Microgrid Stability Definitions, Analysis, and Modeling (IEEE PES PSDPC TF)

Claudio Cañizares and Mostafa Farrokhabadi
University of Waterloo, ECE, ON, Canada
Power & Energy Systems (power.uwaterloo.ca)
WISE (wise.uwaterloo.ca)

Contributors: M. Farrokhabadi, C. Cañizares, J. Simpson-Porco, E. Nasr, L. Fan, P. Mendoza, R. Tonkoski, U. Tamrakar, N. Hatziargyriou, D. Lagos, R. Wies, M. Paolone, M. Liserre, L. Meegahapola, M. Kabalan, A. Hajimiragha, D. Peralta, M. Elizondo, K. Schneider, F. Tuffner, J. Reilly, A. Sumper, M. Aragues

Outline

- Microgrid characteristics relevant to stability
- Stability definitions and classification:
  - Power Balance and Supply Stability:
    - Voltage Stability
    - Frequency Stability
  - Control System Stability:
    - Electric Machine Stability
    - Converter Stability
- Voltage stability and controls examples:
  - V-f dependency and control
  - VSC dc voltage stability
  - PLL bandwidth
  - Droop controls
  - Transformer energization
- Conclusions

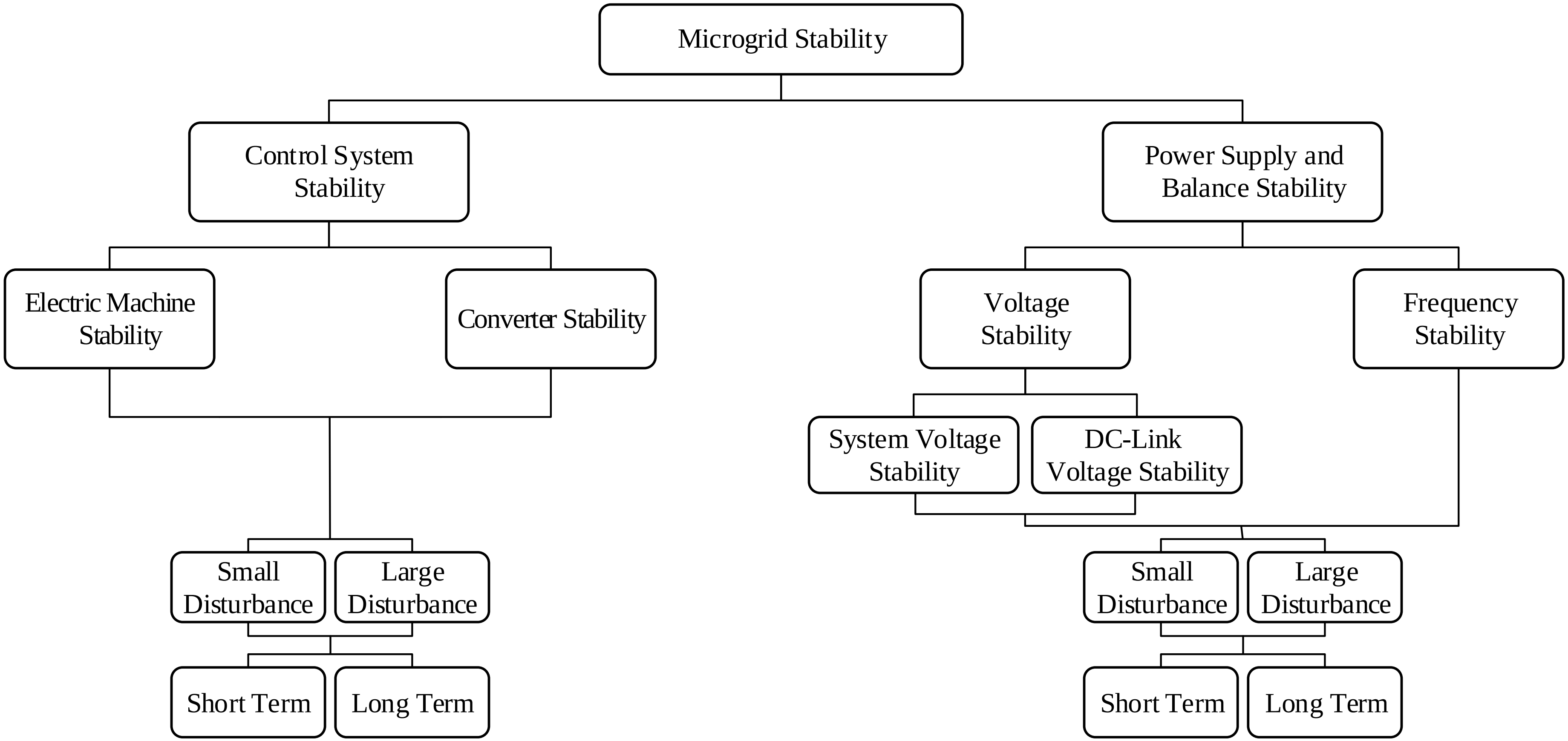
Microgrid Stability Characteristics

- Small system size:
  - Limited number of loads.
  - Short feeders.
- RES:
  - High uncertainty and intermittency.
  - Highly correlated.
- Low system inertia:
  - Small gen. sets.
  - Many DERs are electronically-interfaced.
- High R/X ratio and load voltage dependency:
  - Active and reactive power flows are coupled.
- Unbalanced three-phase loading:
  - New types of instability may occur.

Stability Definition

- A microgrid is stable if all state variables recover after a disturbance to steady-state values that satisfy operational constraints, and *without the occurrence of involuntary load tripping*:
  - Demand response is voluntary load shedding.
  - If loads are disconnected to isolate faulted elements, and not to address voltage and frequency issues, the system is considered stable.
  - Disturbances can be categorized into small and large perturbations.

Classification



Power Supply and Balance Stability

- Ability of the system to maintain power balance, and effectively share the demand power among DERs, so that the system satisfies operational requirements.
