Impact of Active Distribution Networks on voltage stability: A case study using dynamic equivalents

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Opportunities and challenges for voltage stability with power-electronics-interfaced components

Panel session of the 2022 IEEE PES General Meeting, Denver (CO), USA

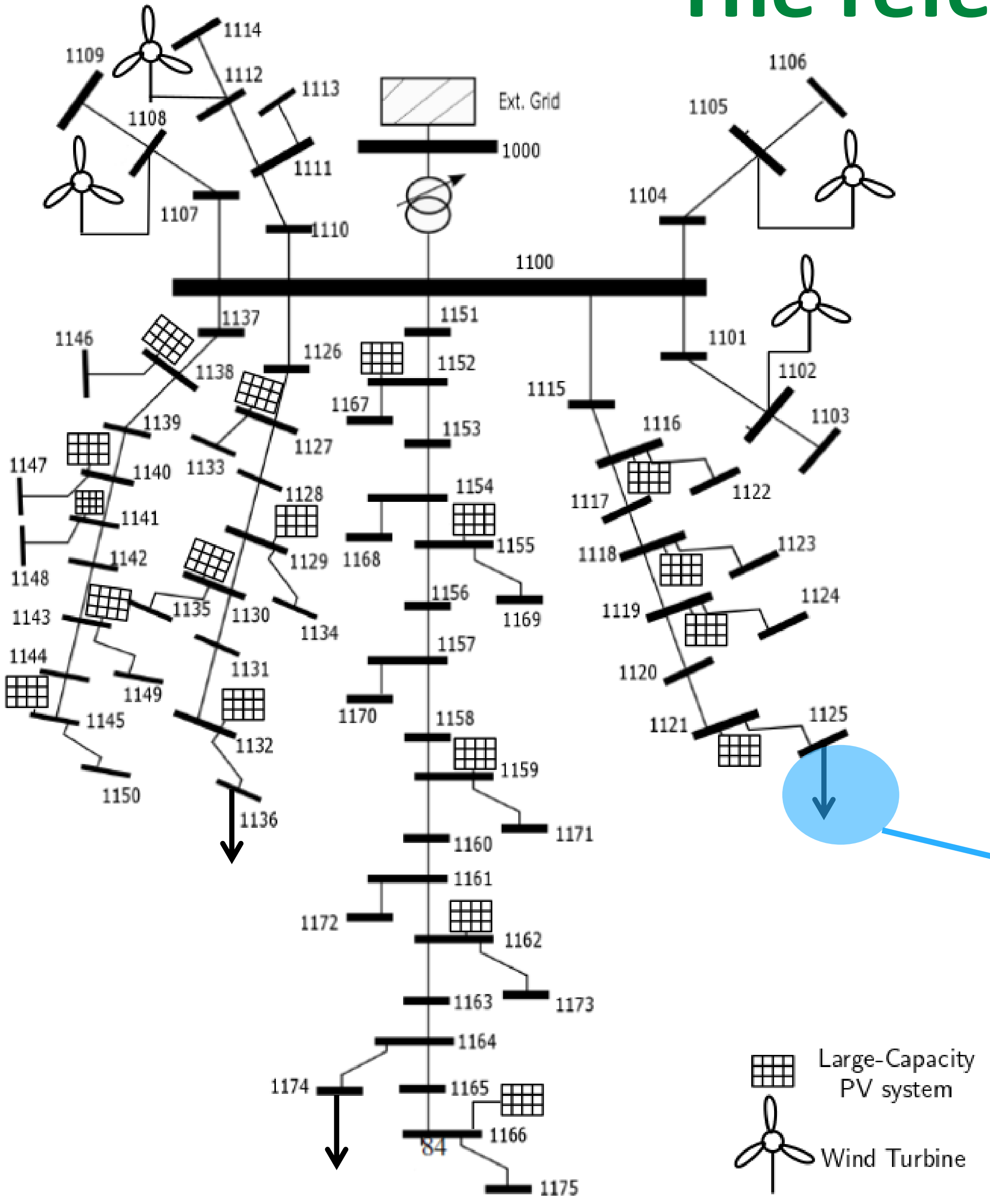
Introduction

- Distribution grids host more and more *Distributed Energy Resources* (DERs) using *Inverter-Based Generators* (IBGs)
- they become *Active Distribution Networks* (ADNs)
- they have a growing impact on the whole system dynamics
  - in particular voltage dynamics and stability, which they can worsen as well as improve.
- This presentation illustrates impacts of DERs through a case study involving:
  - a large population of ADN equivalents attached to a transmission system model
  - short- and long-term dynamics
  - stable, unstable and stabilized voltage responses to a large disturbance (fault) in transmission grid.
- More details can be found in:

G. Chaspierre, G. Denis, P. Panciatici, and T. Van Cutsem, "A dynamic equivalent of Active Distribution Network: Derivation, Update, Validation and Use Cases," *IEEE Open Access Journal in Power and Energy*, Aug. 2021

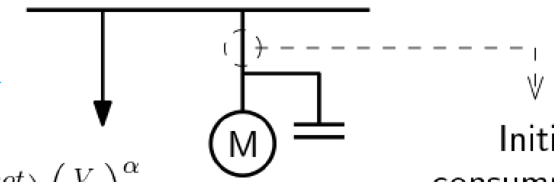
1. Description of the T+Eq model

The reference ADN model



- 11-kV grid
- 75 buses
- 53 loads
  - total consumption: 19.8 MW
- 22 dispersed IBGs :
  - large-capacity photovoltaic systems

    (total capacity: 6.8 MW)
  - wind turbines (total capacity: 8 MW)



$$P = (P_o - P_o^{mot})\left(\frac{V}{V_o}\right)^{\alpha}$$

$$Q = (Q_o - Q_o^{mot})\left(\frac{V}{V_o}\right)^{\beta}$$

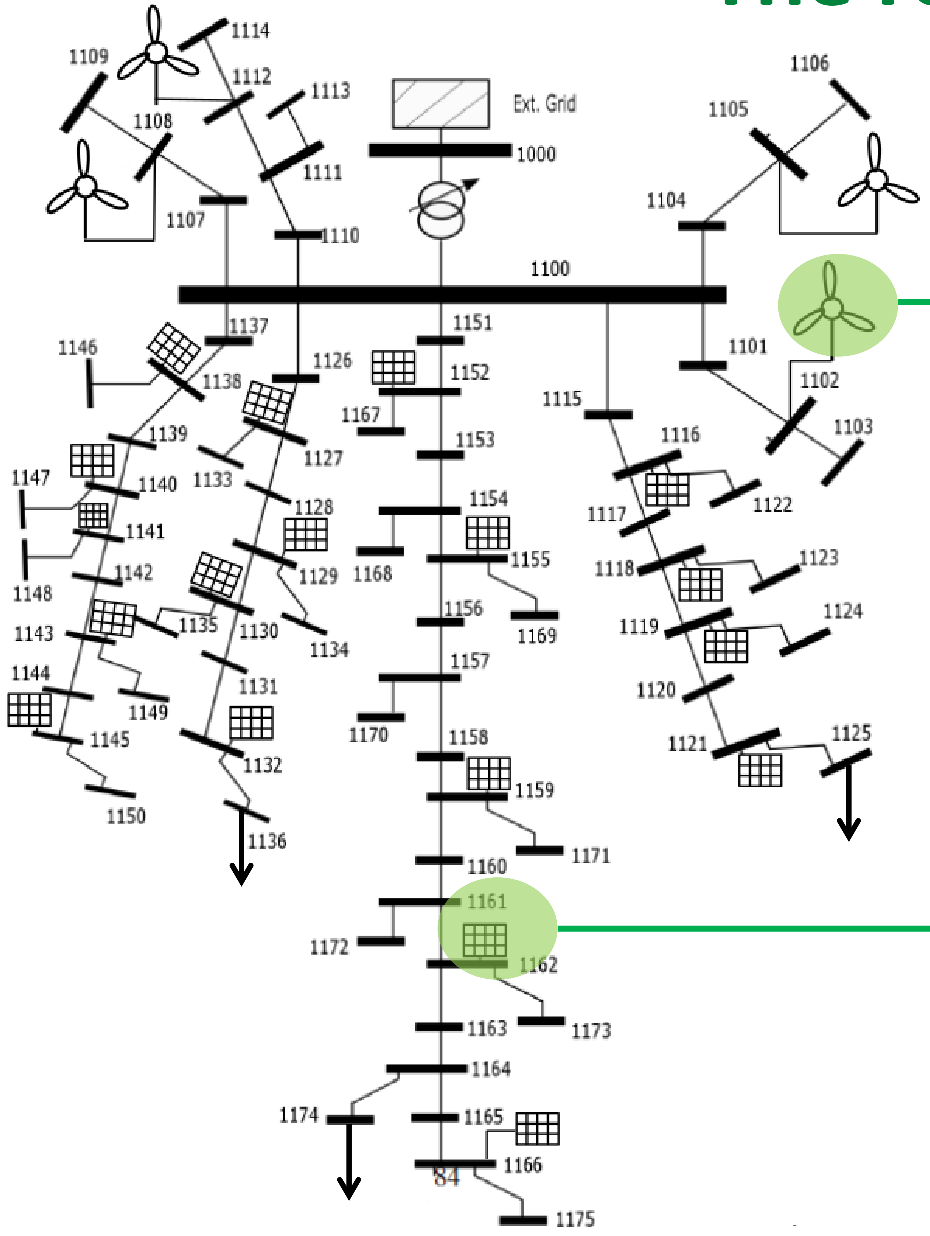
Initial consumption :

