Stabilization of Multiple Unstable Modes for Small-Scale Inverter-Based Power Systems with Impedance-Based Stability Analysis

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Outline

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  - The Impedance Based Stability Criteria(IBSC)
  - The Nyquist Stability Criterion
- Problem in system level analysis
- Statement of stable network and its expansion
- Proposed step by step analysis
- Modeling and Simulation Evaluation
- Experimental results
- Conclusion

Harmonic interaction problem

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

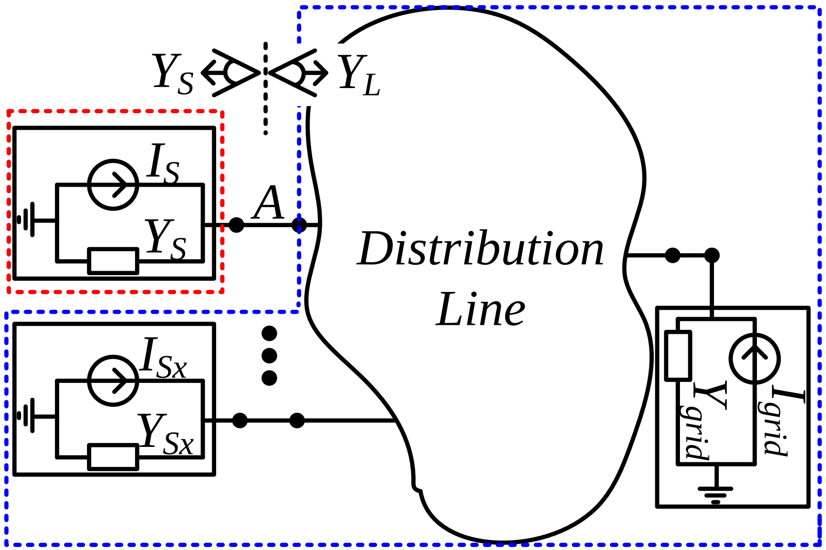
The general objective of this paper is to investigate the power quality problems and the interaction of these inverters with the distribution network. For this paper, the generated current harmonics, the effect of background voltage distortion in the network, and the possible resonances between the inverters and the network are investigated.

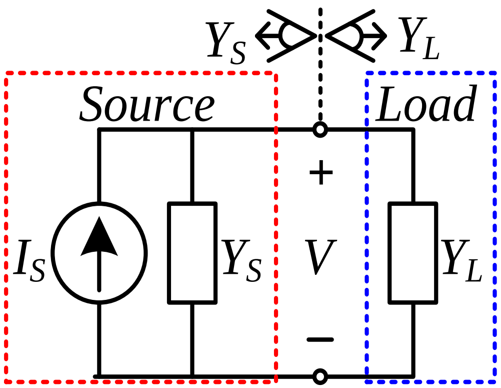
II. Power Quality Problems

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.

[9] 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.

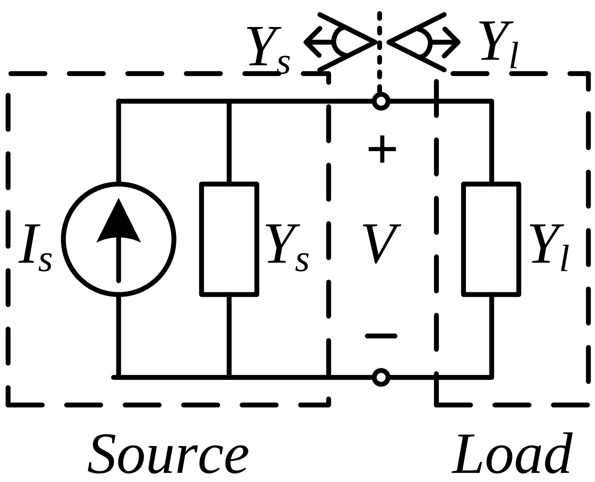
Impedance based model for the stability analysis

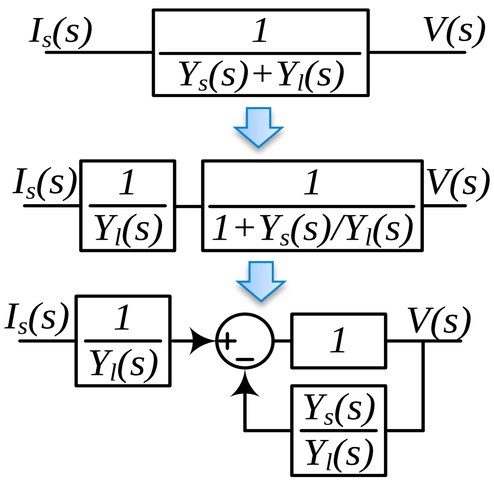




- Power distribution system can be modeled as a lumped impedance(admittance) model
- Distribution lines can be represented as passive components
- Stability of the network can be obtained by analyzing the two interconnected lumped impedances(admittances)

Impedance Based Stability Criterion





Minor loop gain : $T_m = \frac{Y_s}{Y_l}$

- Lumped-Impedance model of the network and the inverter contains information of the network stability
- Classical control theory can be used to judge stability and stability margin from the impedance relation called **Minor loop gain**

