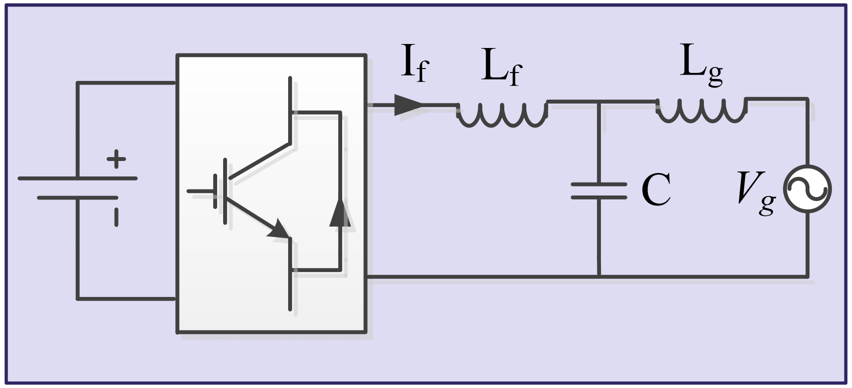
Outline

- **Introduction**
- **Stability analysis**
- **Time-domain simulation results**
- **Conclusion**

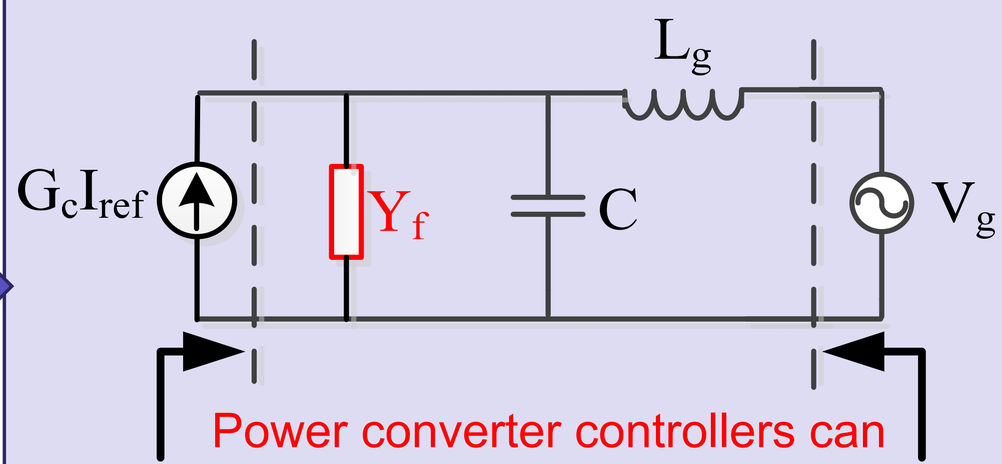
Introduction

An ideal model



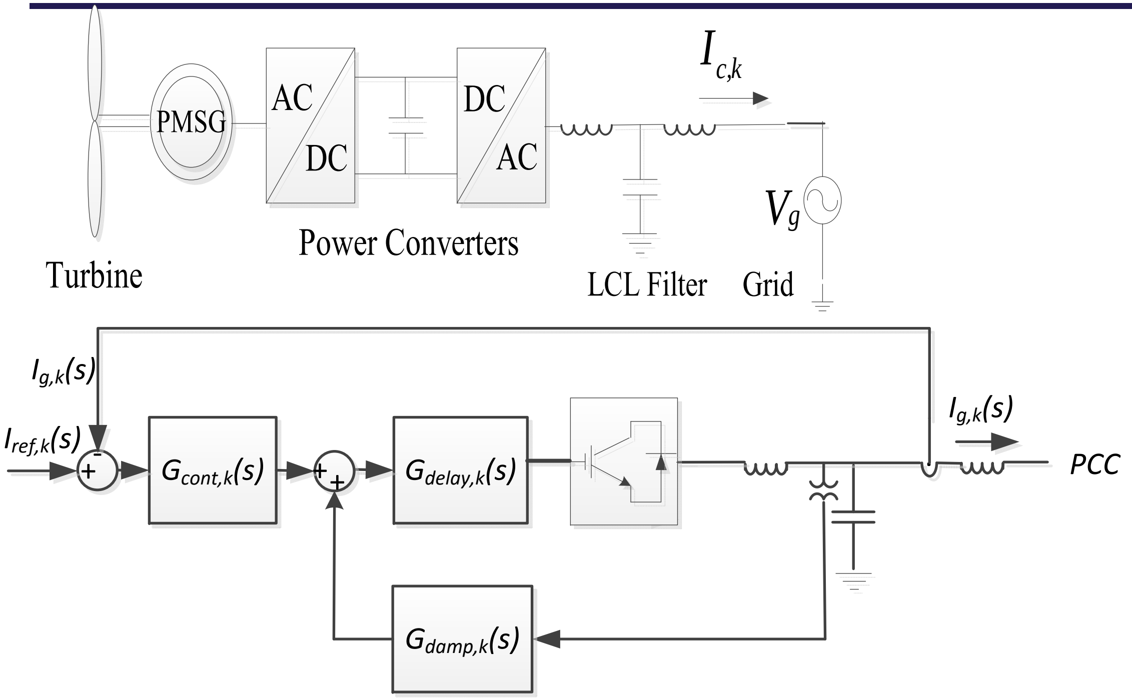


A model with considering the power converter controller



Power converter controllers can effect on stability

Grid-side power converter model



Proportional plus Resonant (PR) current controllers

$$G_c = K_p + \frac{K_i s}{s^2 + \omega_f^2}$$

$$G_{damp,k} = K_{d,k}$$

Approximated digital control delay