$$P_o^{mot} = mP_o$$

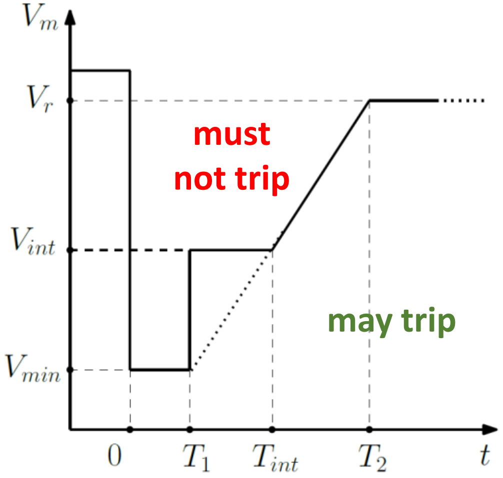
$$Q_o^{mot} = mP_o \tan\phi_m$$

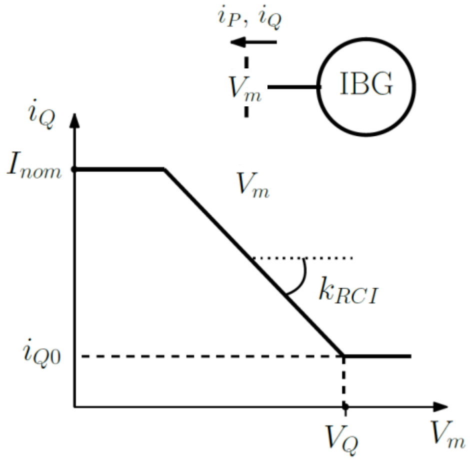
$$0 \leq m \leq 1$$

The reference ADN model



- low-Voltage Ride-Through (LVRT)
- reactive current injection in low voltage conditions





- limit on current with priority to reactive current

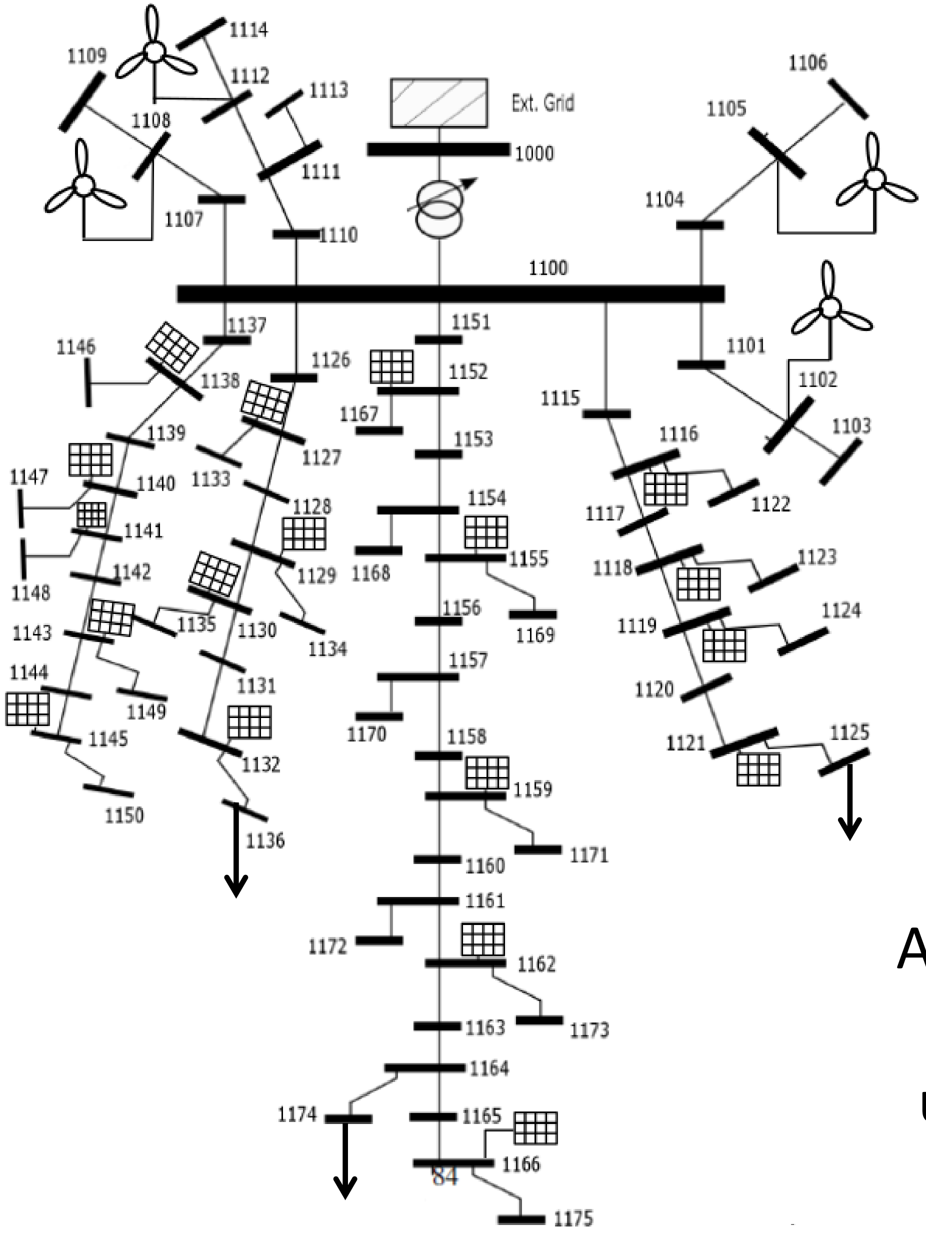
$$i_P^{MAX} = \sqrt{I_{nom}^2 - i_Q^2}$$

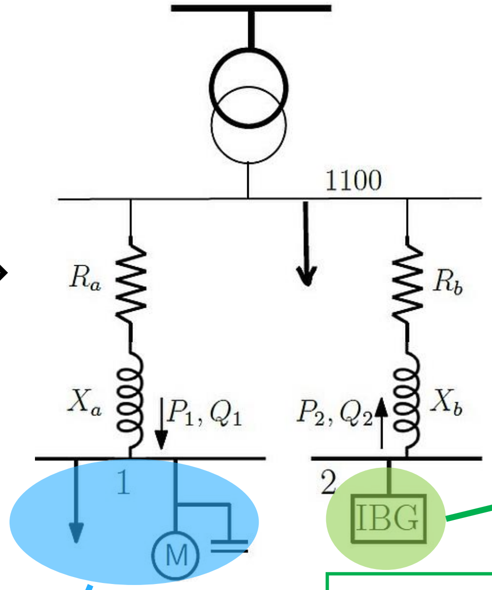
- limit on active current recovery rate $(di_P/dt)_{max}$

in accordance with most grid codes

- Generic model of Phase-Locked Loop (PLL)

