Small scale
Harmonic Power System Stability

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- Effect of equivalent resistance
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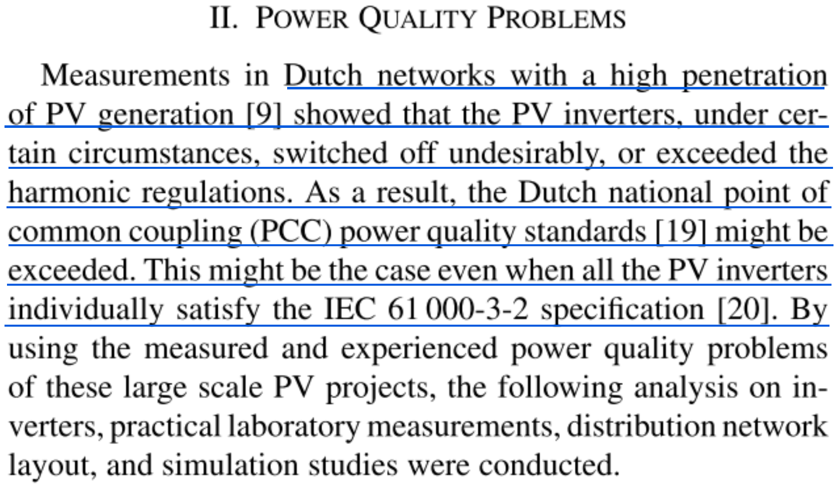
Harmonic interaction problem

Fig. 1. Roofmounted Dutch PV Suburb, Nieuwland, Amersfoort.

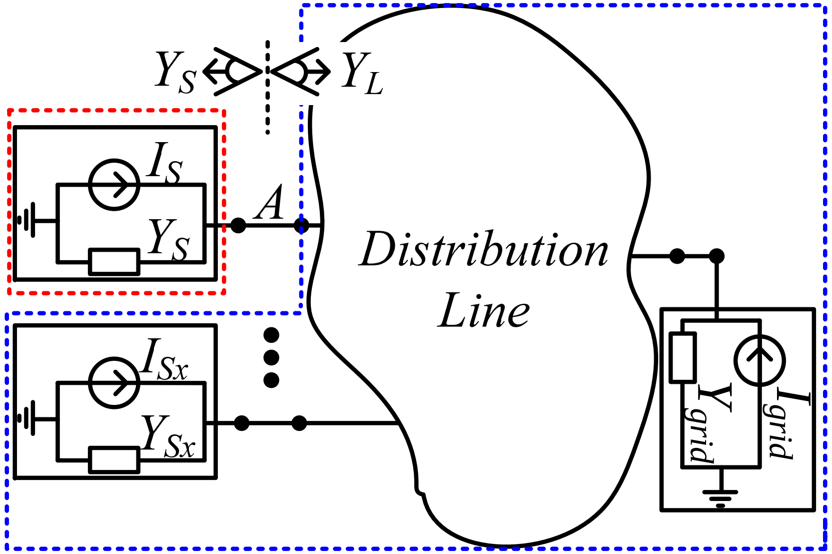


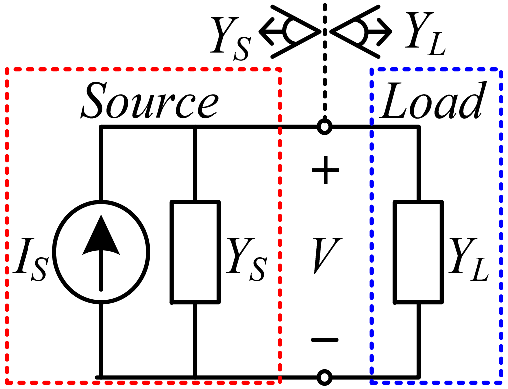
II. POWER QUALITY PROBLEMS

Measurements in Dutch networks with a high penetration of PV generation [9] showed that the PV inverters, under certain circumstances, switched off undesirably, or exceeded the harmonic regulations. As a result, the Dutch national point of common coupling (PCC) power quality standards [19] might be exceeded. This might be the case even when all the PV inverters individually satisfy the IEC 61 000-3-2 specification [20]. By using the measured and experienced power quality problems of these large scale PV projects, the following analysis on inverters, practical laboratory measurements, distribution network layout, and simulation studies were conducted.

[1] J. H. R. Enslin and P. J. M. Heskes, “Harmonic Interaction Between a Large Number of Distributed Power Inverters and the Distribution Network,” *IEEE Trans. Power Electron.*, vol. 19, no. 6, pp. 1586–1593, Nov. 2004.