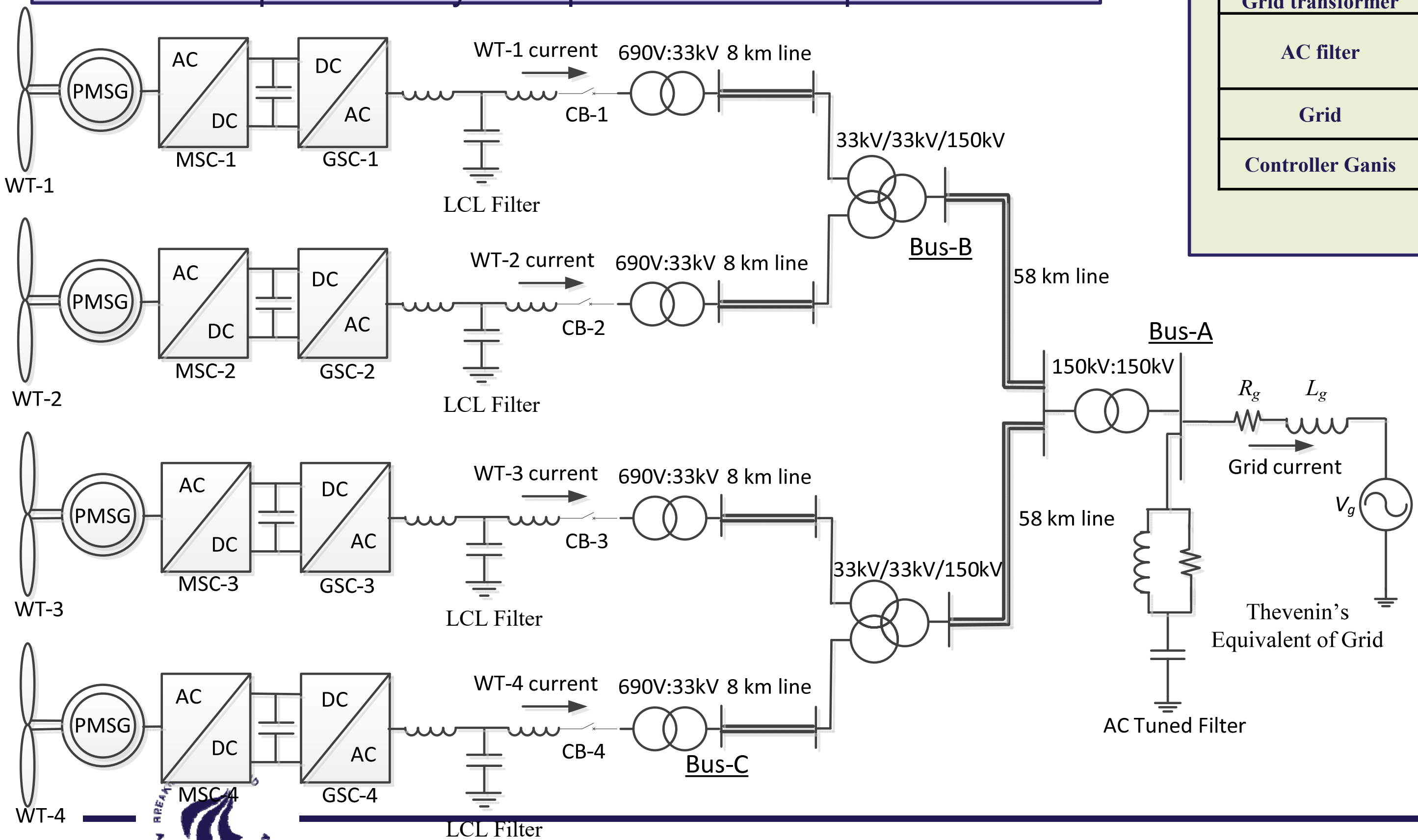
$$G_{pwm} = e^{-1.5T_s s} \approx \frac{1 - \frac{1.5T_s}{2}s + \frac{(1.5T_s)^2}{10}s^2 - \frac{(1.5T_s)^3}{120}s^3}{1 + \frac{1.5T_s}{2}s + \frac{(1.5T_s)^2}{10}s^2 + \frac{(1.5T_s)^3}{120}s^3}$$

400-MW wind power plant as a case study

- The network consists of four branches and each branch is represented by an aggregated 100-MW WT.
- The transformer is modeled by its short-circuit impedance.
- cables are modeled as a nominal π-model.
- Grid is represented by a simple Thévenin's equivalent circuit.