The ADN equivalent



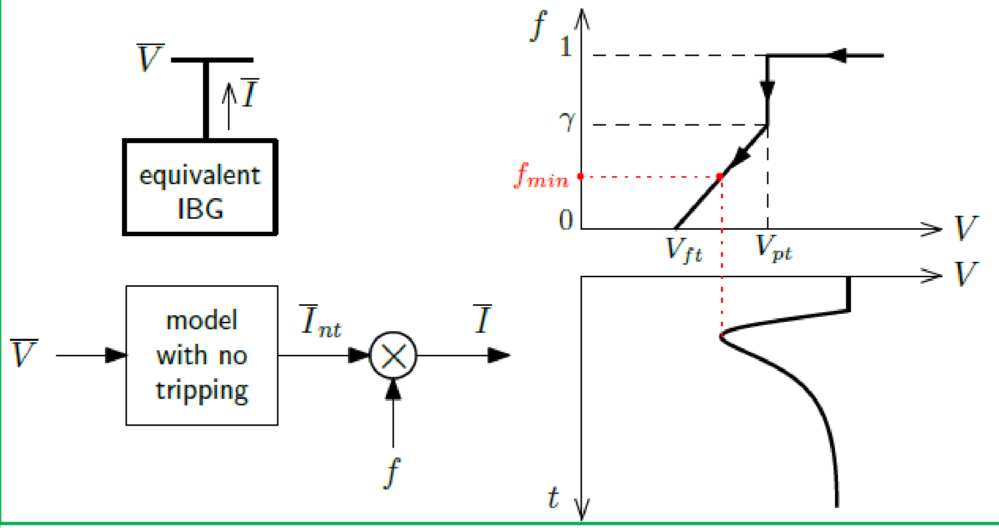


Aggregate IBG with same model as in unreduced system

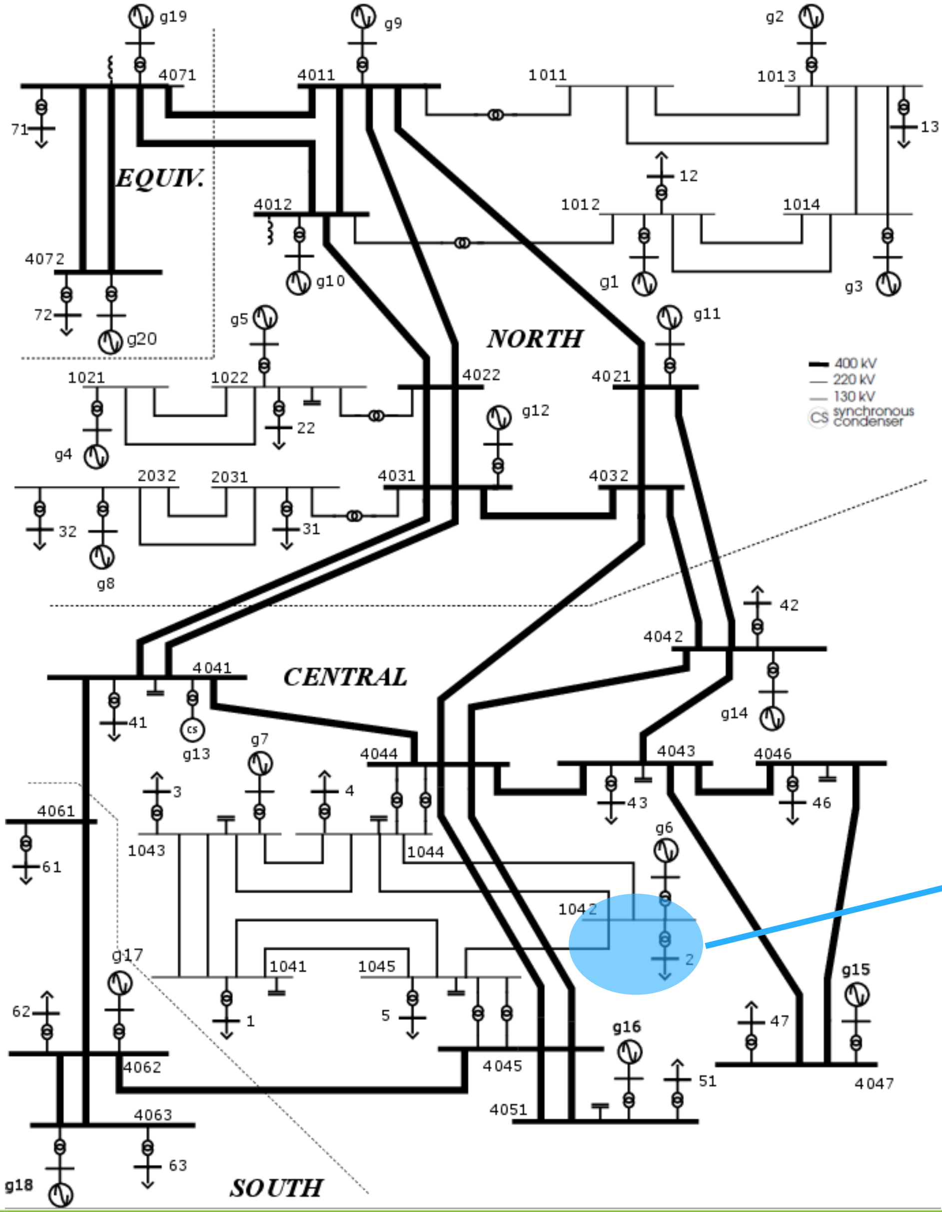
(PLL, LVRT, i_Q injection, limitation with i_Q priority, rate of power recovery)

Aggregate load with same model as in unreduced system

+ "partial tripping"

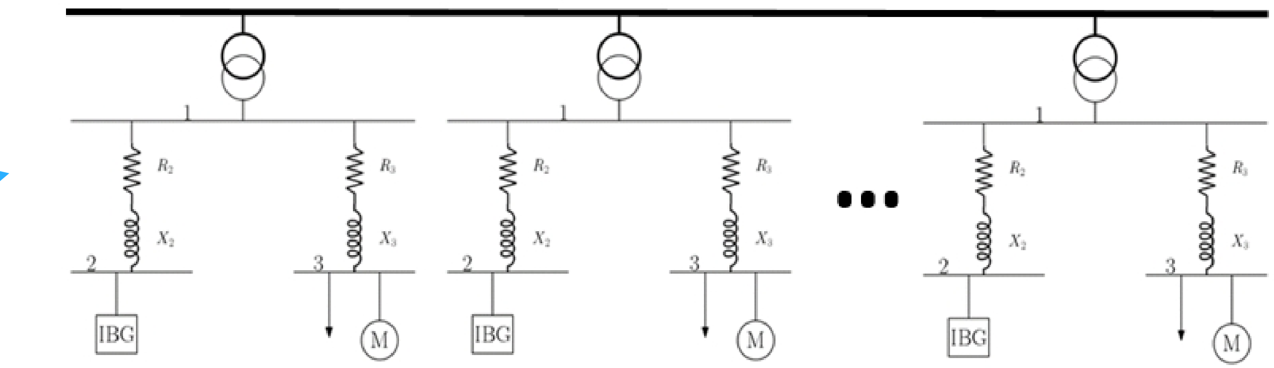


The transmission system



- IEEE Nordic test system for Voltage Stability and Security Analysis
  - fully documented in Tech. Rep. PES-TR19, Aug. 2015
  - overview in *IEEE Trans. on PWRS*, 2020

- 11 loads of the Central area replaced by 627 instances of the ADN equivalent

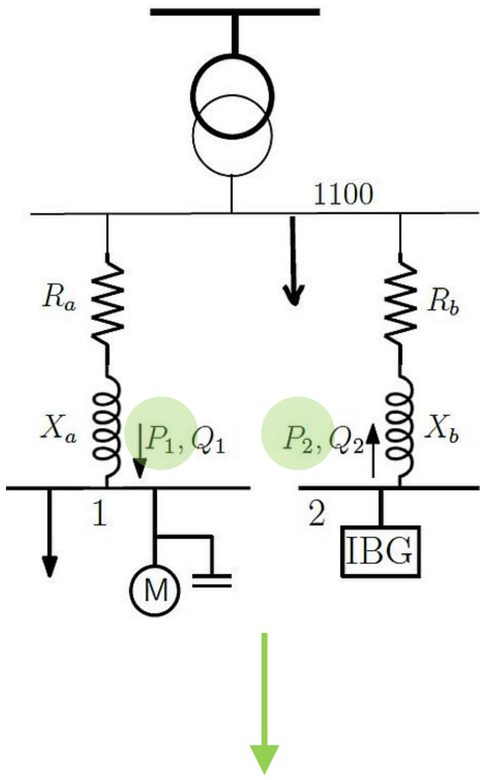


- operating point of transmission grid preserved

Randomization of the ADN equivalents

Variation of parameters

Static part of aggregate load	exponent α in Fig. 2	[1.35 1.83]
	exponent β in Fig. 2	[1.92 2.60]
Motor part of aggregate load	loading factor	[0.48 0.64]
	fraction m of initial power	[0.1 0.3]
Aggregate IBG	nominal apparent power S_{ibg} ("small" and "large" capacity) (MVA)	[5 10] [10 15]
	maximum rate of active power recovery (pu/s)	[0.3 0.4]
	slope k_{RCI} in Fig. 3.b	[2.93 3.96]
	fraction disconnected under low voltage	[0.10 0.15]
Impedances	R_1, X_1, R_2 and X_2	± 15 %
Distribution transformer	nominal apparent power S_{tfo} (MVA)	[18 22]
	delay before first tap change (s)	[28 32]
	time between further tap changes (s)	[8 12]