Impedance based model for the stability analysis

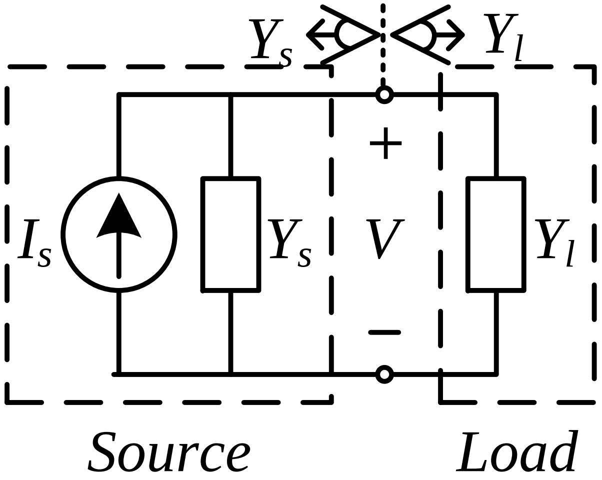


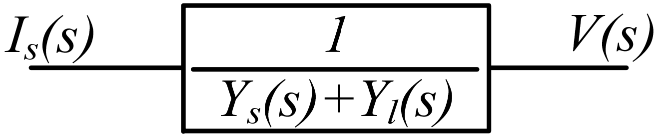


- Power system can be modeled as a lumped impedance model
- Distribution line can be represented as passive components
- Stability of the network can be obtained by analyzing the two interconnected lumped impedances

Stability analysis from the Nyquist plot

- Cauchy's argument principle can be used for observing closed loop unstable poles in the system.





$$N = Z - P$$

where, N : the number of encirclement on (0,0) of the Nyquist plot
Z : the number of unstable poles in the closed loop TF
P : the number of RHP poles in the Y_s+Y_l

[11] F. Liu, J. Liu, H. Zhang, and D. Xue, "Stability Issues of Z+Z Type Cascade System in Hybrid Energy Storage System (HESS)," IEEE Trans. Power Electron., vol. 29, no. 11, pp. 5846-5859, 2014.

Solutions for the harmonic interaction problem

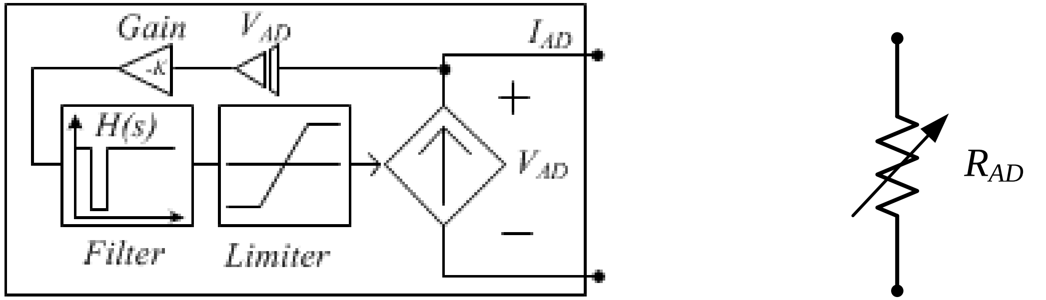
- Passive damping method
  - Simple and cheep, but limited for certain operating conditions
  - Low energy efficiency can be an issue

- Active damping method
  - Expensive, but adaptive to low order harmonics
  - Limited to the sampling frequency of the inverter

- Active damper
  - A specialized high frequency switching unit for harmonic interaction and resonance damping
  - Adaptive to wide range of frequencies up to several kilo-hertz
  - More complex and expensive

Active damper equivalent model

- Simplified Active damper equivalent model



(a) (b)

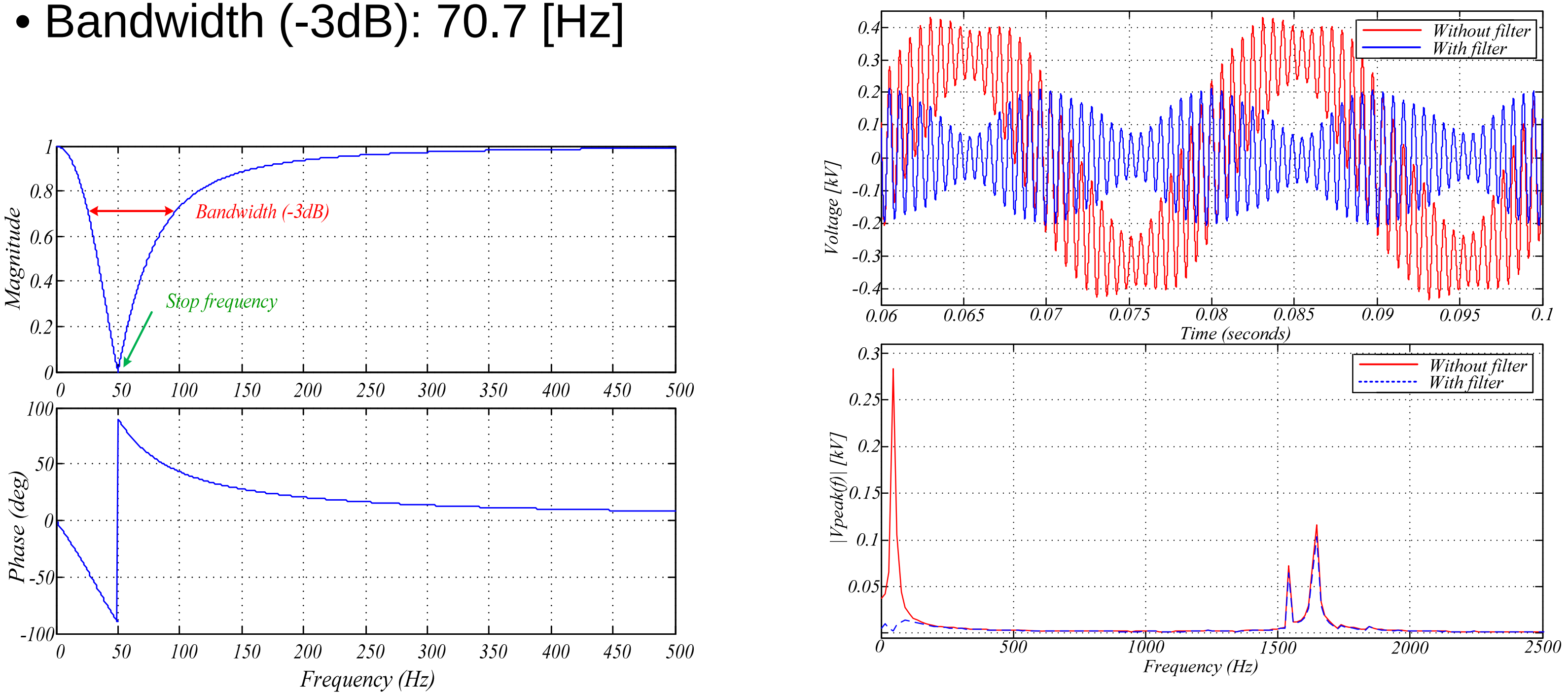
(a) Single-line diagram of the active damper model (b) Frequency dependent resistor.