Parameter		Value (P.U.)
LCL filter	*Grid-side inductor*	8×10^{-4}
	Capacitor	40×10^{-6}
	WTG-side inductor	8×10^{-4}
WT transformer	*Leakage inductance*	3.18×10^{-4}
33 kV cable (8 km)	*Shunt capacitance*	7.841×10^{-6}
	Series inductance	1.802×10^{-4}
	Series resistance	0.022
Three-winding transformer	*Leakage inductance*	3.8×10^{-4}
150 kV cable (58 km)	*Shunt capacitance*	7.54×10^{-5}
	Series inductance	5.8×10^{-4}
	Series resistance	0.018
Grid transformer	*Leakage inductance*	4.46×10^{-4}
AC filter	*Resistance*	2
	Inductance	10.612×10^{-6}
	Capacitance	9.55×10^{-5}
Grid	*X/R ratio*	10
	SCR	5, 8, or 2
Controller Ganis	K_p	4
	K_i	1000

S_{base} = 450 MVA V_{base} = 150 kV f_b = 50 Hz



A large WPP as a MIMO control system

$$V_o(s) = G^{-1}(s)U_{ref}(s)$$

$$U_{ref}(s) = \begin{bmatrix} V_g(s) \\ I_{ref,1}(s) \\ \vdots \\ I_{ref,n}(s) \end{bmatrix}$$

$$G_1(s) = \begin{bmatrix} \frac{Y_{11}(s)}{Y_g(s)} & \frac{-Y_{12}(s)}{Y_g(s)} & \cdots & \frac{-Y_{1n}(s)}{Y_g(s)} \\ \frac{-Y_{21}(s)}{G_{c,2}(s)G_{pwm,2}(s)Y_k(s)} & \frac{Y_{22}(s)+G_{c,2}(s)G_{pwm,2}(s)Y_{2(n+1)}(s)Y_2(s)}{G_{c,2}(s)G_{pwm,2}(s)Y_2(s)} & \cdots & \frac{-Y_{2n}(s)}{G_{c,2}(s)G_{pwm,2}(s)Y_2(s)} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{-Y_{n1}(s)}{G_{c,n}(s)G_{pwm,n}(s)Y_n(s)} & \frac{-Y_{n2}(s)+G_{c,n}(s)G_{pwm,n}(s)Y_{n(n+m)}(s)Y_n(s)}{G_{c,n}(s)G_{pwm,n}(s)Y_n(s)} & \cdots & \frac{Y_{nn}(s)}{G_{c,n}(s)G_{pwm,n}(s)Y_n(s)} \end{bmatrix}$$

$$V_o(s) = \begin{bmatrix} V_1(s) \\ V_2(s) \\ \vdots \\ V_m(s) \end{bmatrix}$$

$$G_2(s) = \begin{bmatrix} \frac{-Y_{1(n+1)}(s)}{Y_g(s)} & \cdots & \frac{-Y_{1(n+m)}(s)}{Y_g(s)} \\ \frac{-Y_{2(n+1)}(s)-G_{c,2}(s)G_{pwm,2}(s)Y_{2(n+1)}(s)Y_2(s)}{G_{c,2}(s)G_{pwm,2}(s)Y_2(s)} & \cdots & \frac{-Y_{2(n+m)}(s)}{G_{c,2}(s)G_{pwm,2}(s)Y_2(s)} \\ \vdots & \ddots & \vdots \\ \frac{-Y_{n(n+1)}(s)}{G_{c,n}(s)G_{pwm,n}(s)Y_n(s)} & \cdots & \frac{-Y_{n(n+m)}(s)-G_{c,n}(s)G_{pwm,n}(s)Y_{2(n+m)}(s)Y_n(s)}{G_{c,n}(s)G_{pwm,n}(s)Y_n(s)} \end{bmatrix}$$

$$G_3(s) = \begin{bmatrix} -Y_{(n+1)1}(s) & -Y_{(n+1)2}(s) & \cdots & -Y_{(n+1)n}(s) \\ \vdots & \vdots & \ddots & \vdots \\ -Y_{(n+m)1} & -Y_{(n+m)2}(s) & \cdots & -Y_{(n+m)n}(s) \end{bmatrix} \quad G_4(s) = \begin{bmatrix} -Y_{(n+1)(n+1)}(s) & \cdots & -Y_{(n+1)(n+m)}(s) \\ \vdots & \ddots & \vdots \\ -Y_{(n+m)(n+1)}(s) & \cdots & -Y_{(n+m)(n+m)}(s) \end{bmatrix}$$