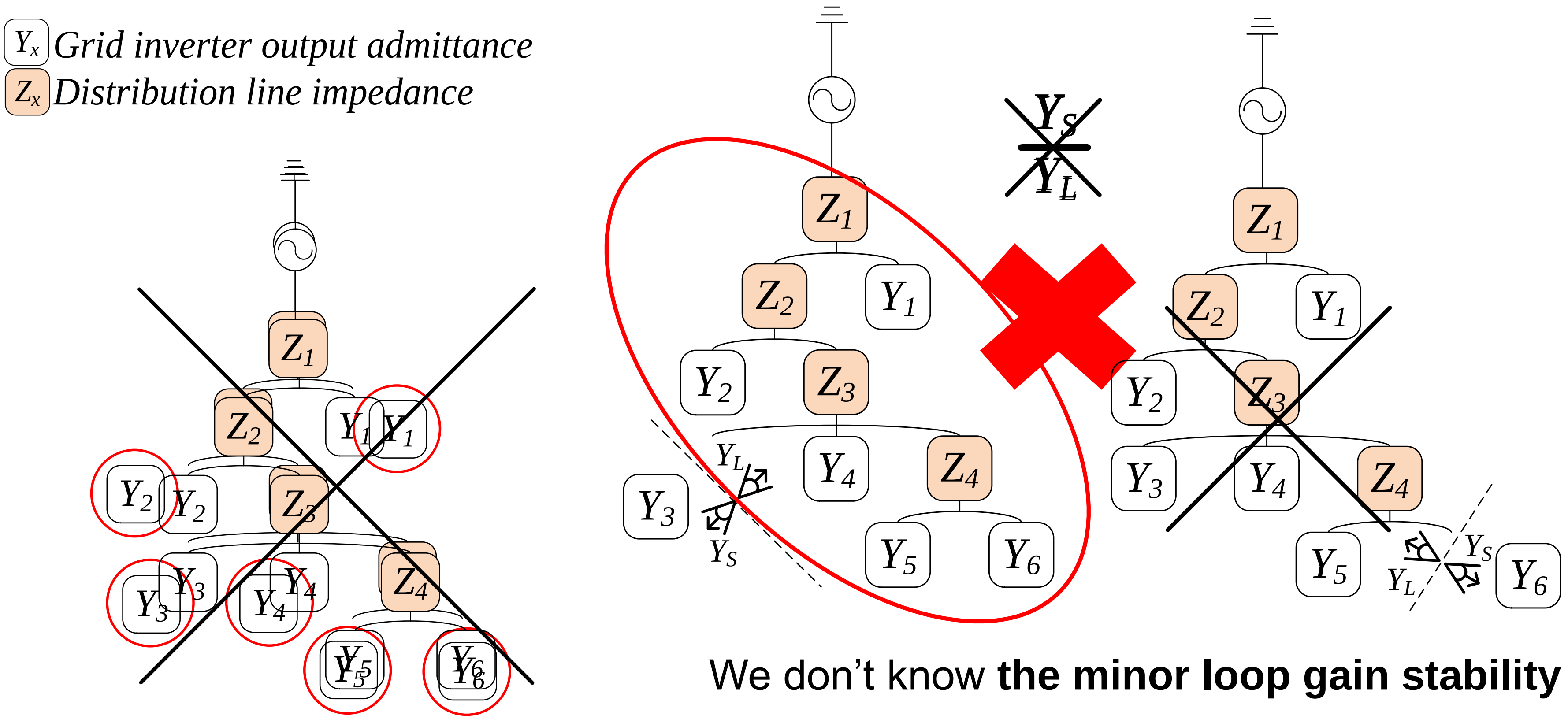
The Nyquist Stabilty Criterion

$$N = Z - P$$

where, N : the number of encirclement on (-1,j0) of the Nyquist plot
Z : the number of unstable poles in the closed loop TF
P : the number of RHP poles in the open loop TF

- Purpose
  - To find the closed loop unstable poles by means of the RHP open loop poles and the Nyquist plot
- Advantage
  - It is intuitive. Stability can be assessed by just counting the number of encirclements (-1,j0) of the Nyquist plot and its rotating direction
  - Absolute and Relative stability can be shown at the same time
- Limitation
  - <u>The number of unstable open loop poles</u> P has to be identified.

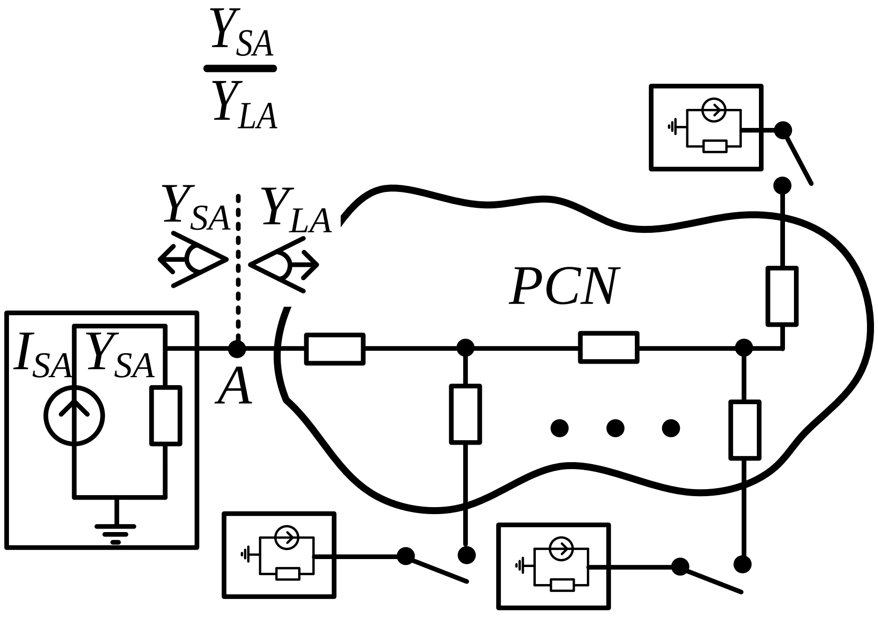
Difficulty in analyzing the system stability



We don't know **the minor loop gain stability**

→ We need to find the unstable components.
We should make the system stable somehow.

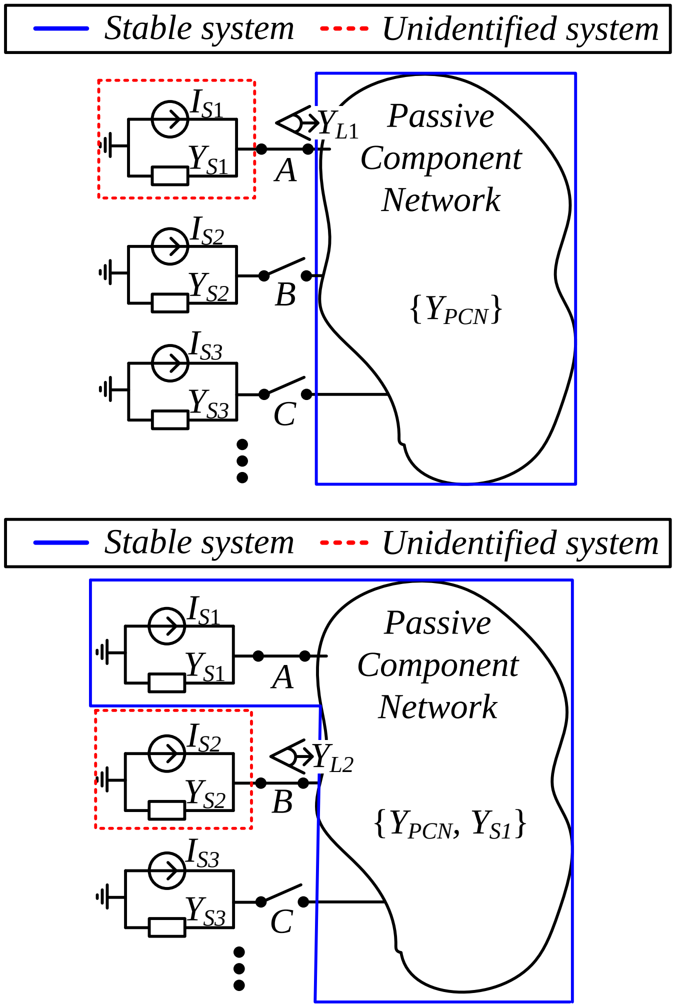
Statement of stable network and its expansion