$$H(s) = \frac{s^2 + \omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

$$R_{AD} = \frac{1}{K \cdot H(s)}$$

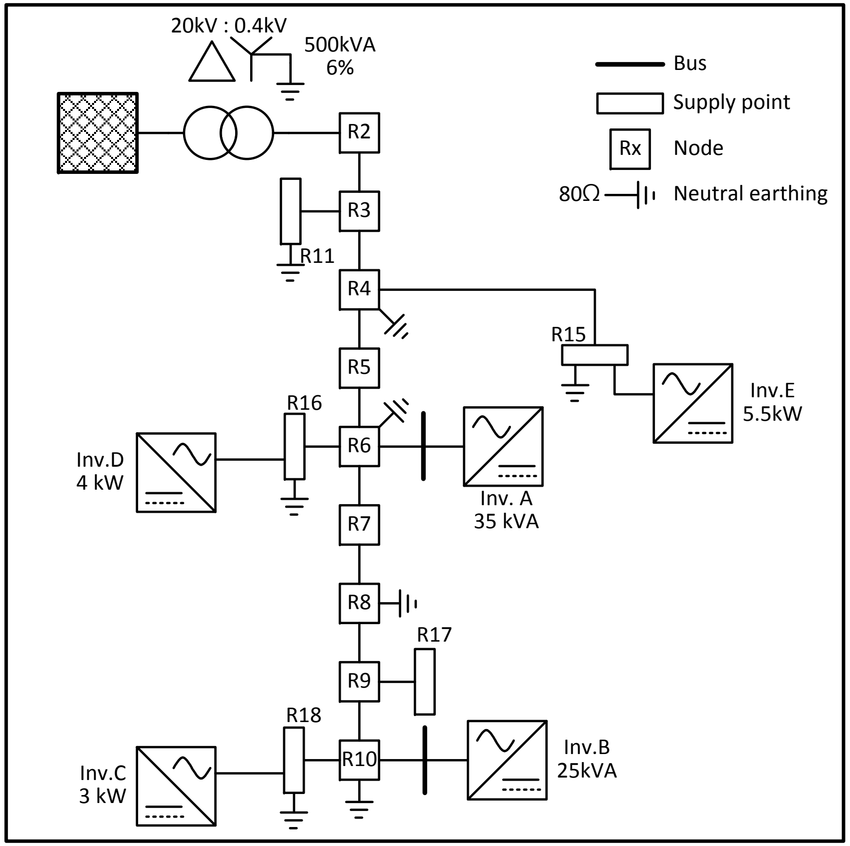
Notch filter design of the Active damper

- Stop frequency: 50 [Hz]
- Damping ratio: 0.707
- Bandwidth (-3dB): 70.7 [Hz]



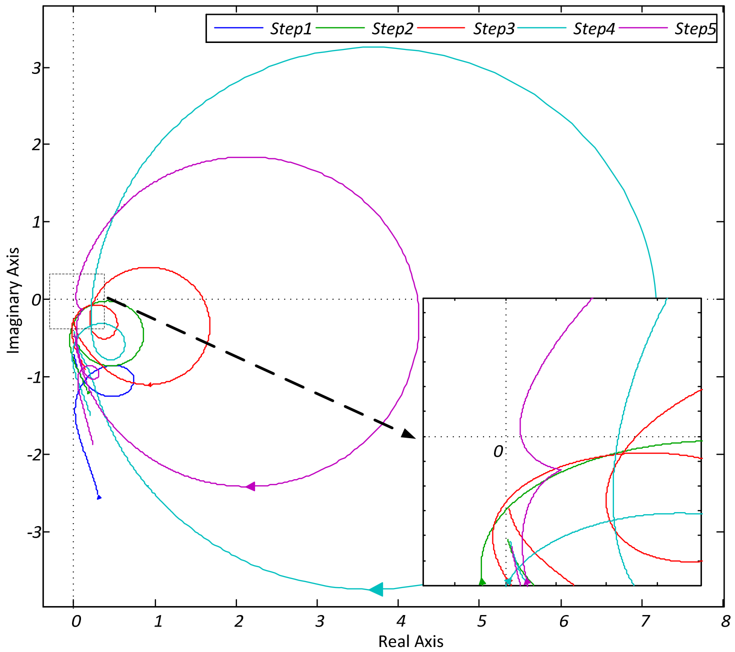
Notch filter response f active damper: (a) Bode plot,
(b) Time domain response (upper) and its FFT (lower).