- Associated with the loss of a generation unit, violation of DERs limits, poor power sharing among multiple DERs, wrong selection of slack(s) resources, and involuntary no-fault load tripping.
- Subcategorized into frequency and voltage stability.

Frequency Stability

- Main concern in isolated/islanded microgrids.
- System frequency may experience large excursions at a high rate of change due to low inertia.
- Control complications due to voltage-frequency coupling:
  - Coupling of active and reactive power.
  - Small system size yields similar voltage changes at sending and receiving ends.
- Poor coordination of multiple frequency controllers and power sharing among DERs may trigger small-perturbation stability issues, which is rarely observed in larger grids.
- Traditional long-term frequency stabilities pertaining to steam turbine overspeed control and boiler protection and control schemes are not relevant in microgrids.
- Short-term and long-term.

Voltage Stability

- Voltage collapse has not been observed in microgrids.
- Unacceptable low steady-state and dynamic voltages may occur due to:
  - DERs limits.
  - Load sensitivity to operating voltages.
  - Poor reactive power sharing :
    - Feeders are short and thus changes in DER terminal voltages are reflected in the rest of the system.
    - Small differences in voltage magnitudes may yield high circulating reactive power flows and thus large voltage oscillations.
    - Voltage droop may exhibit poor performance.
- DERs dc-link voltage issues are observed in microgrids, especially for systems close to their loading limits.
- Short-term and long-term.

Control System Stability

- Due to inadequate control schemes (e.g., harmonic resonance), and/or poor tuning of one or more pieces of equipment controllers.
- The system cannot be stabilized until the controller is re-tuned or the equipment culprit is disconnected.
- Pertains to electric machines and inverters control loops, LCL filters, and PLLs.
- Subcategorized into Electric Machine and Converter Stability.