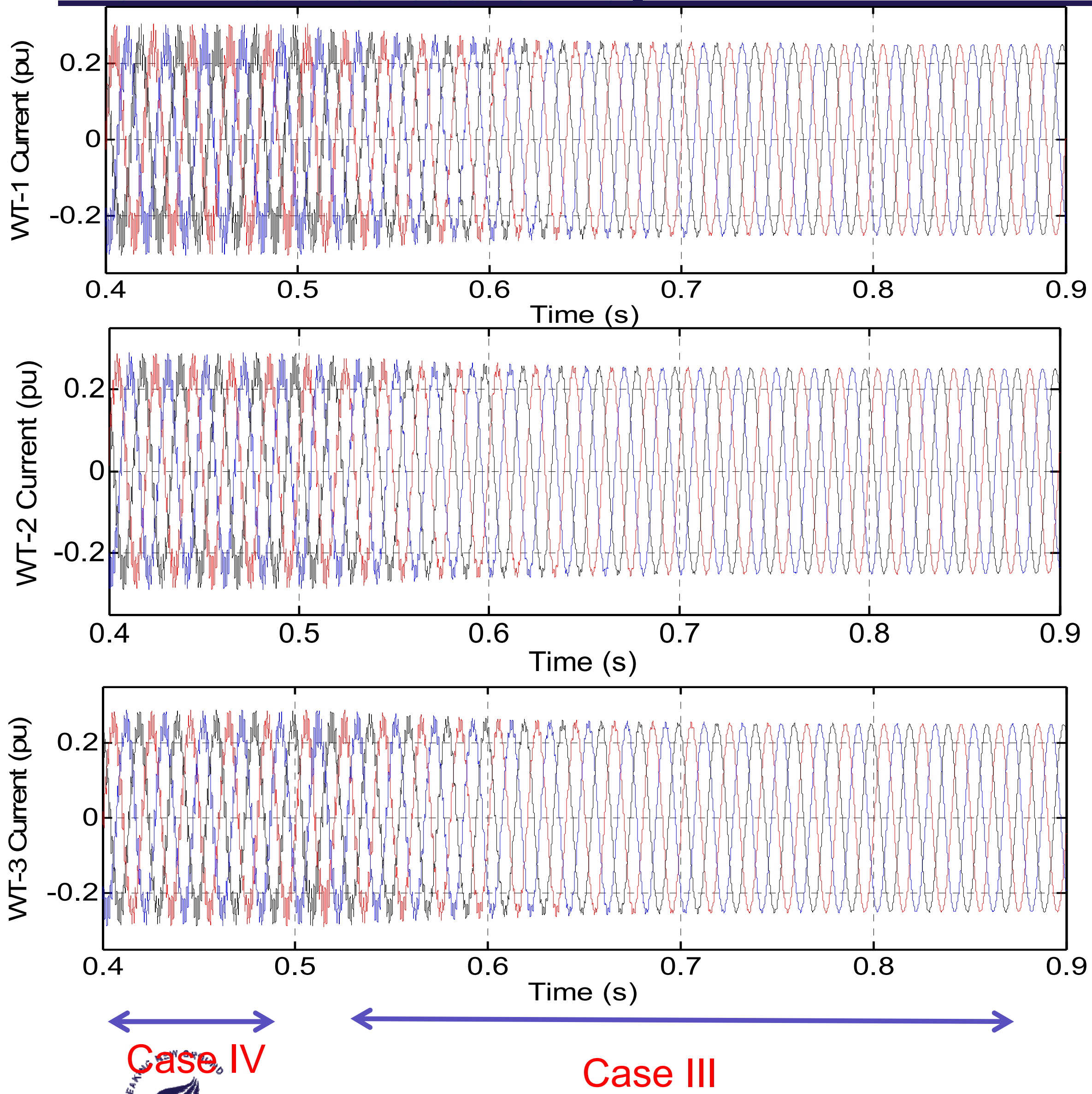
$$G(s) = \left[G_1(s) - G_4^{-1}(s)G_3(s) \right]$$

Influence of connection or disconnection of wind turbines on stability

- Case I: WT-1 is connected to the WPP and the other three WTs are disconnected.
- Case II: WT-1 and WT-2 are connected and other two WTs are disconnected.
- Case III: Only WT-4 is disconnected.
- Case IV: All WTs are connected.

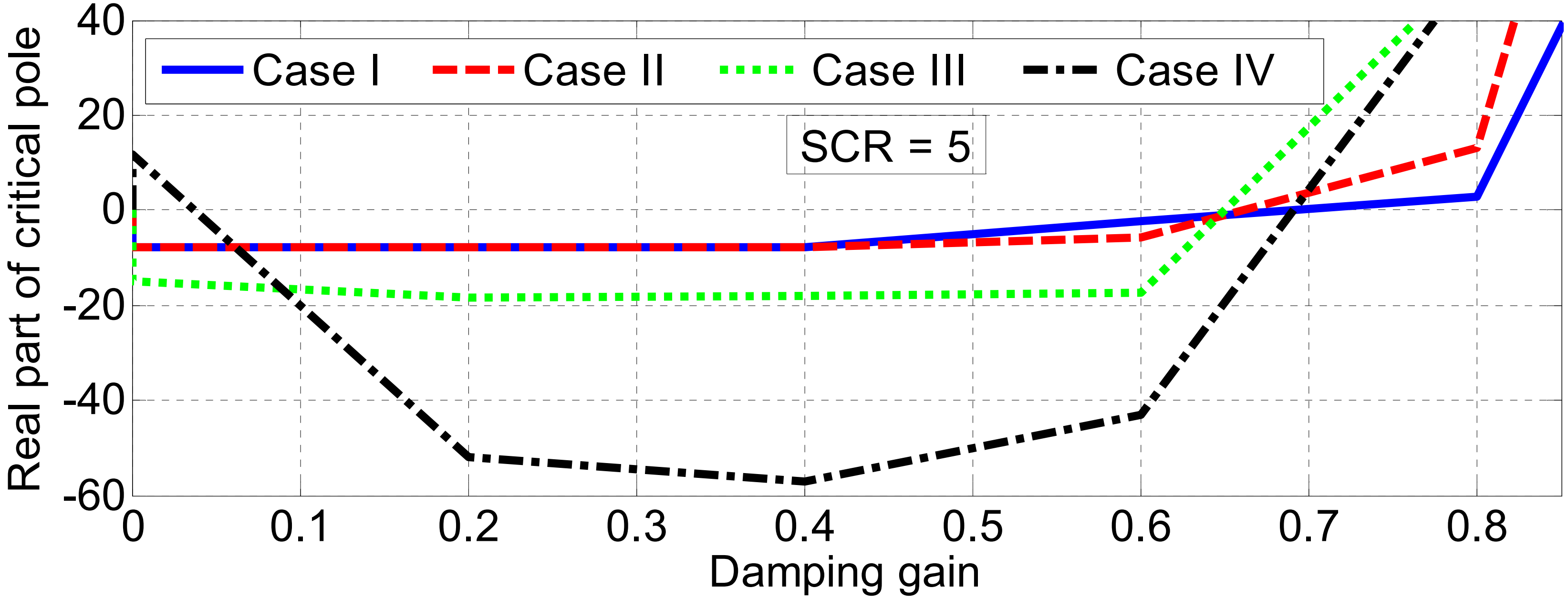
Case	connected wind turbines in WPP	Critical pole	Frequency
I	WT-1	-7.865±12173i	1937 Hz
II	WT-1 and WT-2	-7.865±12173i	1937 Hz
III	WT-1, WT-2, and WT-3	-14.977±5068.2i	806 Hz
IV	WT-1, WT-2, WT-3, and WT-4	11.659 ±5267.1i	838 Hz