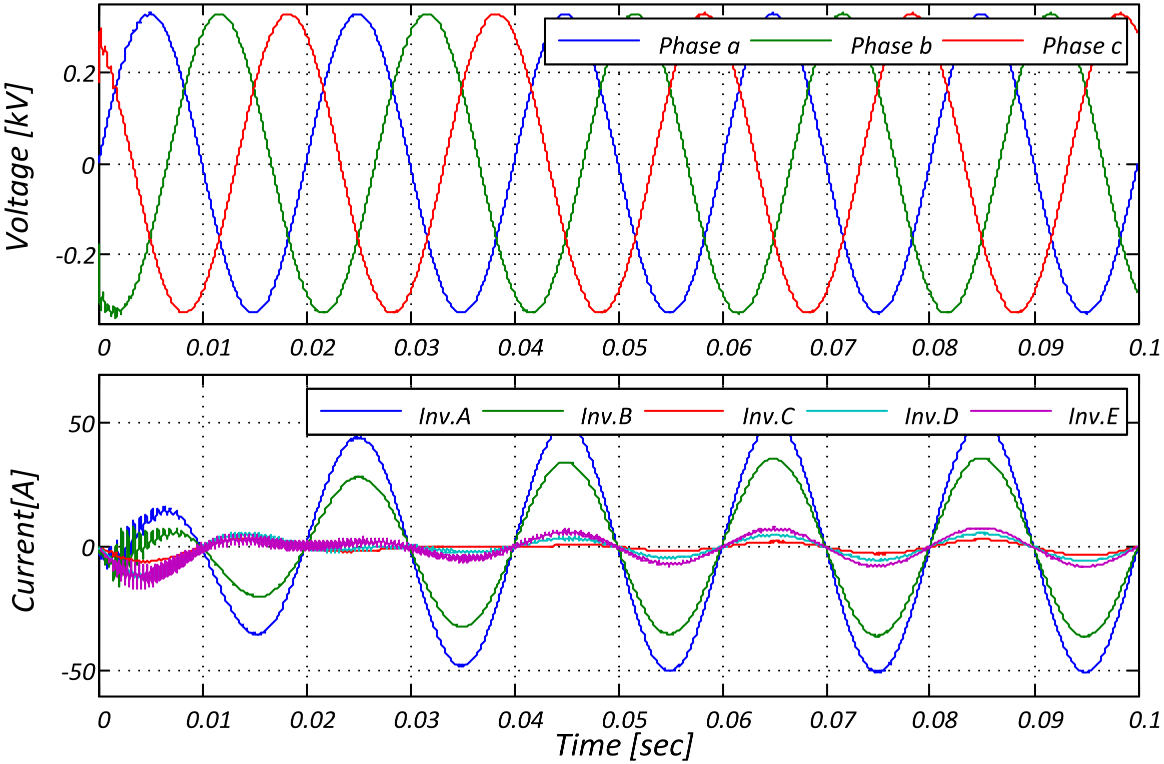
Benchmark system for the active damper placement analysis



“Benchmark Systems for Network Integration of Renewable and Distributed Energy Resources C06.04.02,” Cigré, 2014.

Stable network with five inverters at strong grid





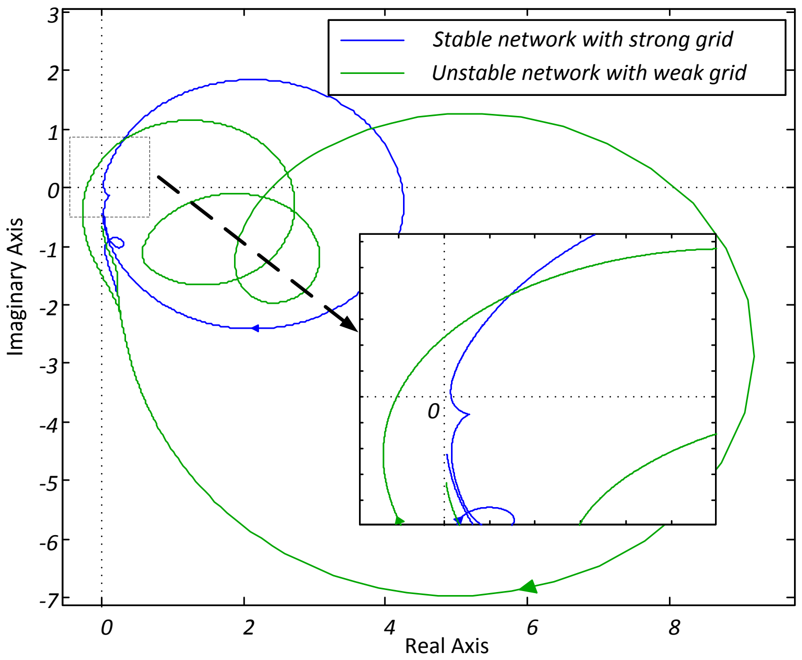
(a)