Electric Machine Stability

- Conventional angle stability issues have not been observed in microgrids:
  - Due to the resistive nature of microgrids, synchronous machines are likely to decelerate during short circuits.
- Primarily associated with poor tuning of synchronous machines exciters and governors.

UNIVERSITY OF WATERLOO

Converter Stability

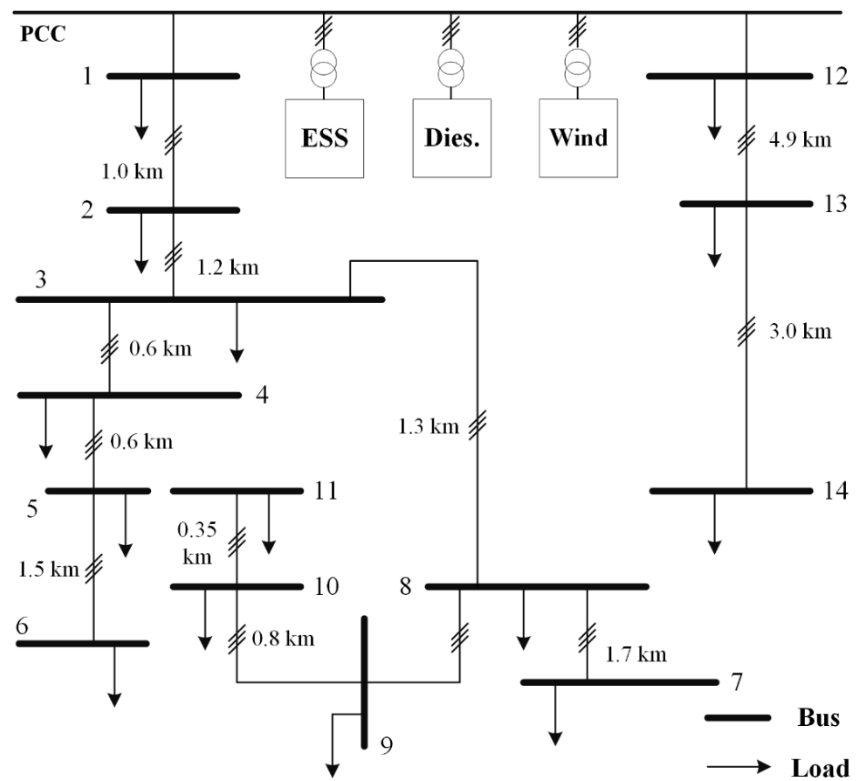
- Inverters inner voltage and current control loops are a major concern for small-perturbation stability.
- System blackout due to DERs tripping after a large disturbance is also a significant concern.
- Interaction of inner current and voltage control loops may cause harmonic instability, as well as high-frequency switching, triggering parallel and series resonances.
- PLLs can create stability issues in microgrids:
  - Introduce negative parallel admittance.
  - Low-bandwidth PLLs may cause instability in heavy-loaded microgrids in the form of low voltage levels
  - PLLs may fail to detect zero crossings during low voltages.

Category	Control System Stability		Power Supply and Balance Stability	
Subcategory	**Electric Machine**	**Converter**	**Voltage**	**Frequency**
Root Cause	Poor controller tuning	Poor controller tuning, PLL bandwidth, PLL synchronization failure, harmonic instability	DERs power limits, inadequate reactive power supply, poor reactive power sharing, load voltage sensitivities, dc-link capacitor	DERs active power limits, inadequate active power supply, poor active power sharing
Manifestation	Undamped oscillations, aperiodic voltage and/or frequency increase or decrease	Undamped oscillations, low steady-state voltages, high-frequency oscillations	Low steady-state voltages, large power swings, high dc-link voltage ripples	High rate of change of frequency, low steady-state frequency, large power and frequency swings