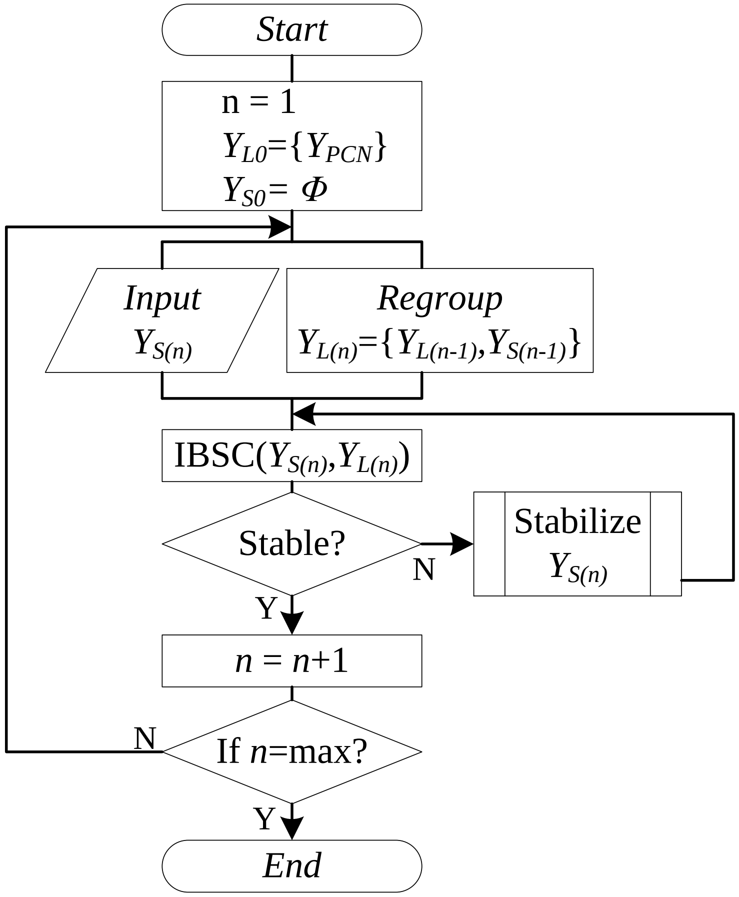


1. The network with only passive components is always stable;

2. The arbitrary node in the PCN is stable when all active components connected nodes are stable.

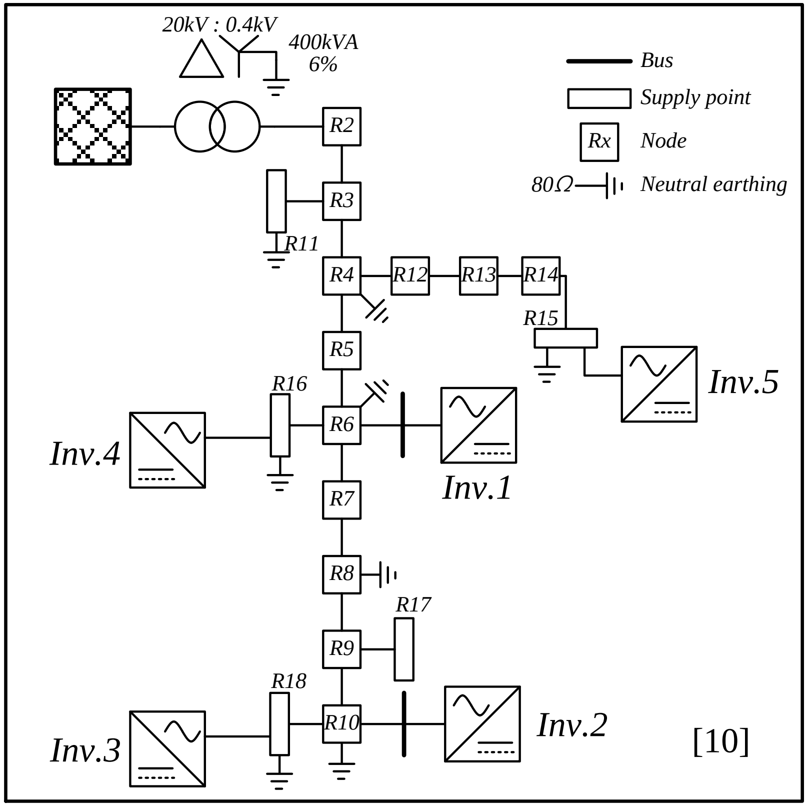
Step by step stabilizing procedure





Test system for proposed stabilizing method

A Cigré Benchmark case of European LV network



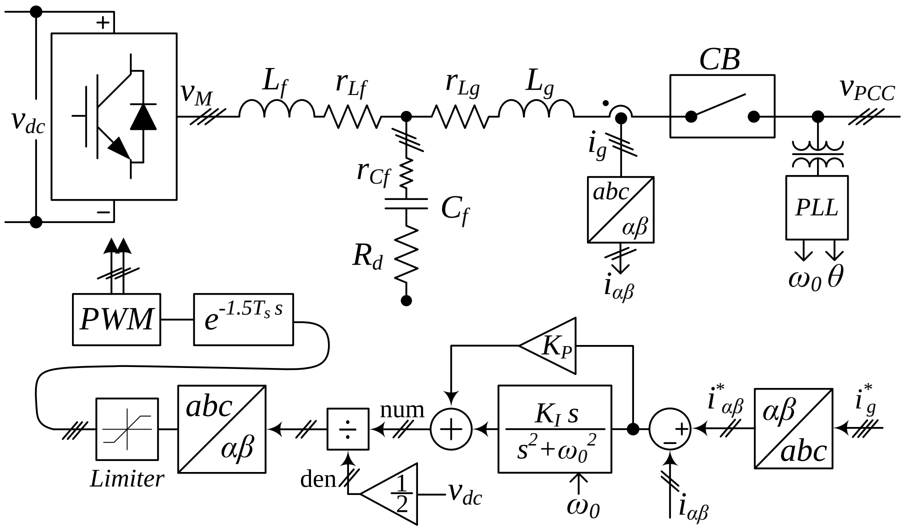
[10]"Benchmark Systems for Network Integration of Renewable and Distributed Energy Resources C06.04.02," Cigré, 2014.

Node (From-To)	Length [m]	Resistance [mΩ]	Inductance [uH]
R1-R2	35	10.045	18.6052
R2-R3	35	10.045	18.6052
R3-R4	35	10.045	18.6052
R4-R6	70	20.09	37.2104
R6-R9	105	30.135	55.8156
R9-R10	35	10.045	18.6052
R4-R15	135	155.52	196.811
R6-R16	30	34.56	43.7358
R9-R17	30	34.56	43.7358
R10-R18	30	34.56	43.7358
Transformer		3.2	40.7437

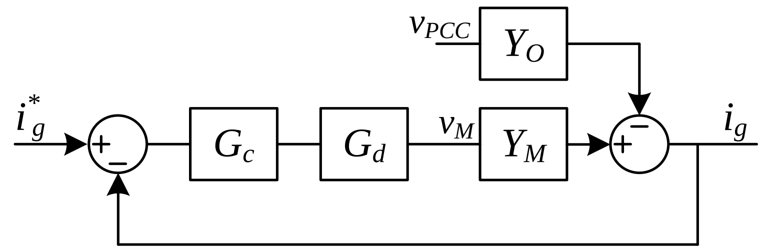
		Inverter name				
		Inv. 1	Inv. 2	Inv. 3	Inv. 4	Inv. 5
Power rating [kVA]		35	25	3	4	5.5
Base Frequency, f_0 [Hz]		50				
Switching Frequency, f_s [kHz] (Sampling Frequency)		10		16		
DC-link voltage, v_{dc} [kV]		0.75				