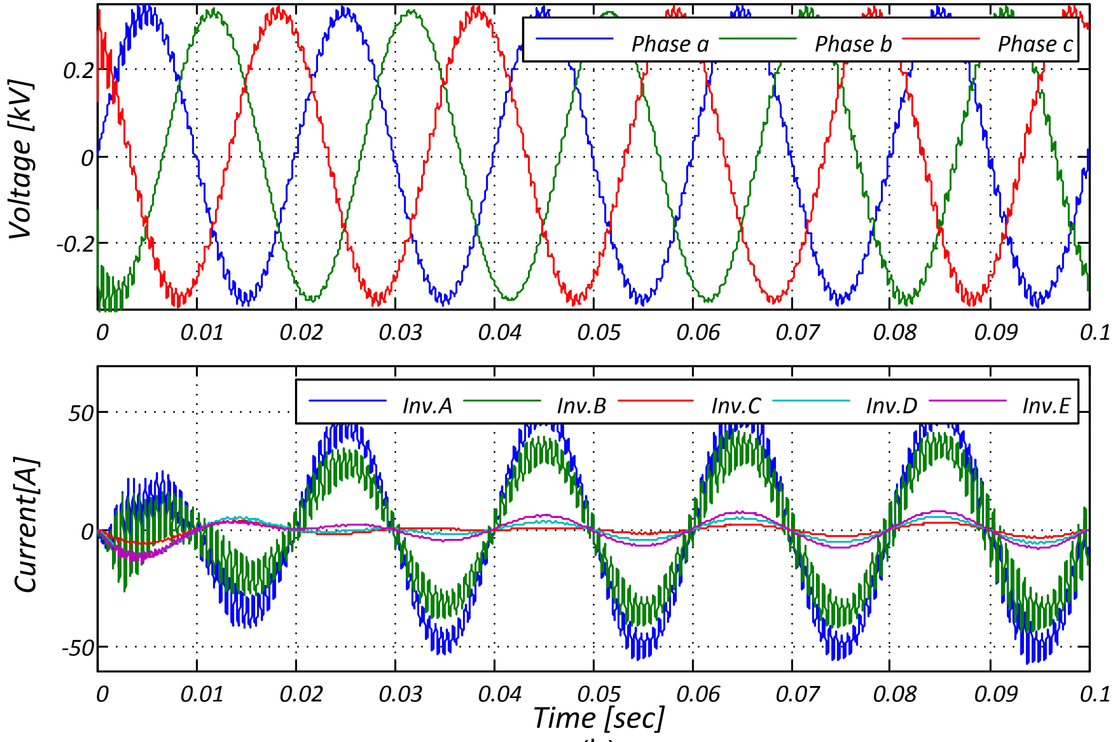
- Step by step stabilizing procedure can provide overall system stability for a certain grid condition (Inv.A → Inv.B → ⋯ → Inv.E)
  - Step1 (Inv.A with distribution line)
  - Step2 (Inv.B with distribution line + Inv.A)

    …

  - Step5 (Inv.E with distribution line + Inv.A ~ Inv.D)