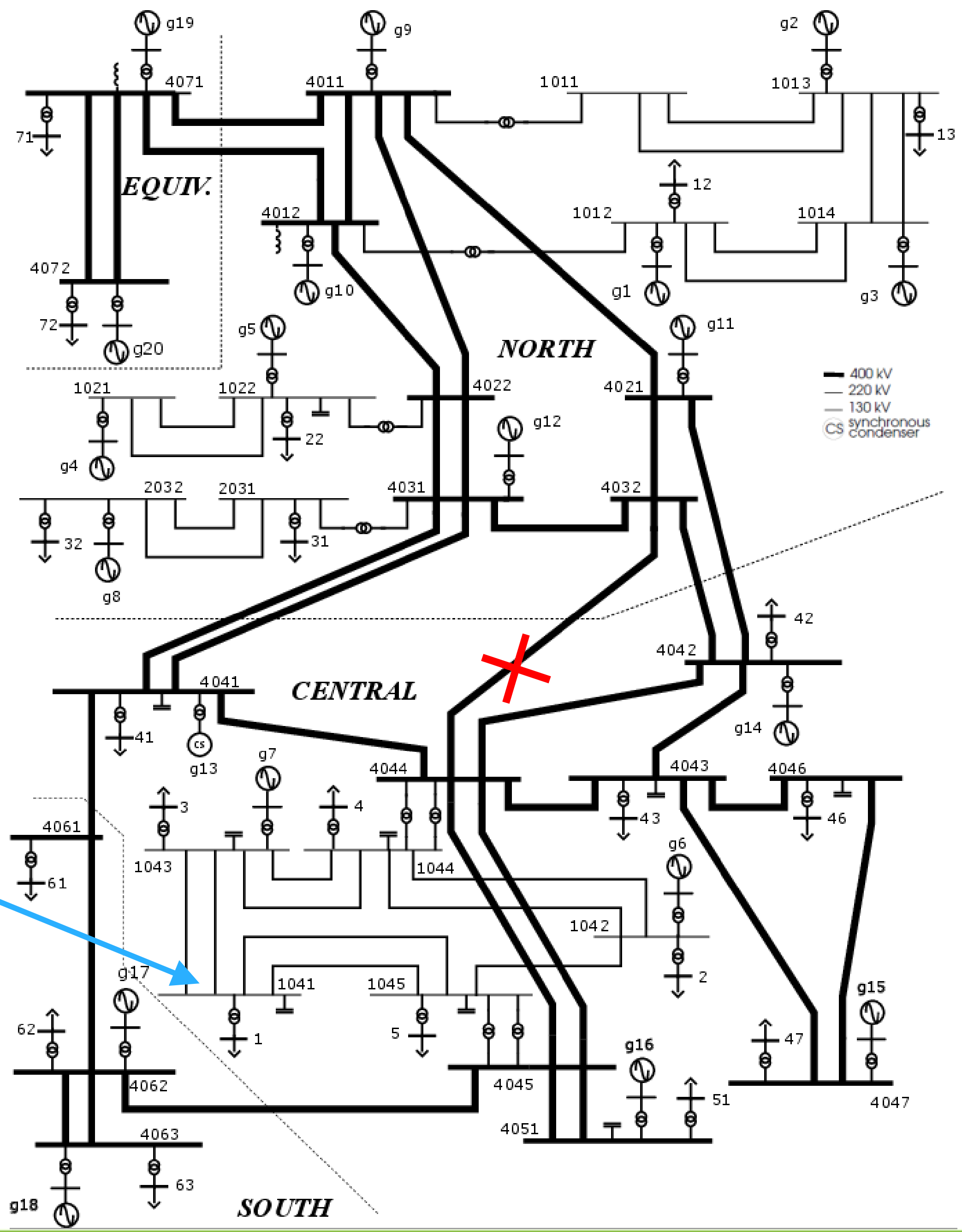
Variation of operating point

Capacity ratio : $CR = S_{ibg}/S_{tfo}$

Penetration level : $PL = P_2/(P_1 - P_2)$

Scenario

Bus with most impacted voltage



Disturbance

- 3-ph short-circuit on line 4032-4044
- cleared in 100 ms by opening the line

Operating point "A"