Harmonic regulations of LCL filters		IEEE519-1992				
Filter values	L_f [mH]	0.87	1.2	5.1	3.8	2.8
	C_f [uF]/R_d [Ω]	22/0	15/1	2/7	3/4.2	4/3.5
	L_g [mH]	0.22	0.3	1.7	1.3	0.9
Parasitics values	r_{Lf} [mΩ]	11.4	15.7	66.8	49.7	36.7
	r_{Cf} [mΩ]	7.5	11	21.5	14.5	11
	r_{Lg} [mΩ]	2.9	3.9	22.3	17	11.8
Controller gain	K_P	5.6	8.05	28.8	16.6	14.4
	K_I	1000	1000	1500	1500	1500

Grid Inverter model of the network

Time domain model (PSCAD)



Average switching model



Output admittance of grid inverter

$$Y_{Sx} = \left.\frac{-i_g}{v_{PCC}}\right|_{i_g^*=0} = \frac{Y_O}{1+T_{OL}}$$

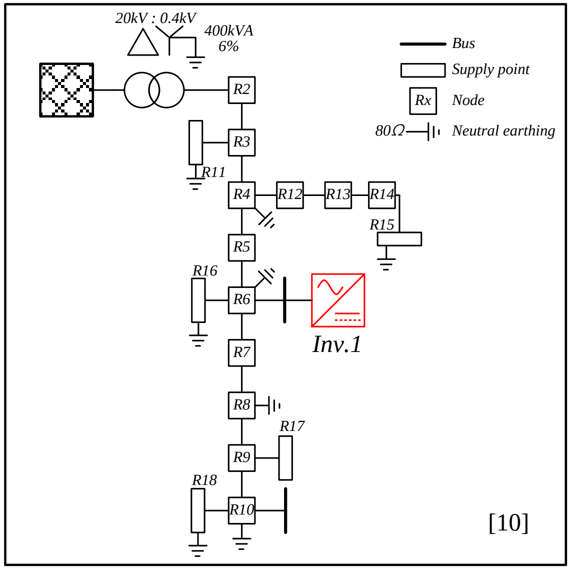
$$G_C = K_P + \frac{K_I s}{s^2+\omega_0^2} \qquad G_d = e^{-1.5T_S s} \qquad T_S = 1/f_S \qquad \omega_0 = 2\pi f_0$$

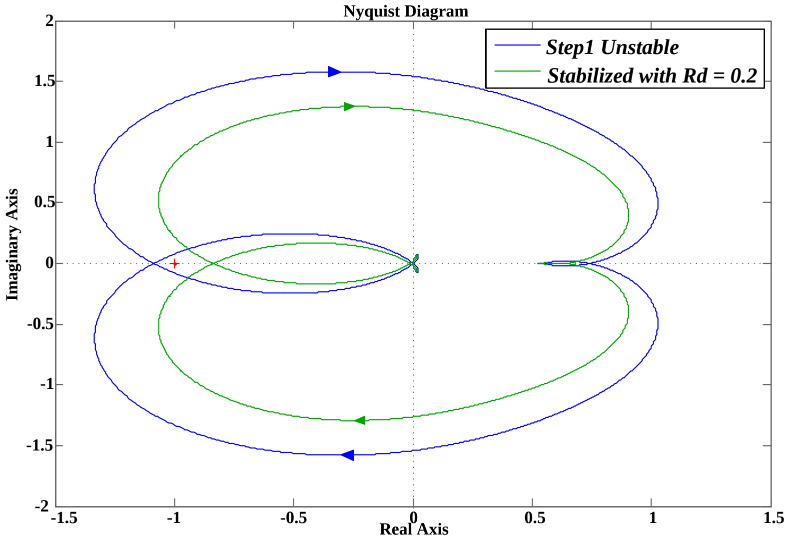
$$Y_M = \left.\frac{i_g}{v_M}\right|_{v_{PCC}=0} = \frac{Z_{Cf}}{Z_{Cf}Z_{Lf}+Z_{Lg}Z_{Lf}+Z_{Cf}Z_{Lg}} \qquad Z_{Cf} = r_{Cf} + \frac{1}{sC_f} + R_d \qquad Z_{Lf} = r_{Lf} + sL_f$$

$$Y_O = \left.\frac{-i_g}{v_{PCC}}\right|_{v_M=0} = \frac{Z_{Lf}+Z_{Cf}}{Z_{Cf}Z_{Lf}+Z_{Lg}Z_{Lf}+Z_{Cf}Z_{Lg}} \qquad Z_{Lg} = r_{Lg} + sL_g$$