Unstable network with weak grid condition

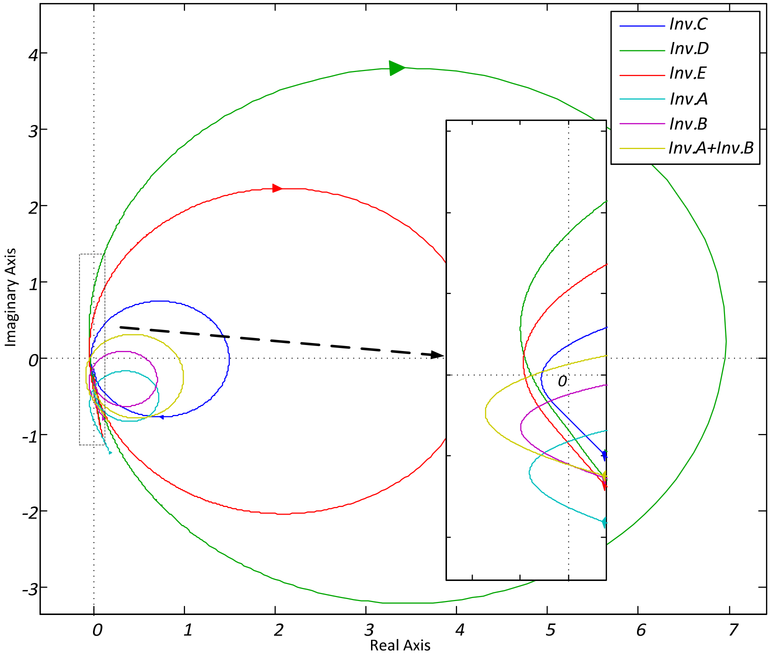


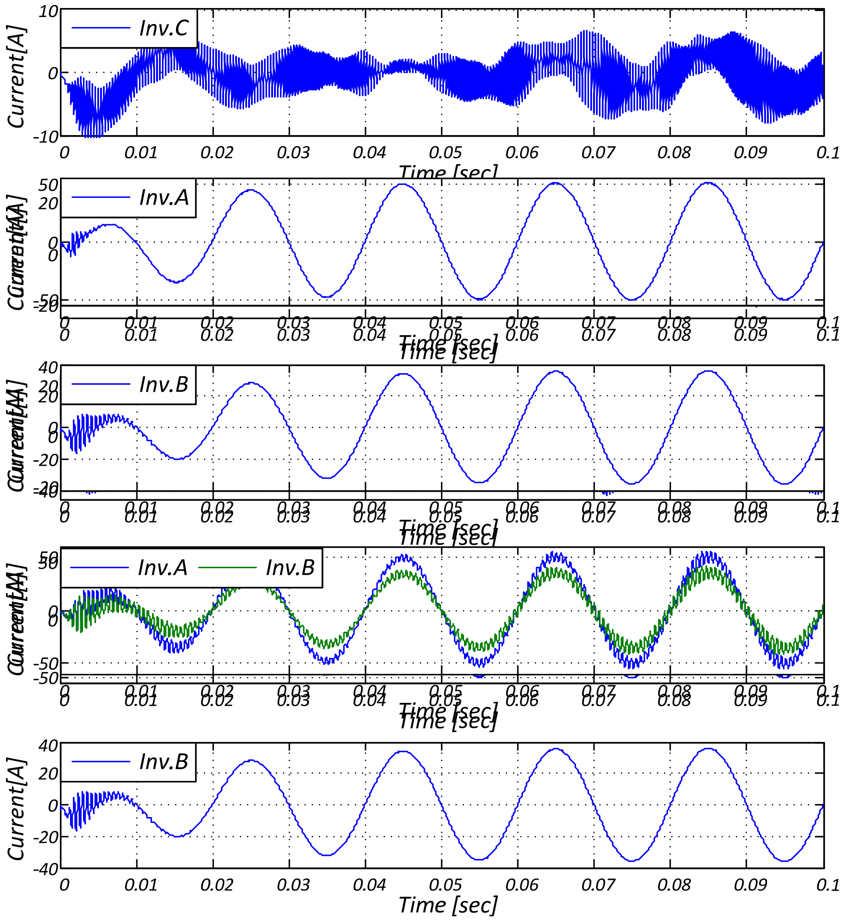


(b)

- System stability changes with varying grid impedance
- Overall network becomes unstable with weak grid condition

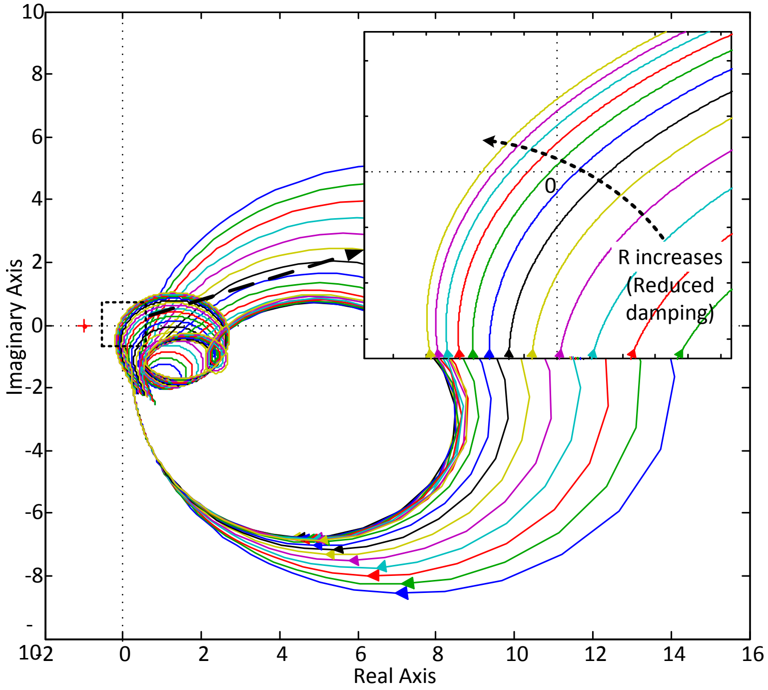
Destabilized inverters and interacting inverters





- Some of the inverters become unstable and some are stable
- For certain case, the interaction appears among inverters when they are operating together
  (Inv.A and Inv.B stable individually, Inv.A + Inv.B becomes unstable)