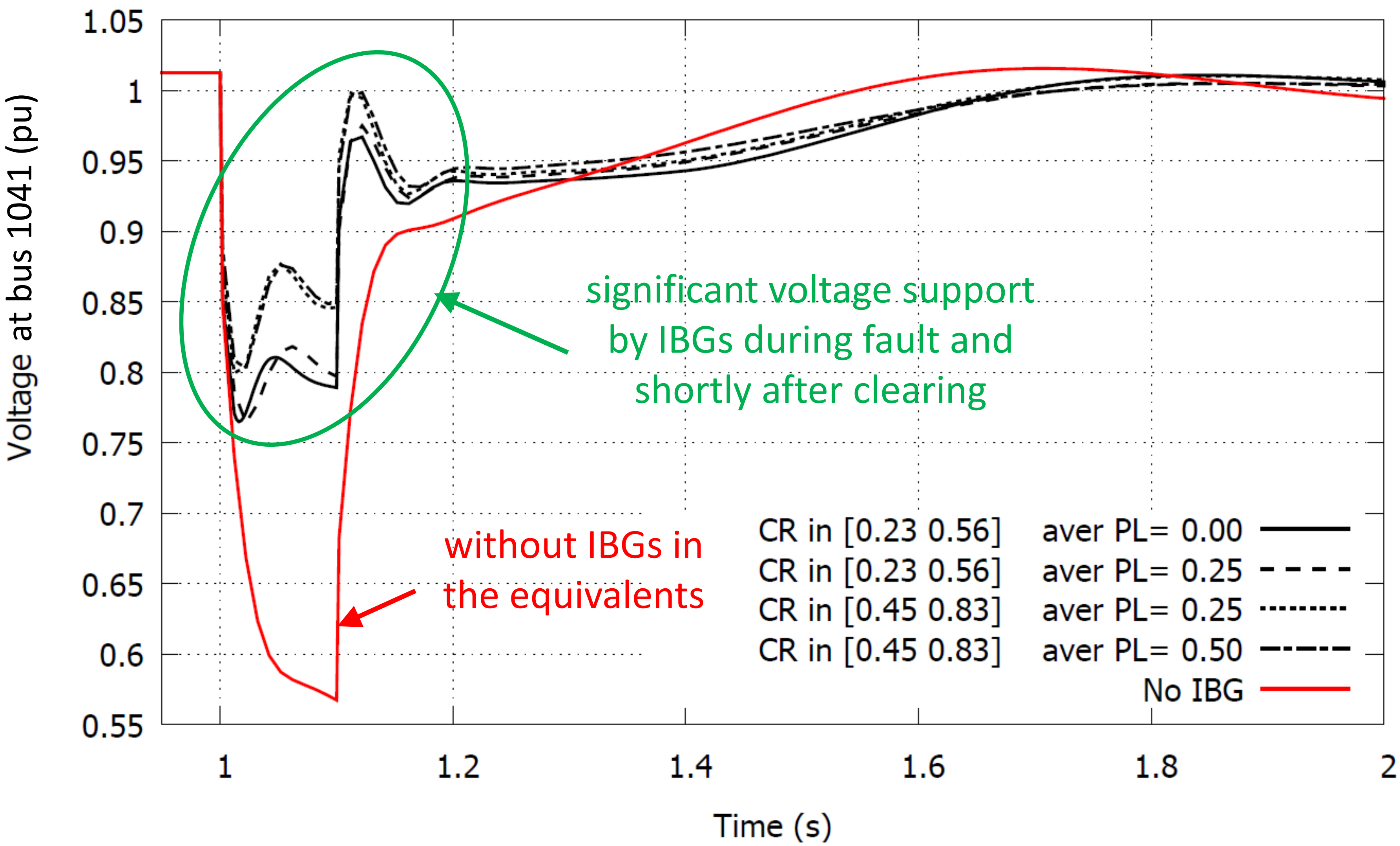
- insecure

System response

- stable in the short term
- unstable in the long term

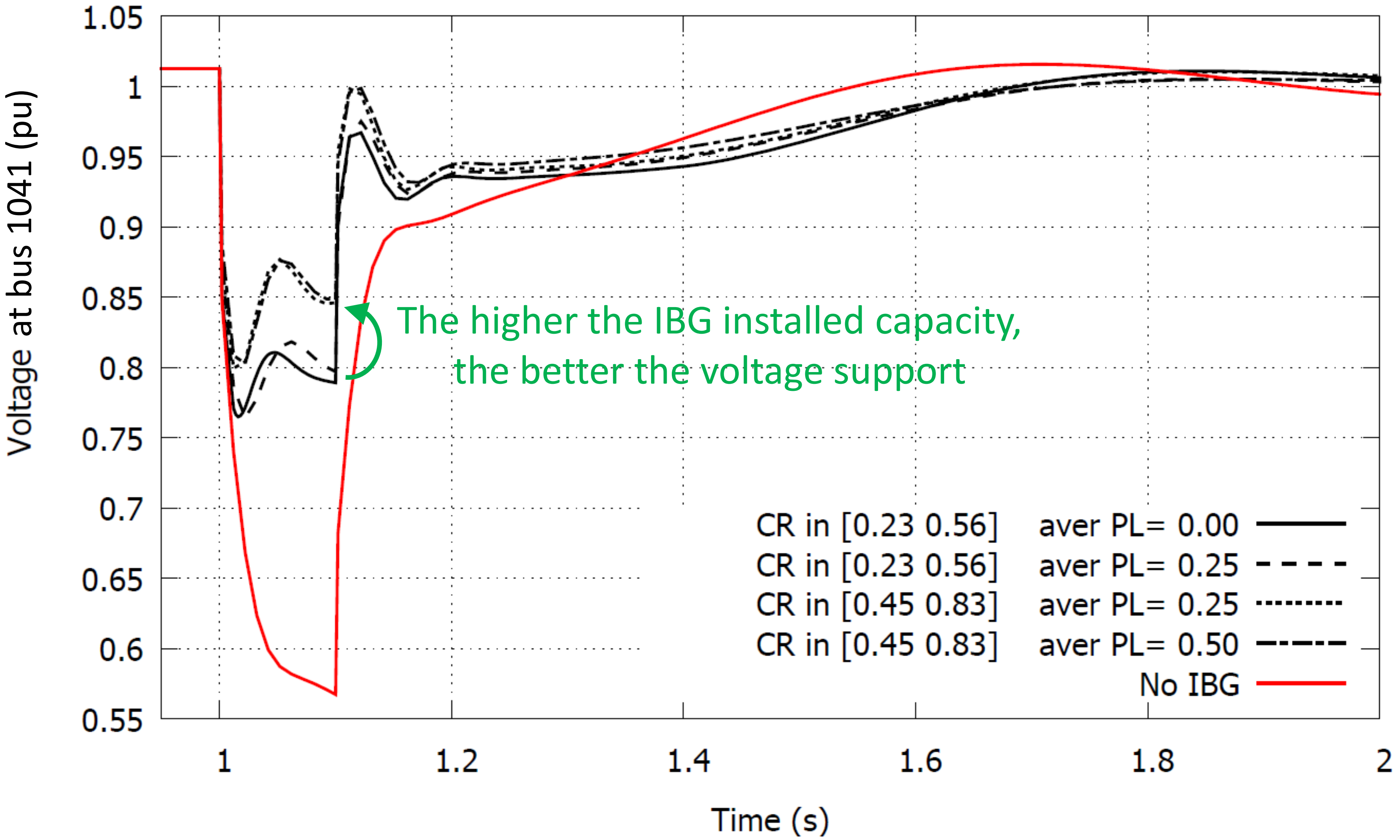
2. Short-term dynamics

Short-term dynamics



IBG disconnections due to low voltage are not considered

Short-term dynamics



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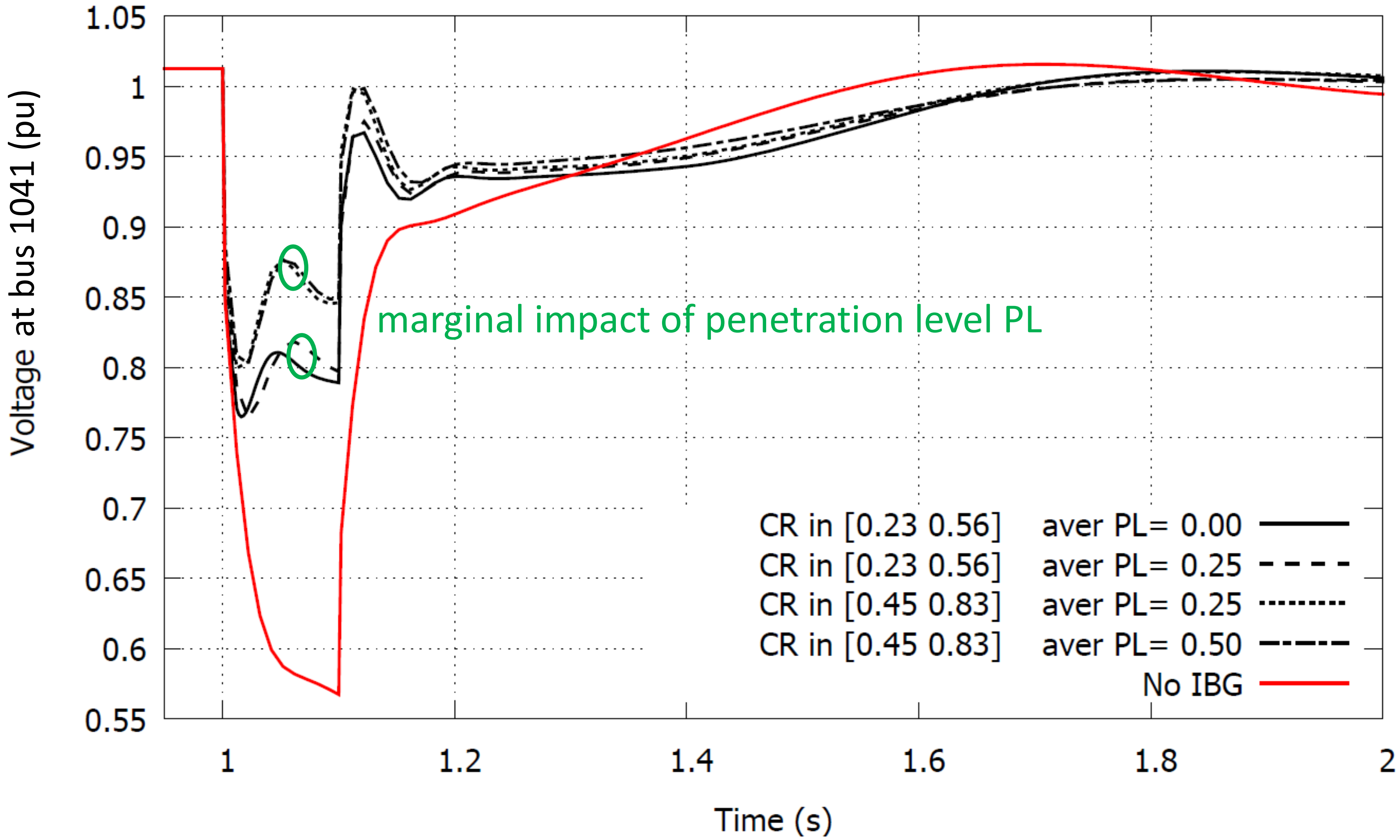