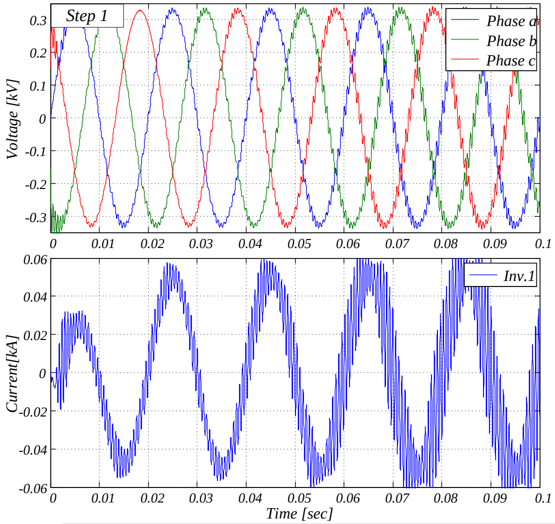
$$T_{OL} = G_C G_D Y_M$$

Simulation result : Step 1) Stabilizing Inv.1

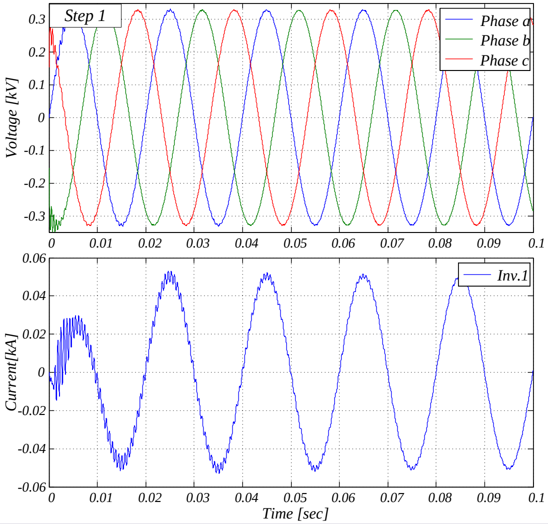




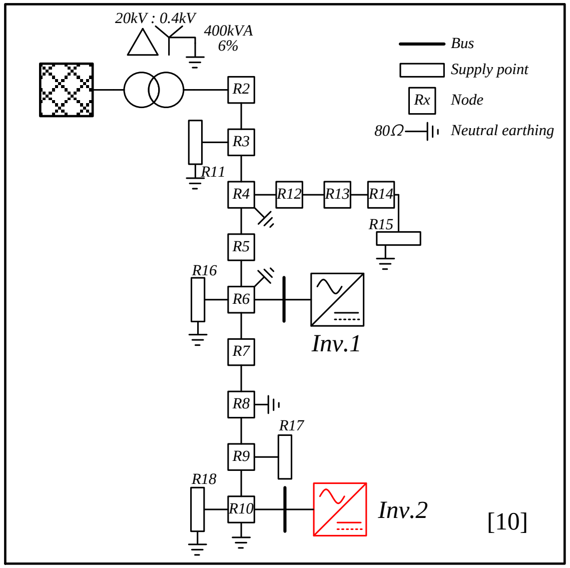
Unstable Case

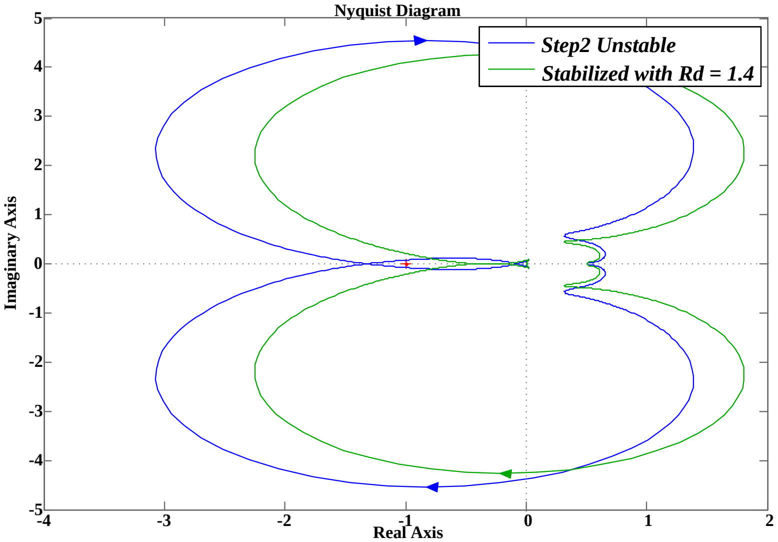


Stabilized

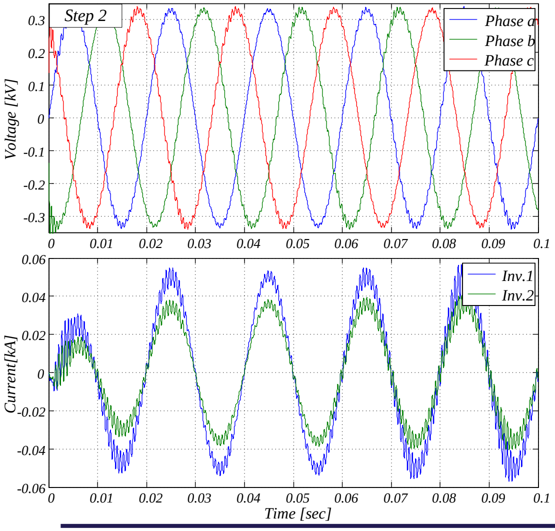