Applying damping solution for the unstable cases



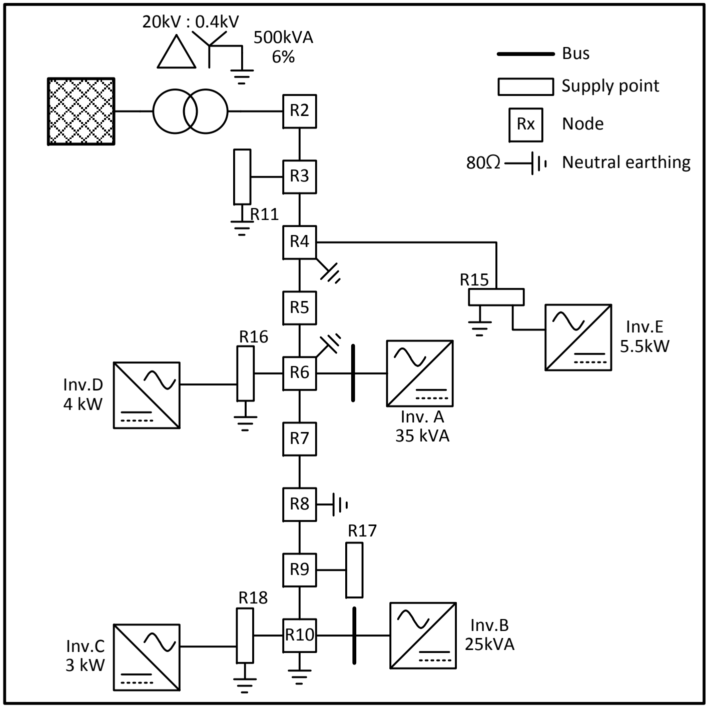
- Stability on node R4, when the active damper is placed at the node R16 with different values of the resistance (From 1 ohm to 30 ohms).

- An active damper for providing damping into the network can restore the destabilized inverters
- Parameter sweep can be used to find the necessary equivalent resistance for making a stable network

Damping resistance map for finding optimal place for the Active damper

		Node name							
		R3	*R4*	*R6*	*R9*	*R10*	*R15*	*R16*	*R18*
Inverter operating combination	{E}	*5.0*	*7.2*	*7.2*	*7.2*	*7.2*	*21.0*	*7.2*	*7.2*
	{D}	*5.0*	*8.6*	*14.7*	*12.3*	*12.3*	*7.2*	*25.0*	*12.3*
	{C}	*2.9*	*6.0*	*8.6*	*17.5*	*20.9*	*4.2*	*8.6*	*30.0*
	{A,B}	*5.0*	*7.2*	*14.7*	*21.0*	*25.1*	*7.2*	*14.7*	*25.1*
	{C, D, E}	*3.5*	*5.1*	*7.2*	*10.3*	*10.3*	*8.6*	*10.3*	*12.3*
	{A, B, C, D, E}	*4.2*	*7.2*	*12.3*	*17.5*	*21.0*	*7.2*	*12.3*	*21.0*
	{A}	*Stable*							
	{B}	*Stable*							
Ranking		8	7	5	3	2	6	4	1

- Possible inverter operating conditions ${}_5C_1 + {}_5C_2 + {}_5C_3 + {}_5C_4 + {}_5C_5 = 31$



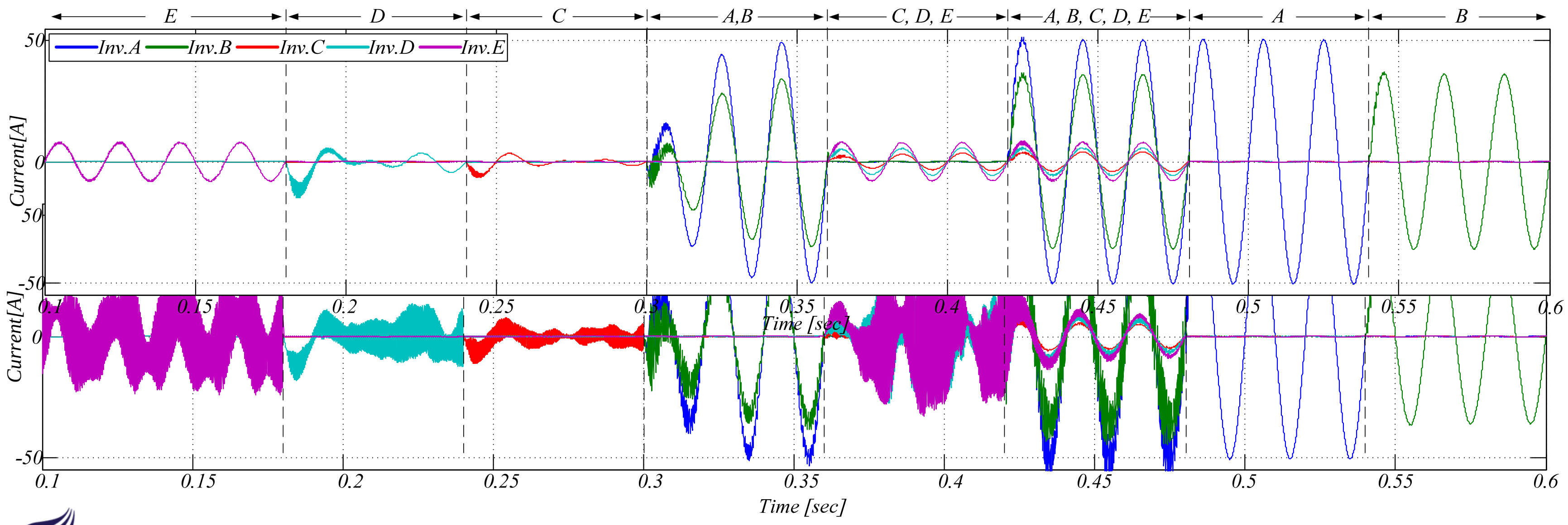
- Necessary damping resistances are measured and listed in the table for the different locations and different operating conditions of inverters
- The Active damper can be placed at each node
- The optimal site for all conditions can be ranked where the minimum damping is required.