UNIVERSITY OF WATERLOO

Examples: V-f Dependency and Control

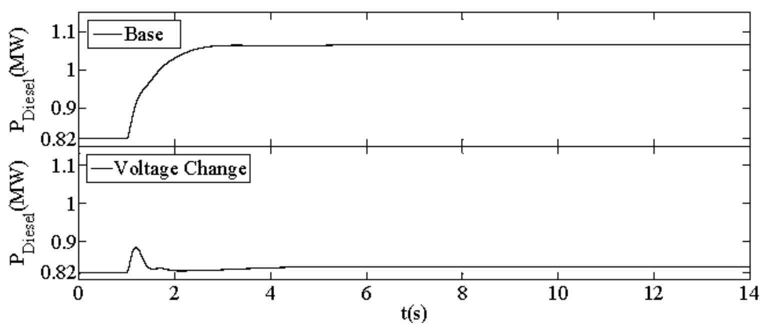
- Modified CIGRE benchmark.
- 1.3 MVA diesel genset, 1 MW ESS, 1 MW wind turbine.
- Voltage-dependent loads with an exponent of 1.5.
- Example of Frequency Stability, associated with voltage control.

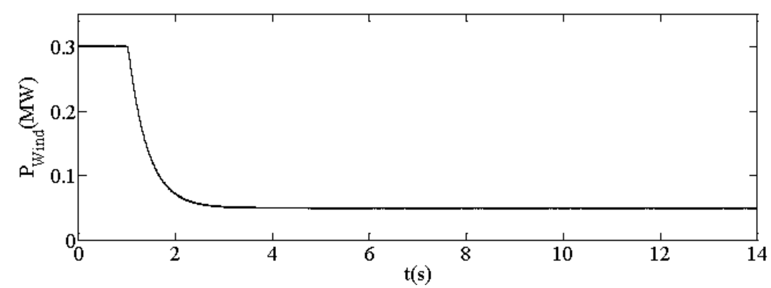


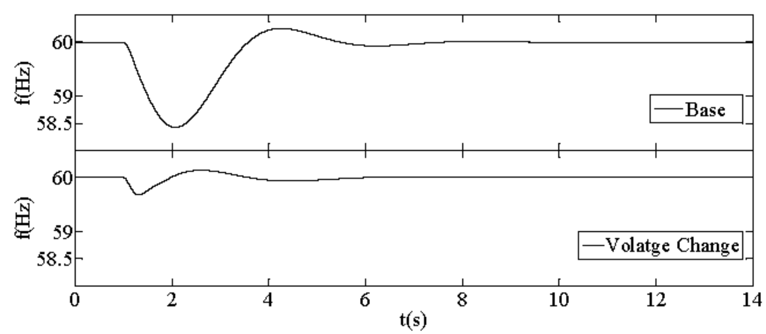
UNIVERSITY OF WATERLOO

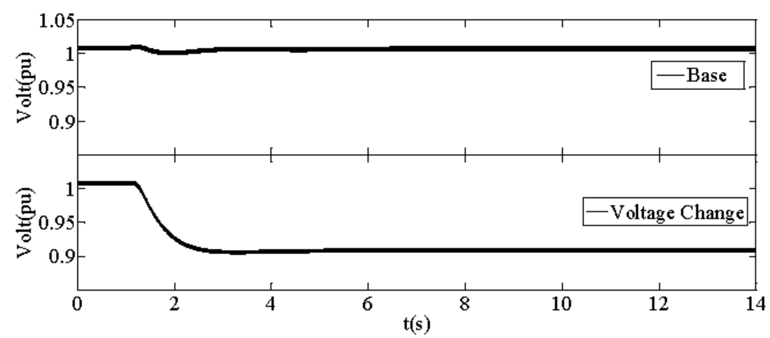
Examples: V-f Dependency and Control

- ESS is injecting 0.5 MW; wind is generating 300 kW; load is 1.6 MW + 0.2 Mvar.
- At t=1 s, the wind output is decreased to 50 kW, and a -0.1pu step change is passed through a lag filter (0.4 s) to the genset AVR.