Simulation result : Step 2) Stabilizing Inv.2

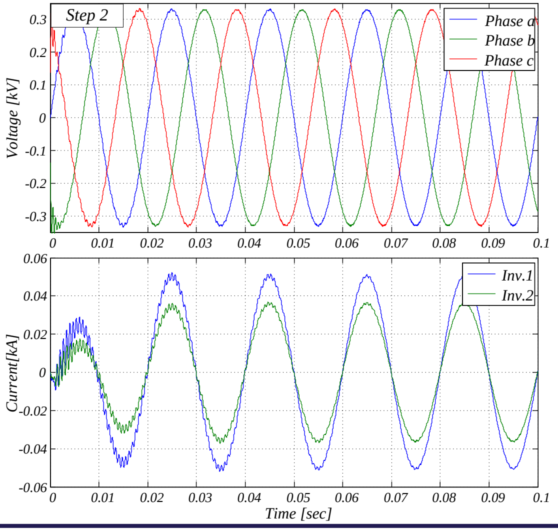




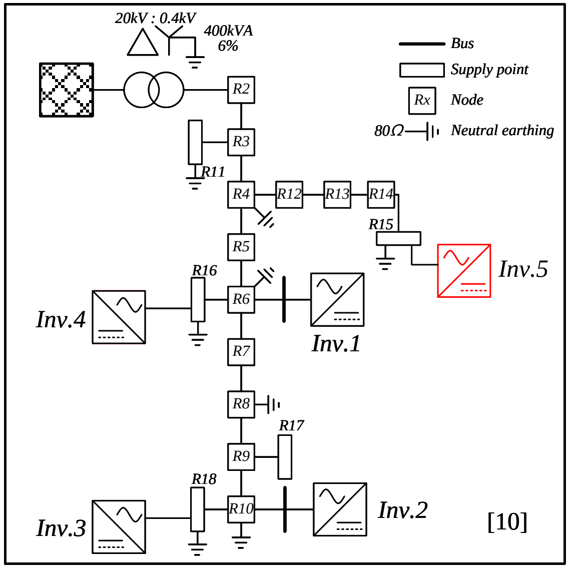
Unstable Case

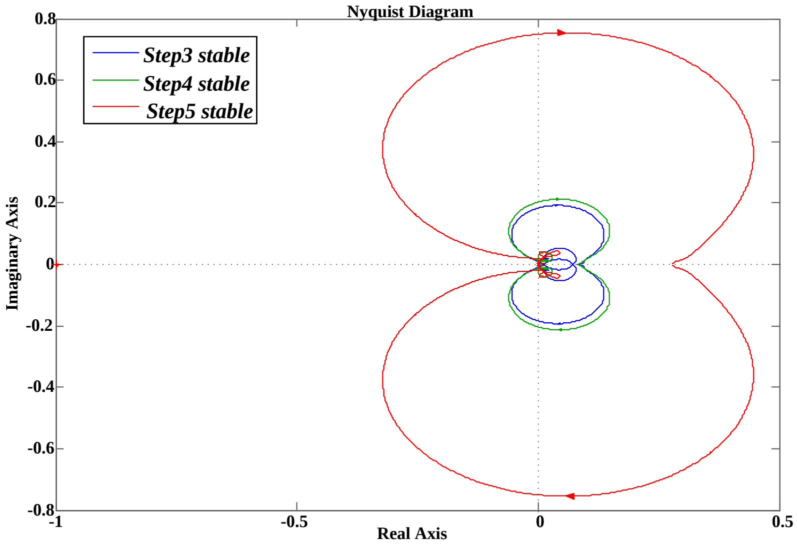


Stabilized

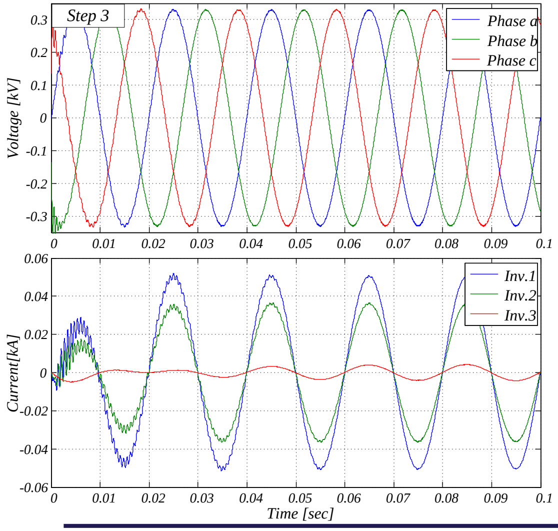


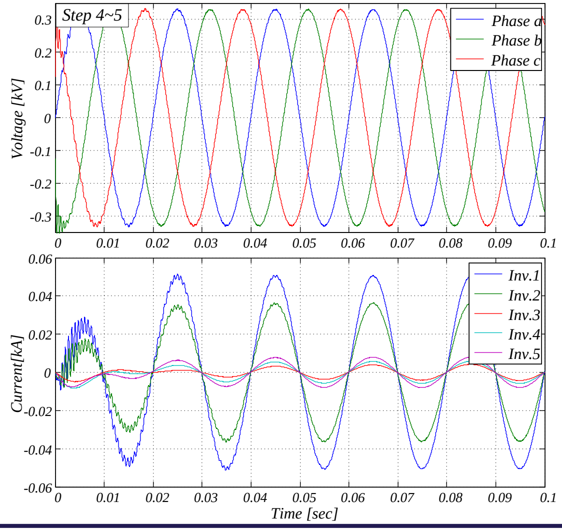
Simulation result : Step 3~5) Stabilizing Inv. 3~5