Influence of the number of wind turbines on harmonic stability



Case	Critical pole
I	-7.865
II	-7.865
III	-14.977
IV	11.659

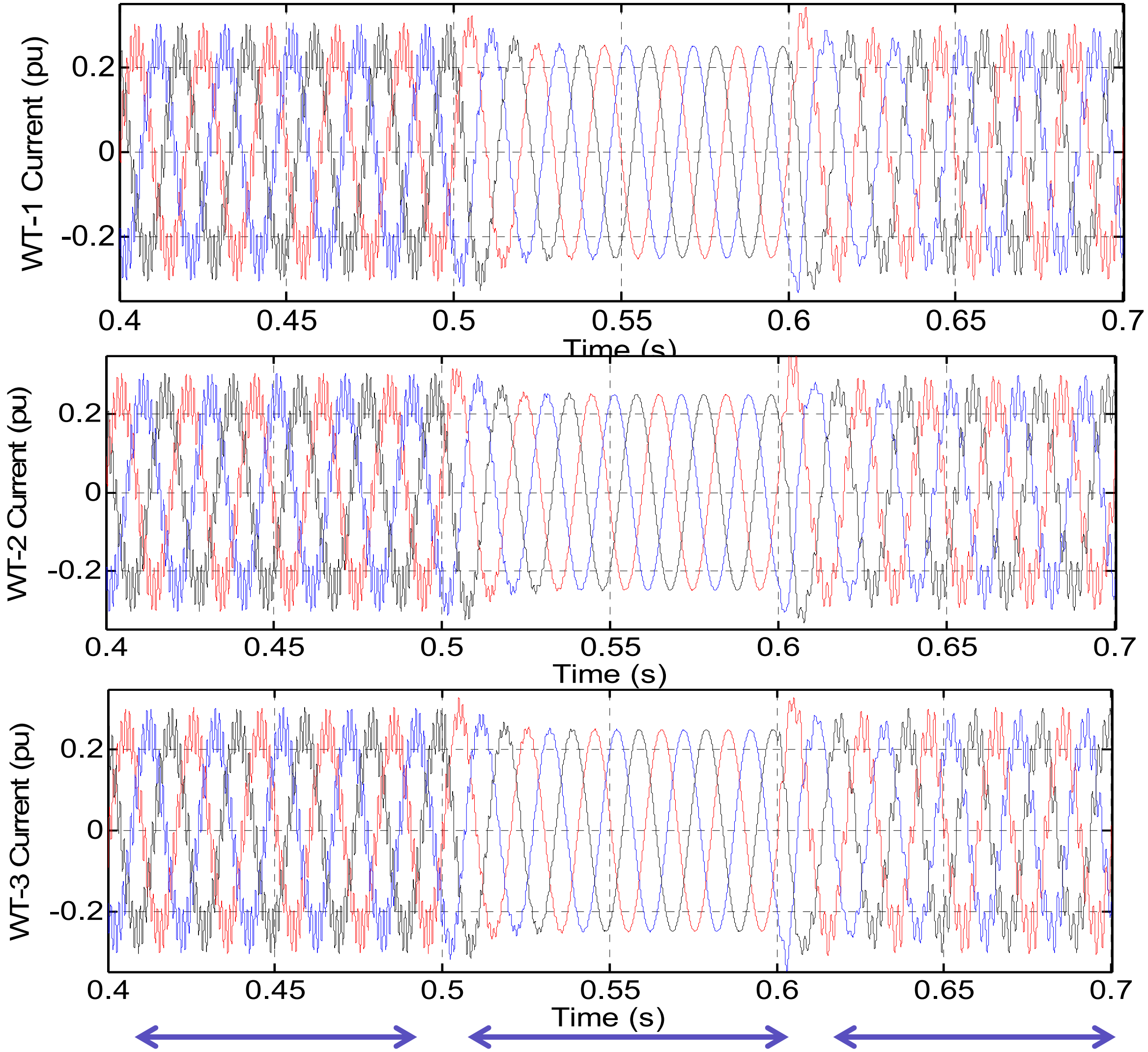
Influence of the active damping on harmonic stability



Real part of the critical pole in terms of damping controller gain (K_d) for different cases under SCR = 5.