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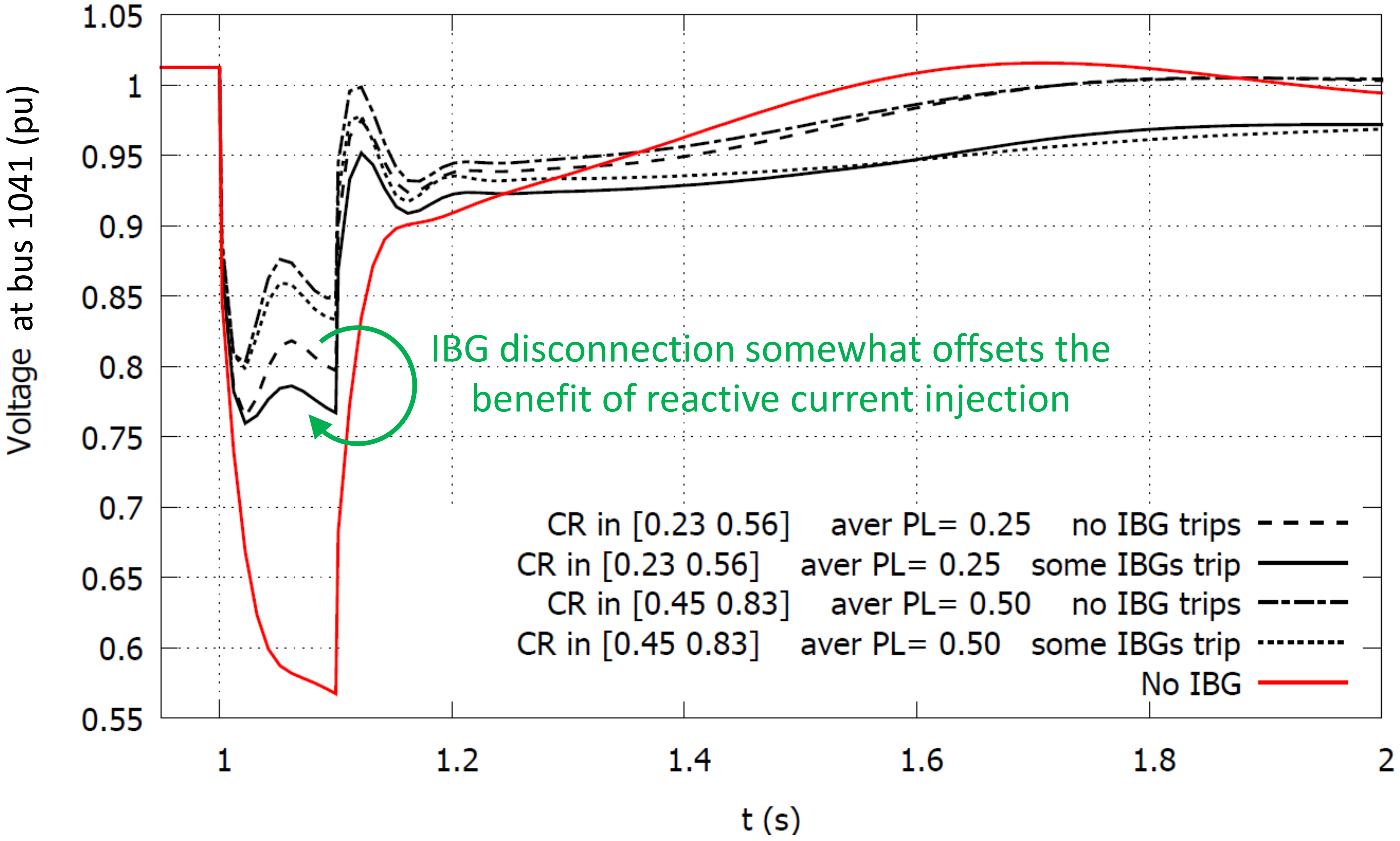
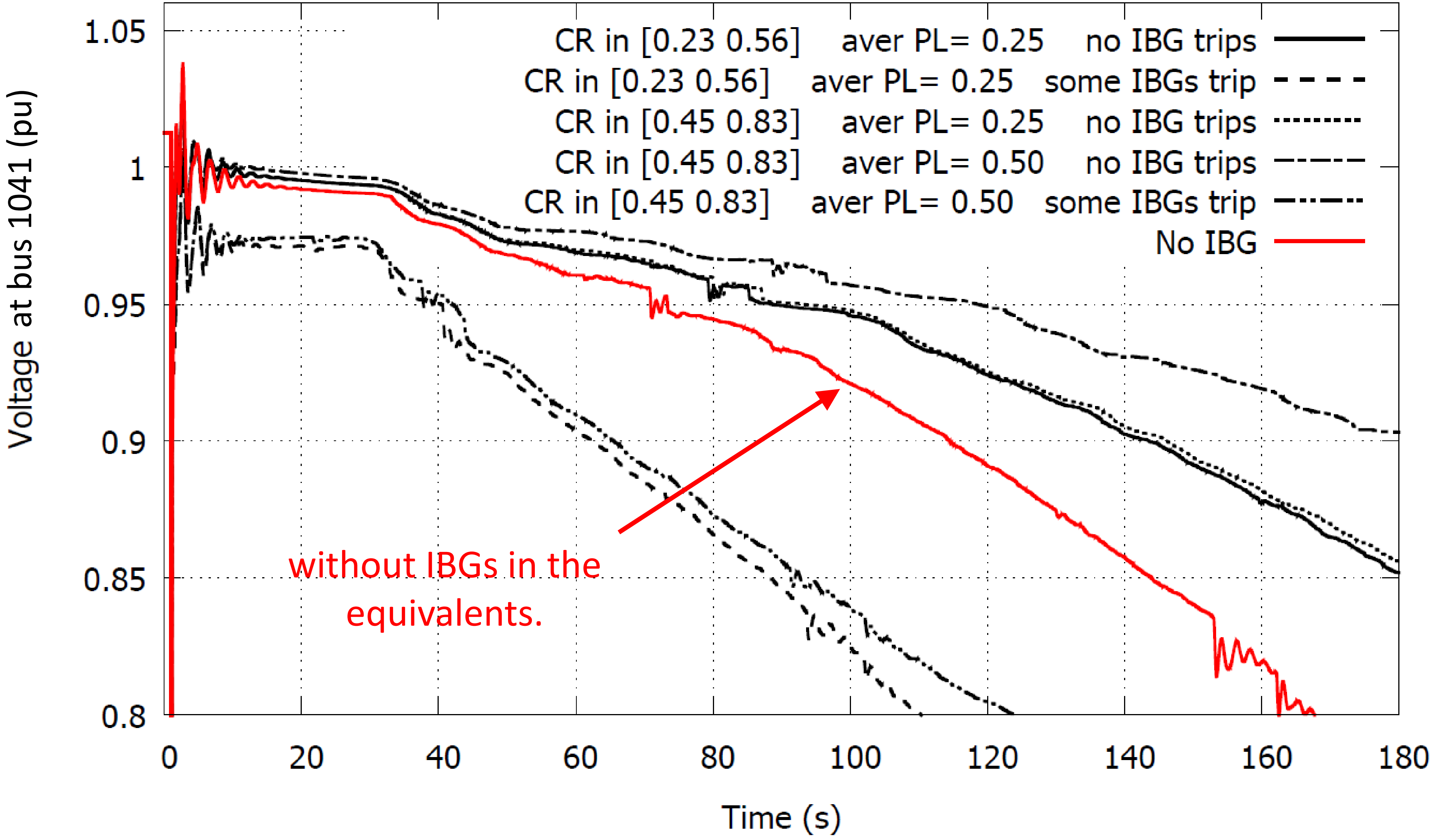