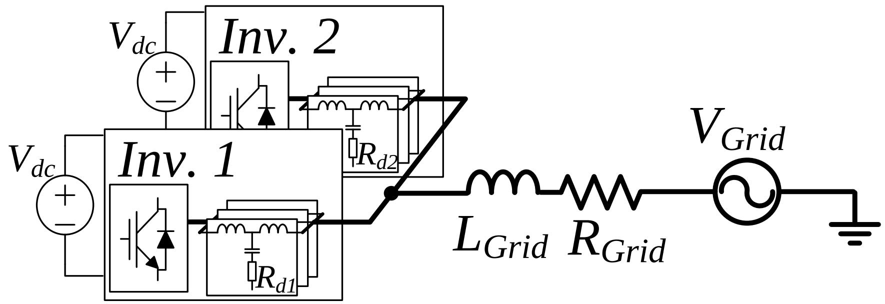


Stable Cases





Experimental verification



Test condition

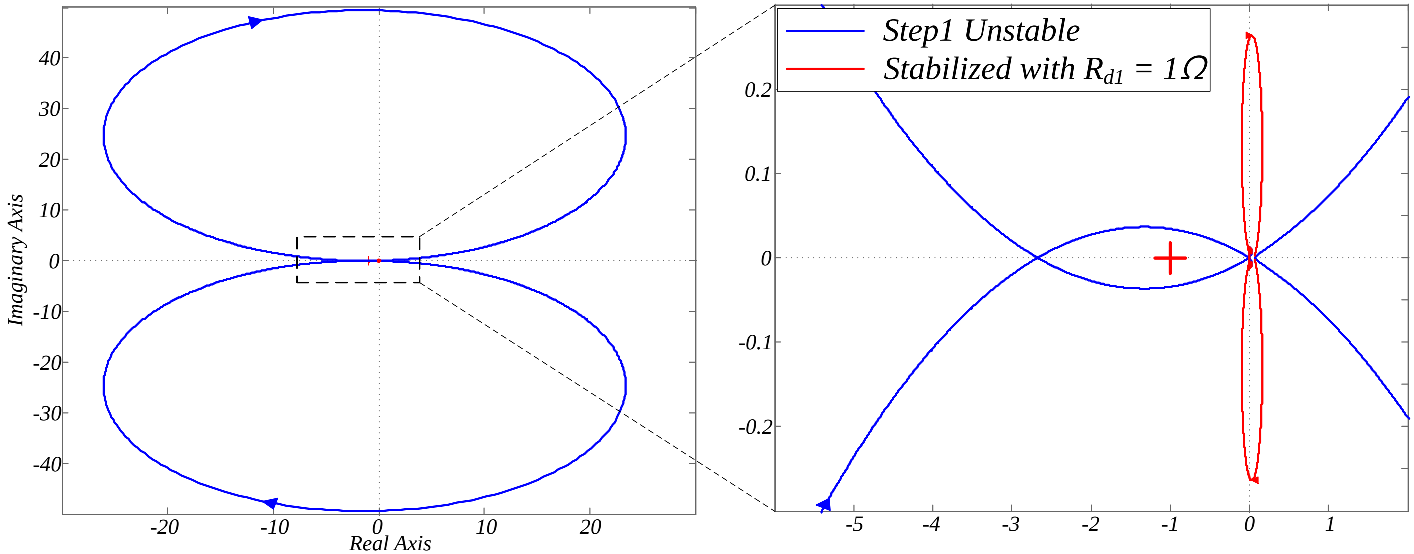
V_{Grid} : 3-phase, 400V_{rms} line to line

L_{Grid} : 150uH, R_{Grid} : 0.1 Ohm (Grid simulator)

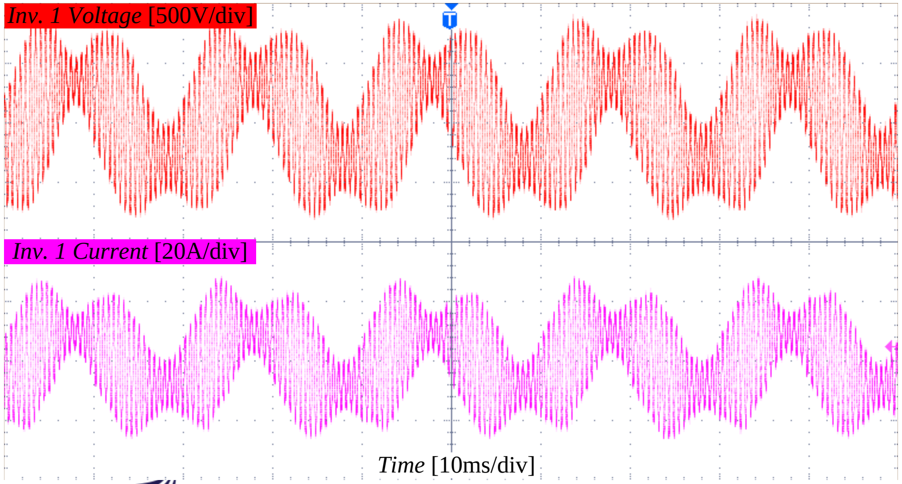
Inverter Parameters

	Power Rating	Switching Frequency	DC Link	Filter Topology	Filter Value	Controller Gain
Inv. 1	5 kVA	10 kHz	750 V	LCL	L_f = 1.8 mH C_f = 9.4 uF L_g = 1.8 mH	K_P = 6 K_I = 1000
Inv. 2	5 kVA	10 kHz	750 V	LCL	L_f = 3 mH C_f = 4.7 uF L_g = 3 mH	K_P = 15.5 K_I = 1000