$$G_{\mathrm{damp},k} = K_d$$

Influence of the active damping on harmonic stability

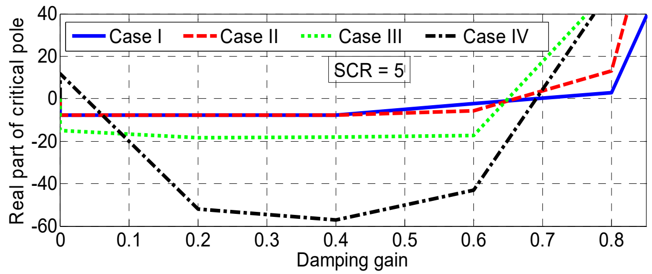


Kd = 0

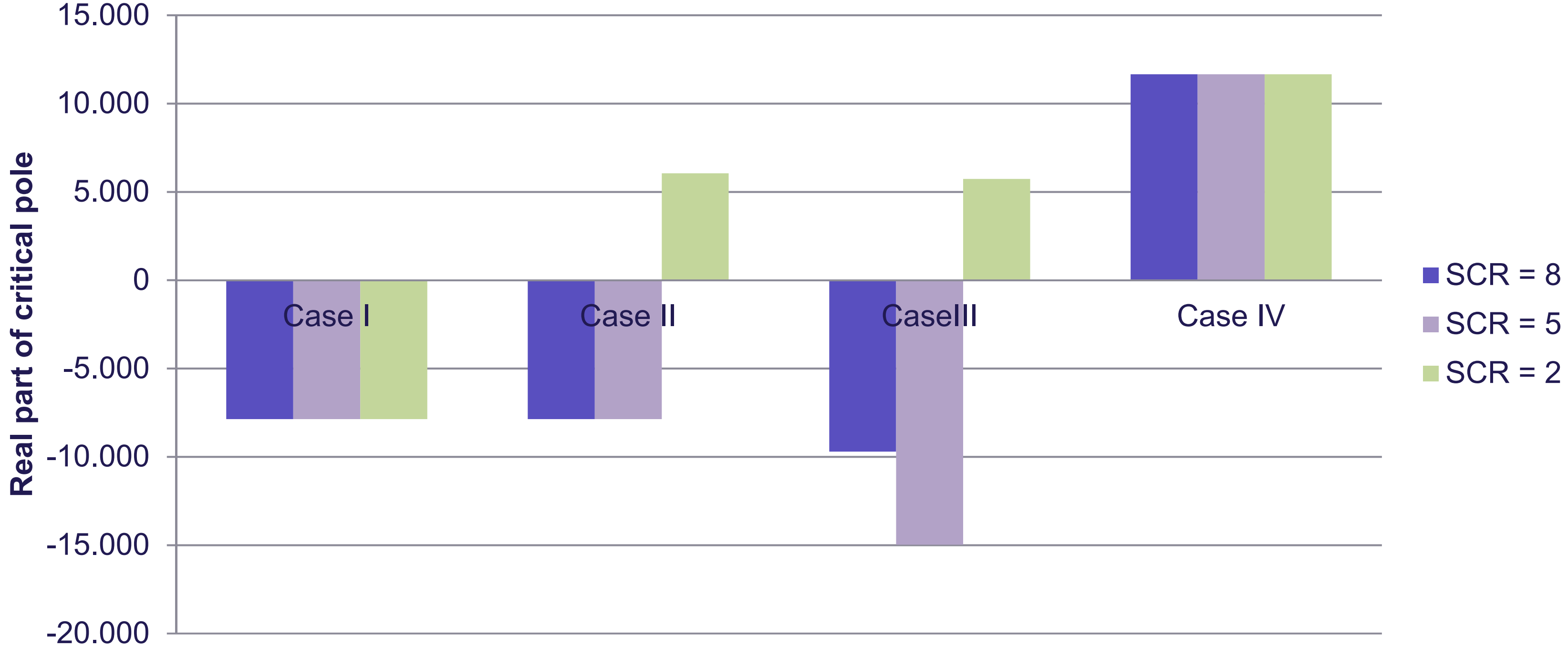
Kd = 0.3

Kd = 0.75

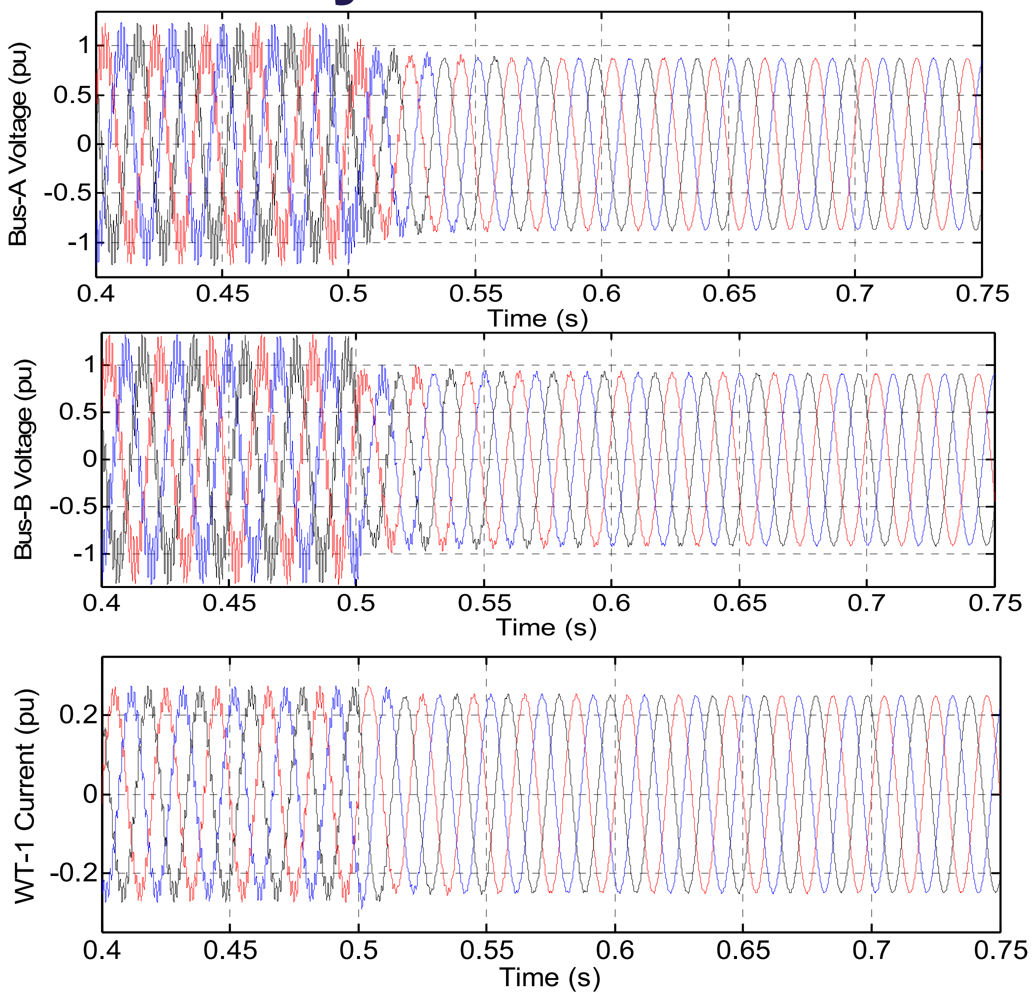
Case	Critical pole
I	-7.865
II	-7.865
III	-14.977
IV	11.659