Disconnection of some IBGs due to low voltage

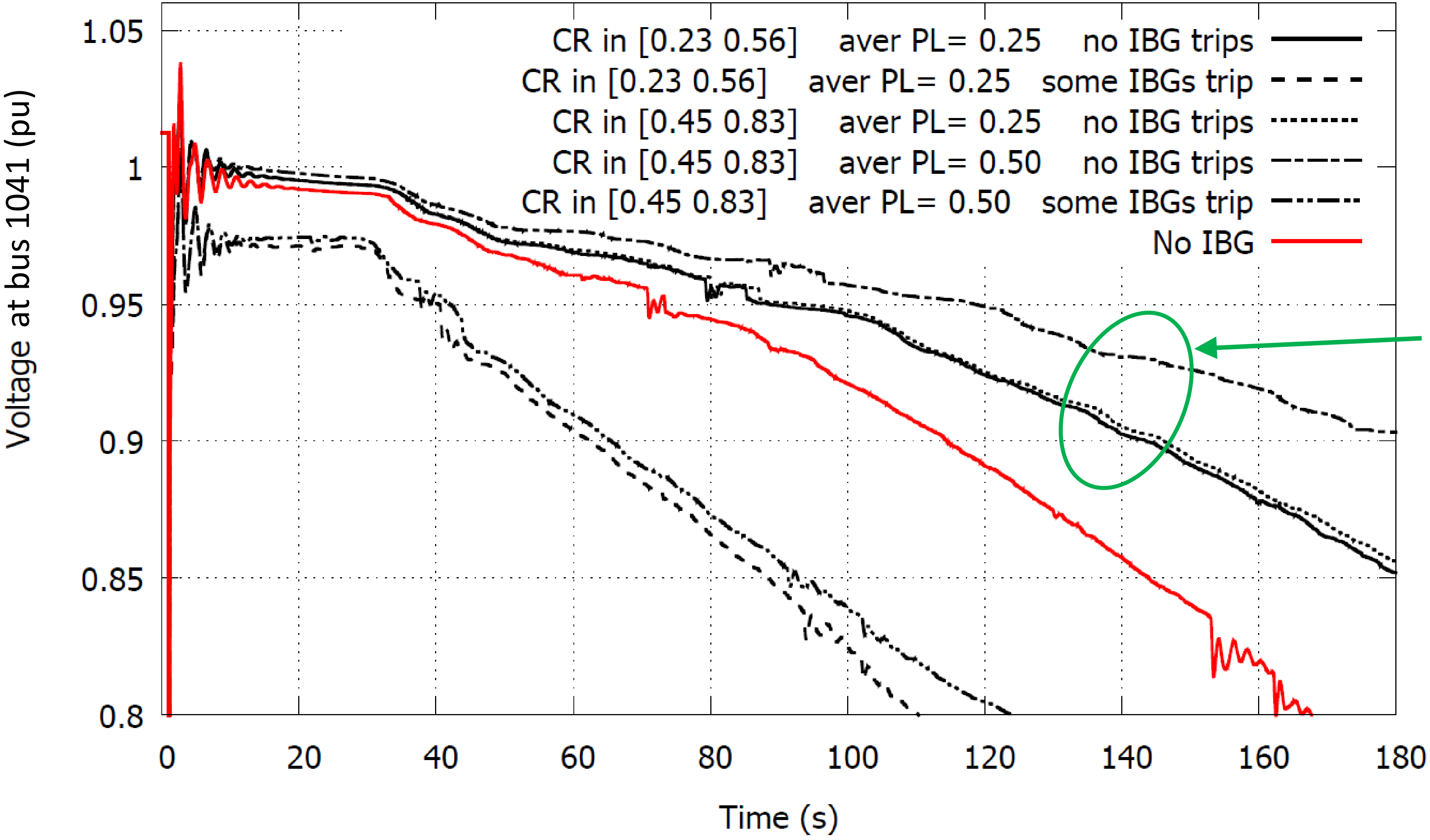
3. Long-term dynamics

Long-term dynamics



Voltage instability driven by LTCs and OELs

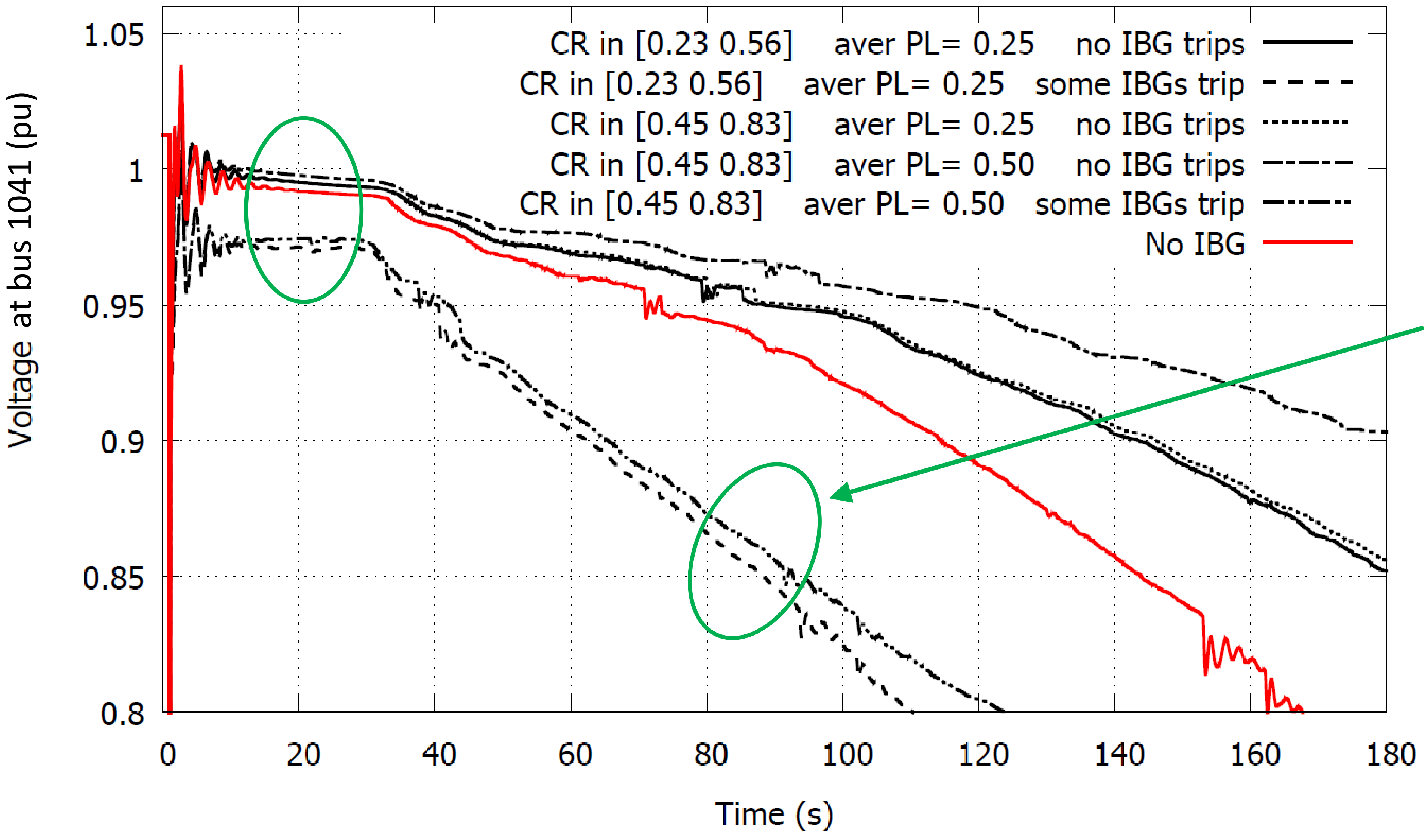
Long-term dynamics



IBG disconnections due to low voltage are not considered

Fall of voltage slowed down by IBGs but LT voltage instability cannot be avoided

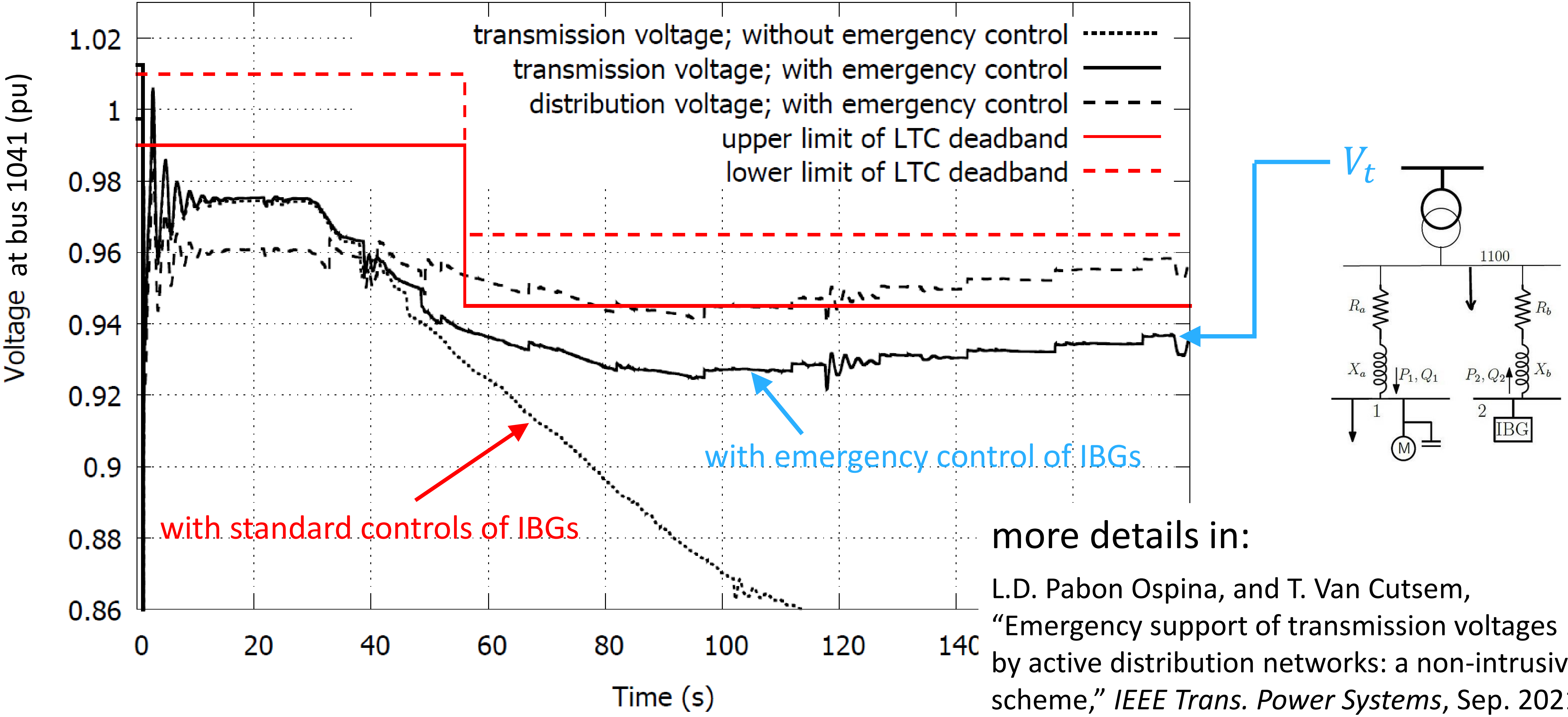
Long-term dynamics



Disconnection of some IBGs due to low voltage

Fall of voltage accelerated by IBG disconnections

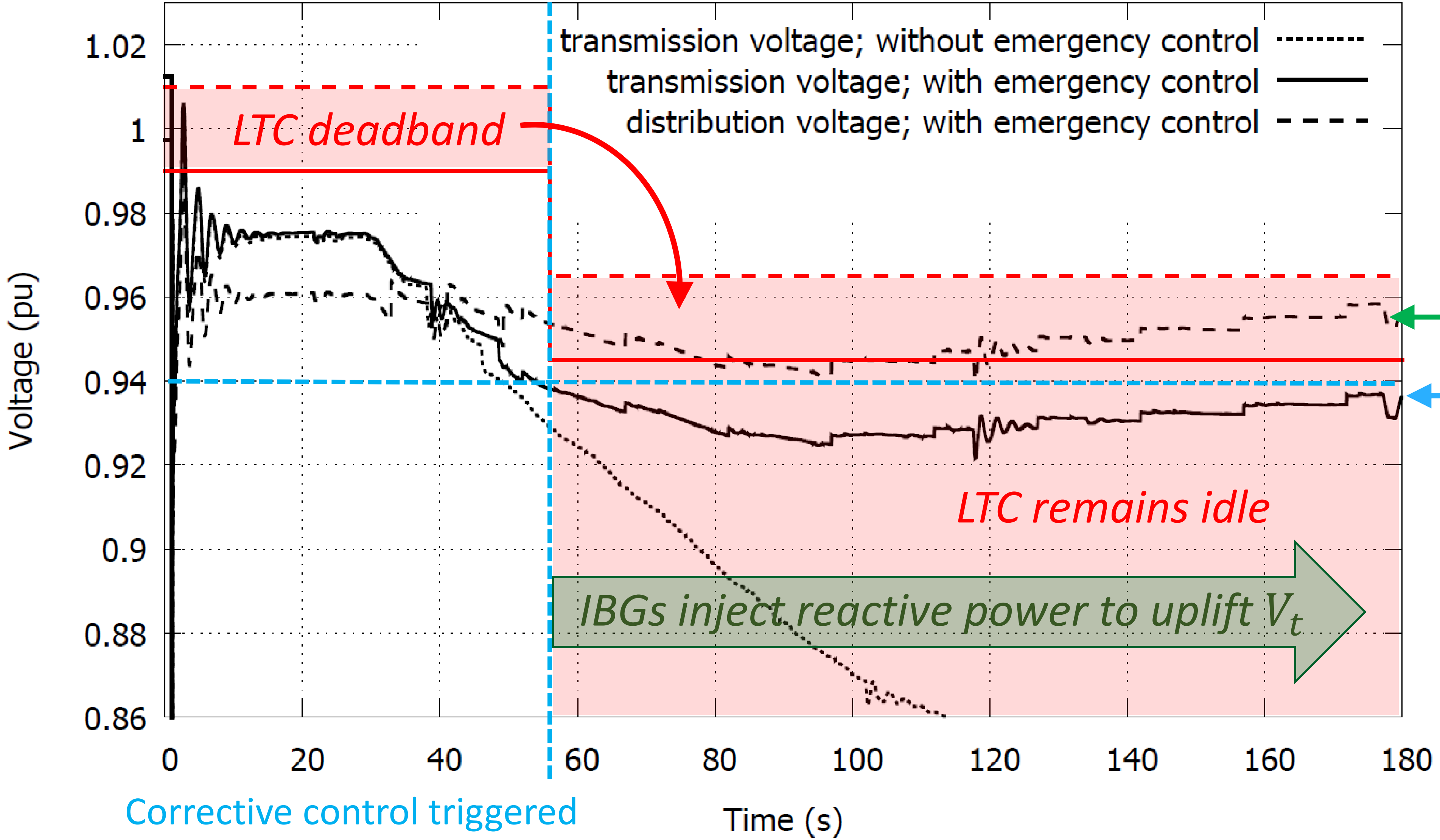
Emergency control of long-term instability

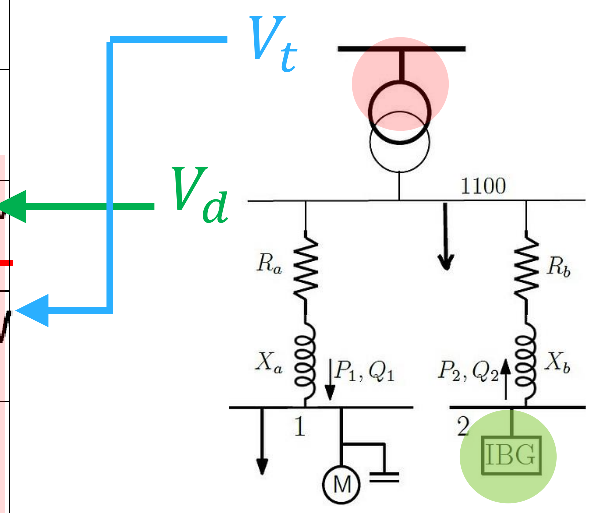


more details in:

L.D. Pabon Ospina, and T. Van Cutsem, "Emergency support of transmission voltages by active distribution networks: a non-intrusive scheme," *IEEE Trans. Power Systems*, Sep. 2021

Corrective control of long-term instability





Conclusion

- Important to account for ADNs in dynamic simulations at transmission level
- individual control of DERs as specified in grid codes impact voltage dynamics
  - 👍 reactive current injection
  - 👎 disconnection of some IBGs due to low voltage
- *additional* emergency control of DERs may improve long-term voltage stability
- "grey-box" dynamic equivalents of ADNs
  - offer a compromise between simplicity and accuracy
  - must account for the above controls.

Thank you for your attention !