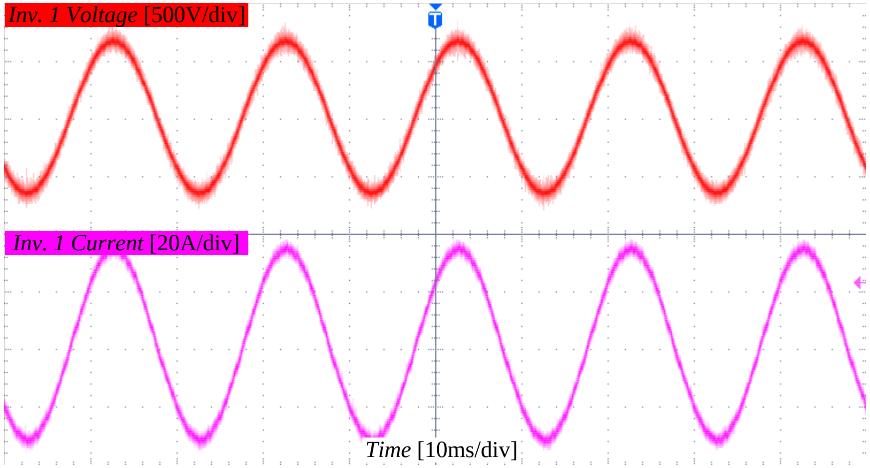
Step 1) Stabilizing Inv.1



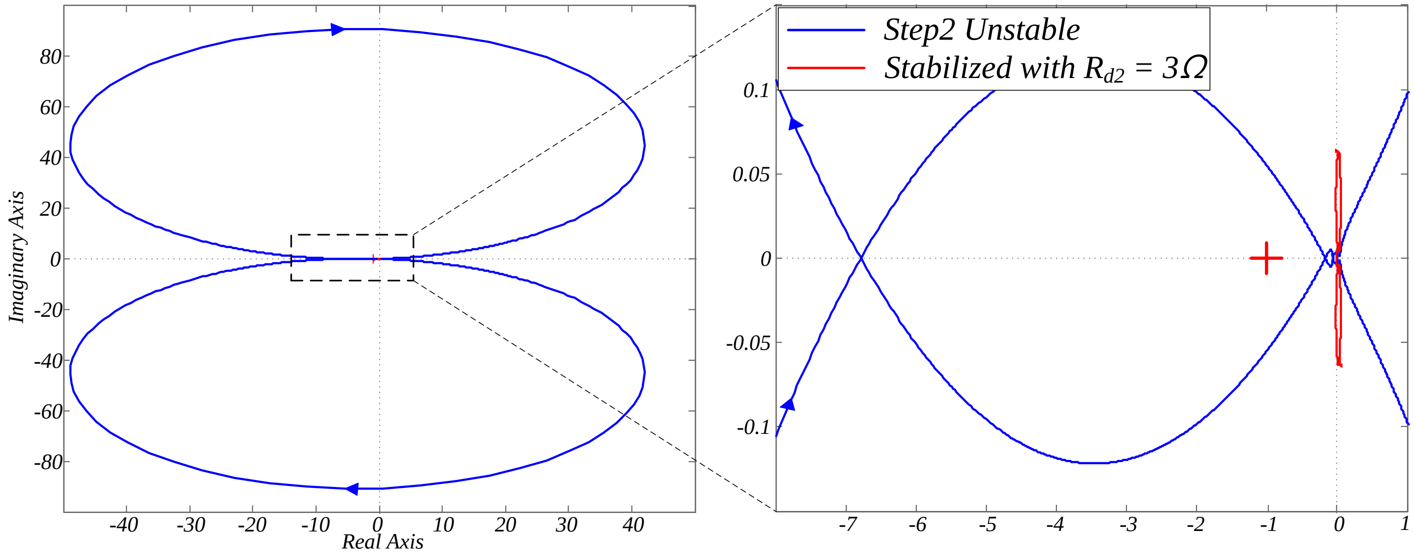
Unstable condition



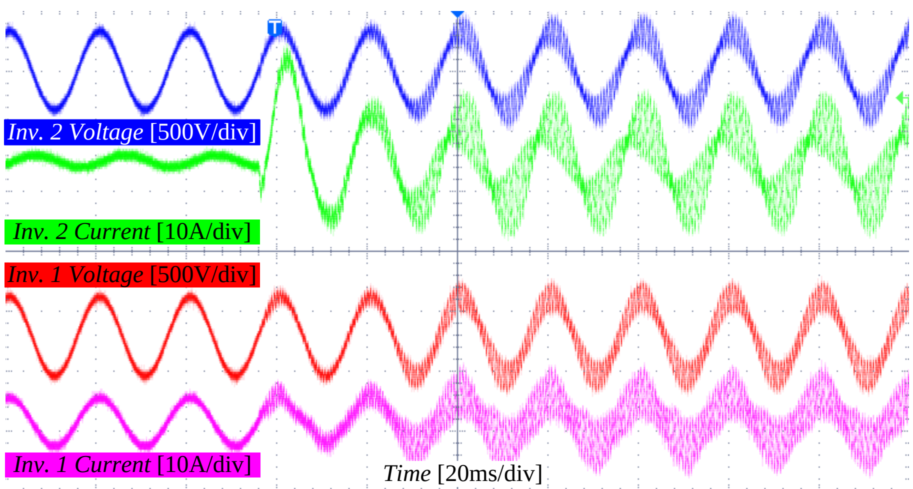
Stabilized system



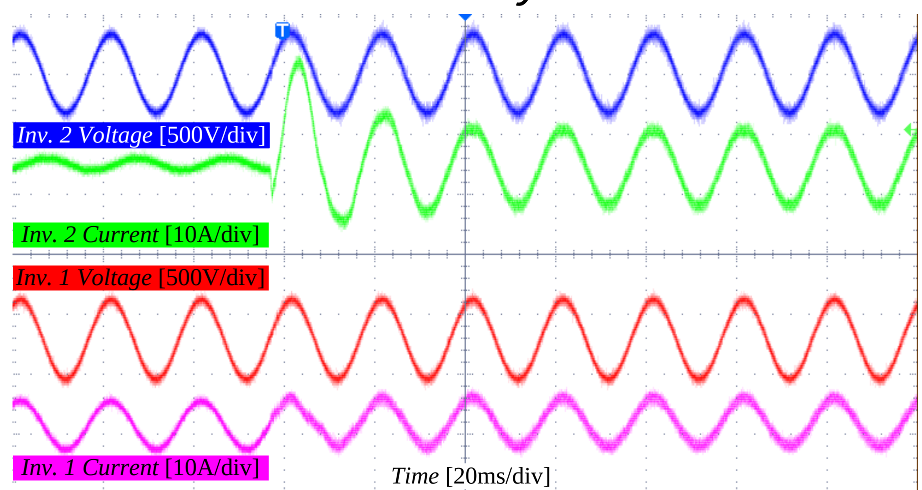
Step 2) Stabilizing Inv.2



Unstable condition



Stabilized system



Conclusion

- In order to analyze the system stability from the impedance based criterion, stability of the minor loop gain should be assured.
- The assured stable minor loop gain can be obtained from the pure passive components in the network such as, distribution lines.
- Overall system stability can be obtained by using the step-by-step stabilizing approach.

- Future works
  - If the stabilizing sequence is changed, the required damping resistance may be changed.
  - Optimum values for stabilizing the network are still difficult to obtain. There are many combinations of the stabilizing sequence.

Thank you for your attention