Influence of grid impedance variations on stability

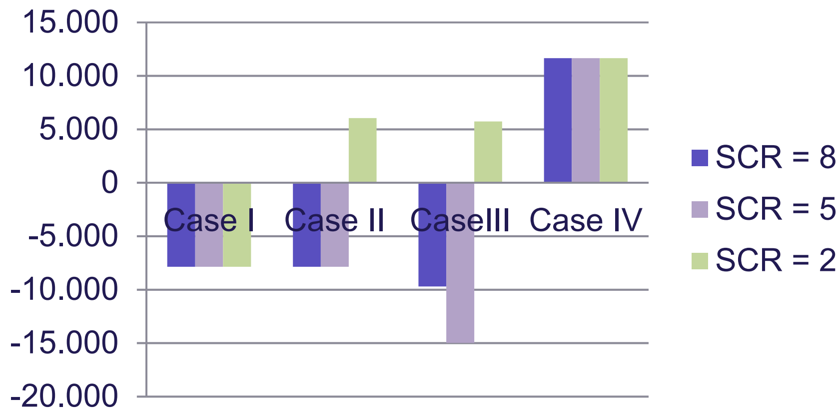


Influence of grid impedance variations on stability

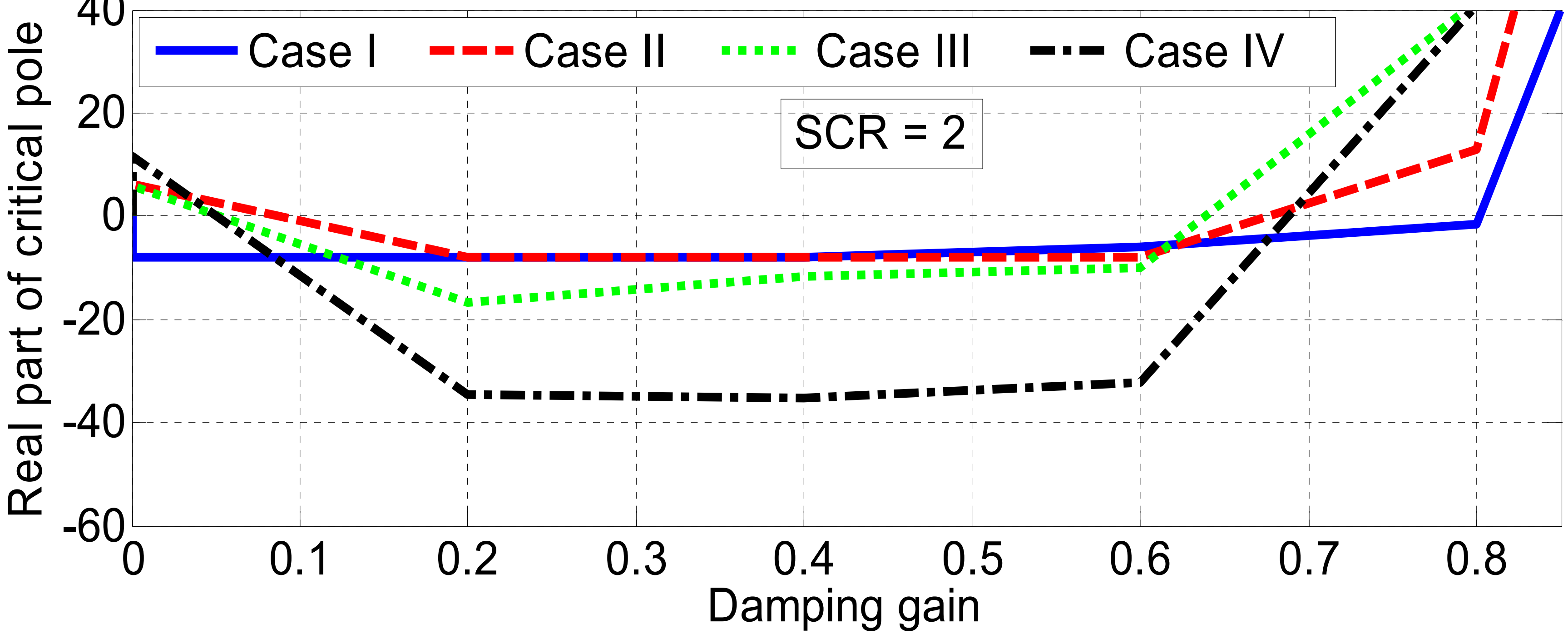


SCR = 2

SCR = 5



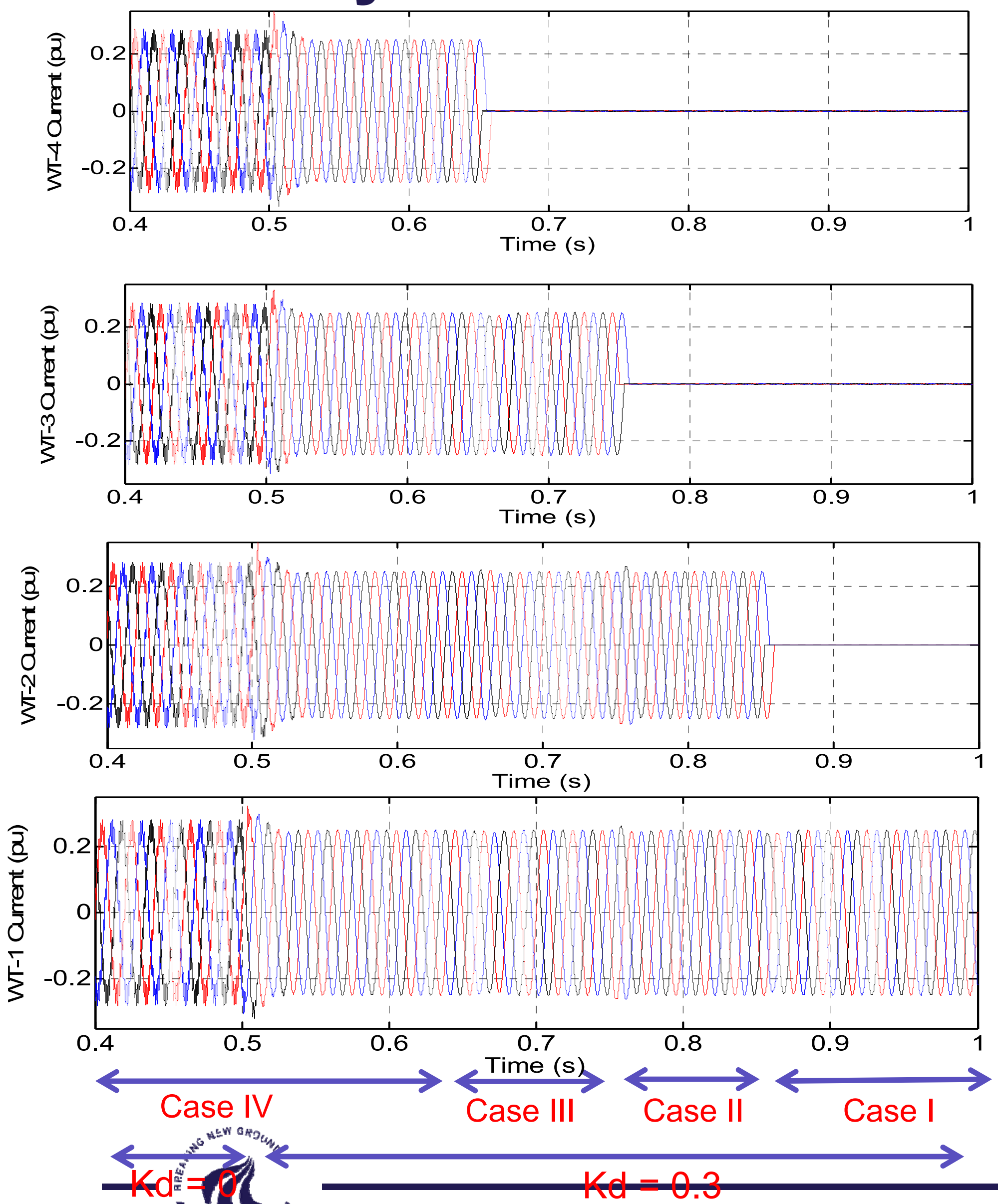
Influence of the active damping on harmonic stability

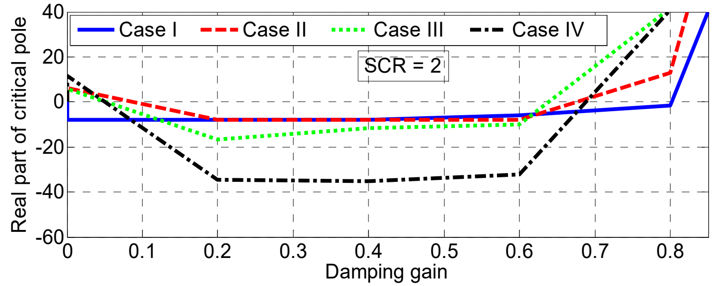


Real part of the critical pole in terms of damping controller gain (K_d) for different cases under SCR = 2.

$$G_{\text{damp},k} = K_d$$

Influence of the active damping on harmonic stability





Conclusion

- Both controller parameters of power converters and passive components of wind power plants can effect on harmonic stability.
- Connecting or disconnecting of the wind turbines in a wind power plant can vary the stability conditions.
- Impedance variations of main grid may change the stability of the system.
- Future work: Sensitivity analysis respect to the wind farm elements

Thanks for your attention