Simulation verification for the analyzed result 1

- Active damper at the node R18 with the equivalent resistance of 7.2 ohm

- All the cases in the table are stabilized
- Without having the active damper at the node R18
- Only the cases {A} and {B} are stable

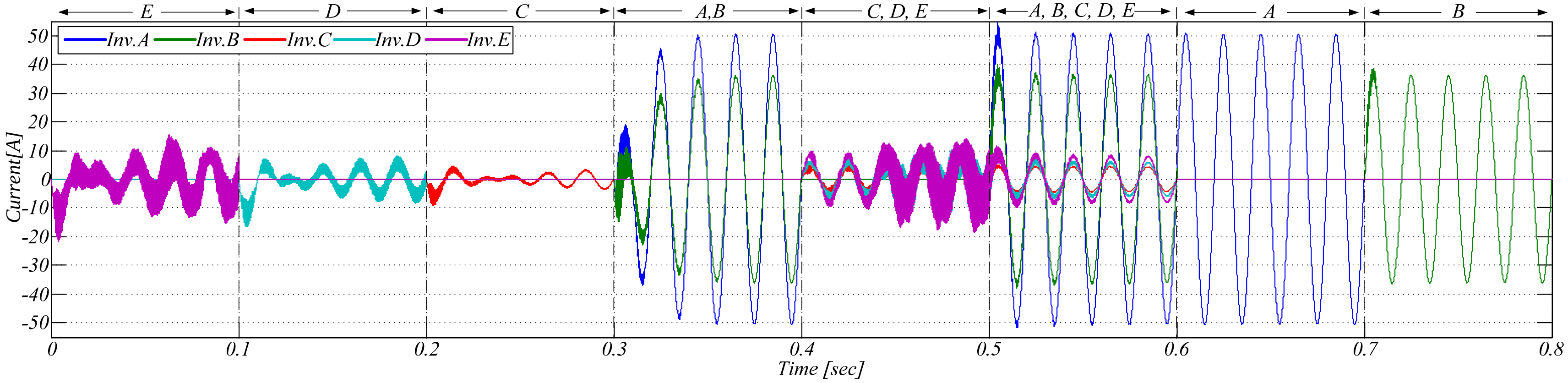
		Node name							
		R3	*R4*	*R6*	*R9*	*R10*	*R15*	*R16*	*R18*
Inverter operating combination	{E}	*5.0*	*7.2*	*7.2*	*7.2*	*7.2*	*21.0*	*7.2*	*7.2*
	{D}	*5.0*	*8.6*	*14.7*	*12.3*	*12.3*	*7.2*	*25.0*	*12.3*
	{C}	*2.9*	*6.0*	*8.6*	*17.5*	*20.9*	*4.2*	*8.6*	*30.0*
	{A,B}	*5.0*	*7.2*	*14.7*	*21.0*	*25.1*	*7.2*	*14.7*	*25.1*
	{C, D, E}	*3.5*	*5.1*	*7.2*	*10.3*	*10.3*	*8.6*	*10.3*	*12.3*
	{A, B, C, D, E}	*4.2*	*7.2*	*12.3*	*17.5*	*21.0*	*7.2*	*12.3*	*21.0*
	{A}	*Stable*							
	{B}	*Stable*							
Ranking		8	7	5	3	2	6	4	1



Simulation verification for the analyzed result 2

- Active damper at the node R9 with the equivalent resistance of 17.5 ohm
- Cases which need the equivalent resistance less than 17.5 ohm remain unstable.

		Node name							
		R3	*R4*	*R6*	*R9*	*R10*	*R15*	*R16*	*R18*
Inverter operating combination	{E}	*5.0*	*7.2*	*7.2*	*7.2*	*7.2*	*21.0*	*7.2*	*7.2*
	{D}	*5.0*	*8.6*	*14.7*	*12.3*	*12.3*	*7.2*	*25.0*	*12.3*
	{C}	*2.9*	*6.0*	*8.6*	*17.5*	*20.9*	*4.2*	*8.6*	*30.0*
	{A,B}	*5.0*	*7.2*	*14.7*	*21.0*	*25.1*	*7.2*	*14.7*	*25.1*
	{C, D, E}	*3.5*	*5.1*	*7.2*	*10.3*	*10.3*	*8.6*	*10.3*	*12.3*
	{A, B, C, D, E}	*4.2*	*7.2*	*12.3*	*17.5*	*21.0*	*7.2*	*12.3*	*21.0*
	{A}	*Stable*							
	{B}	*Stable*							
Ranking		8	7	5	3	2	6	4	1



Conclusion

- There are several unstable cases from the varying grid impedance
- Active damper for providing damping is discussed
- Stabilizing effect of an active damper for different inverter operating conditions
- The optimal site for the active damper can be the location where the minimum damping is required, which is near to the unstable inverters.

Thank you for your attention.