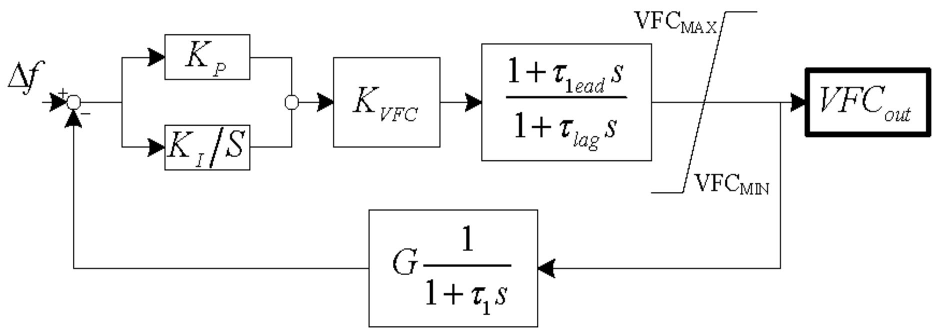


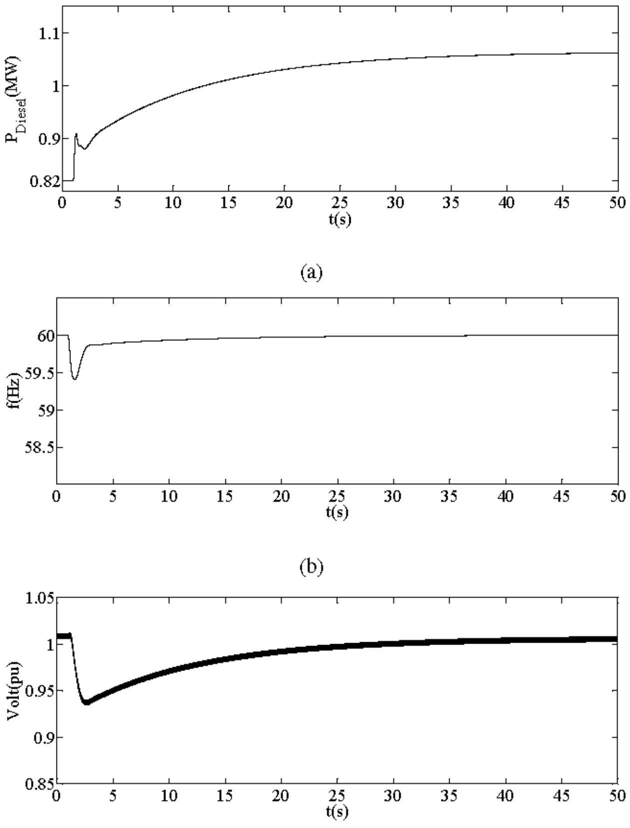


UNIVERSITY OF WATERLOO

Examples: V-f Dependency and Control

- Based on the V-f link, a V-f Controller (VFC) can be added to the genset or other DERs' voltage regulators:





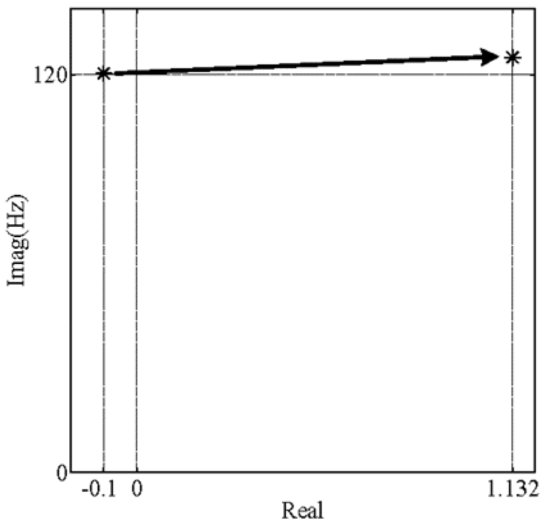
UNIVERSITY OF WATERLOO

Examples: VSC DC Voltage Stability

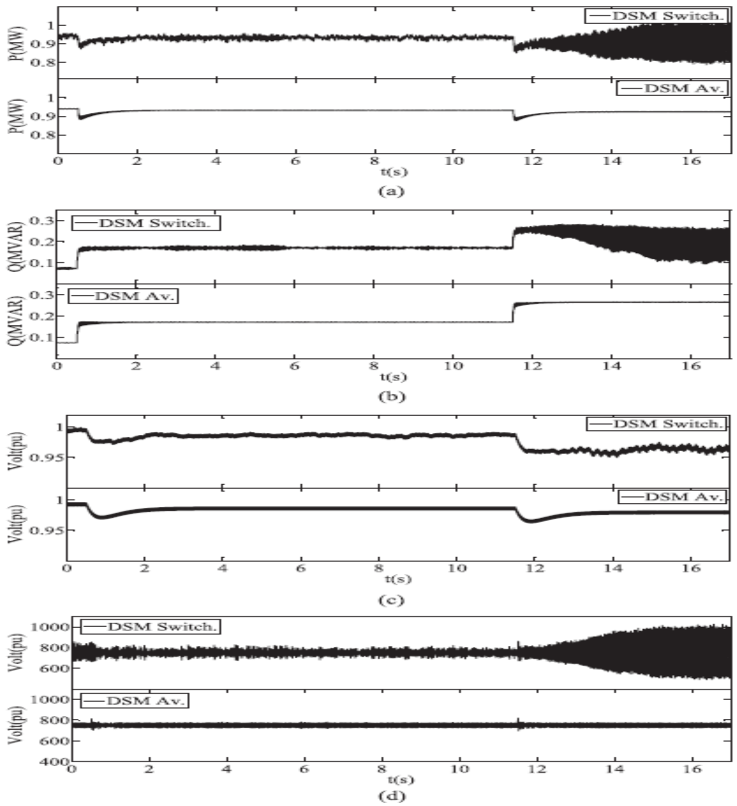
- In the CIGRE benchmark system:
  - Diesel and wind generators disconnected with ESS controlling voltage and frequency (grid-forming mode).
  - Balanced loads are scaled down to 950 kW and 100 kVar, so that that the active power load is near the ESS rated power.
  - At *t* = 0.5s, the loads are proportionally increased by a total of 100 kVar, and at *t* = 11.5s, the total load is again by 100 kVar.
- Example of Voltage Stability.

Examples: VSC DC Voltage Stability

- Stability problem due to dc-link voltage dynamic problems:



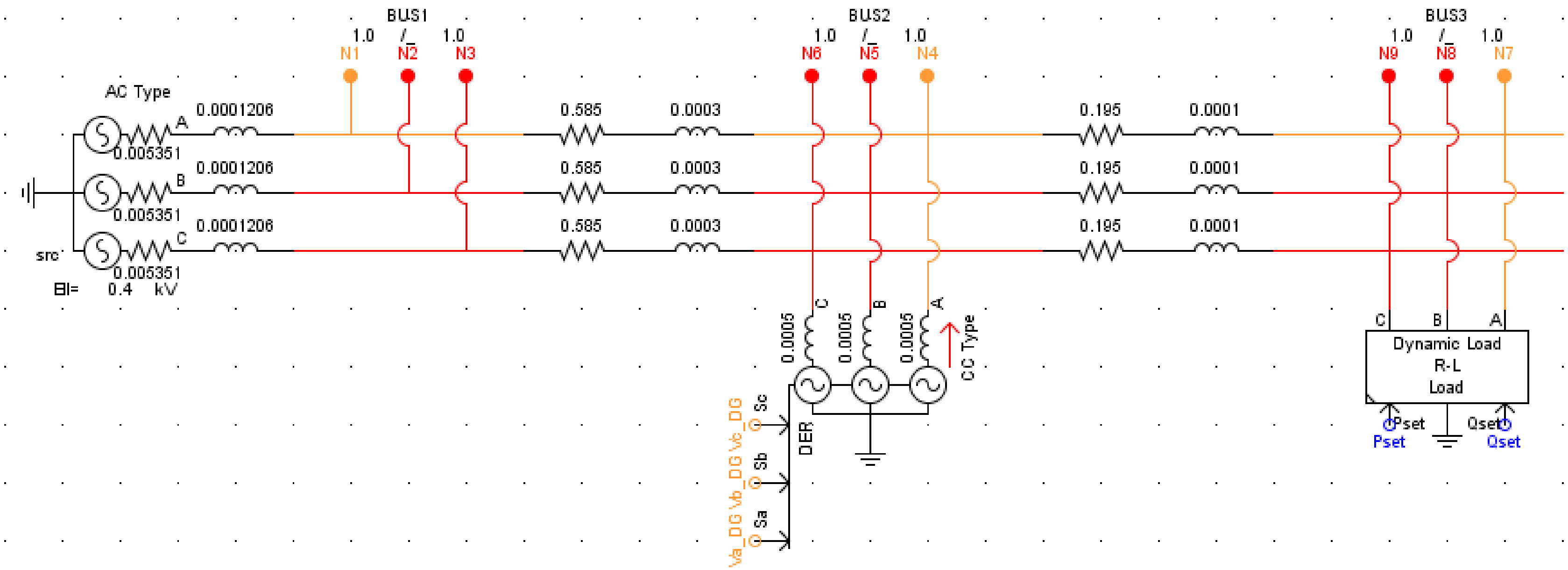
Dominant e-value before and after instability



VSC average model does not show instability

Examples: PLL Bandwidth

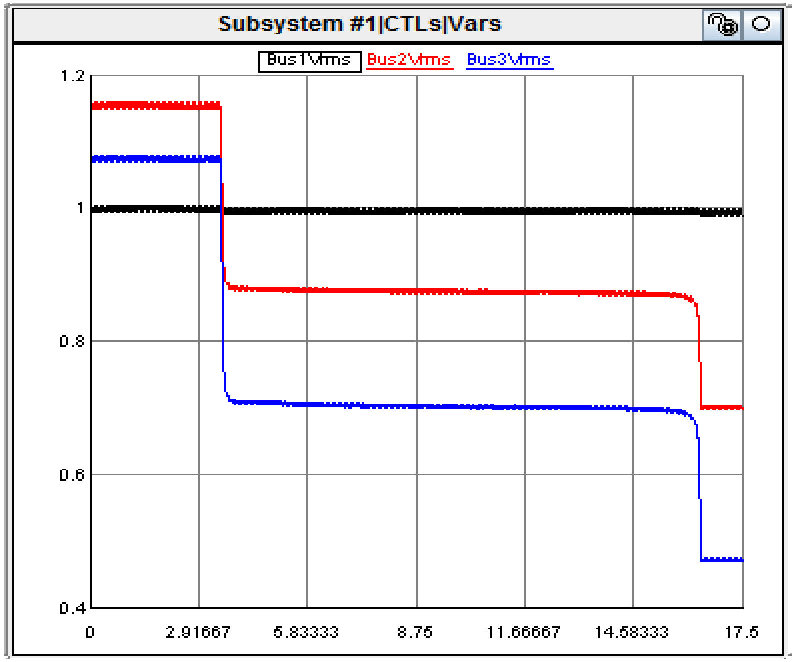
- Three-bus system.
- When Loadability is close to 1pu, a slow PLL introduces stability issues.
- Example of Converter Stability.



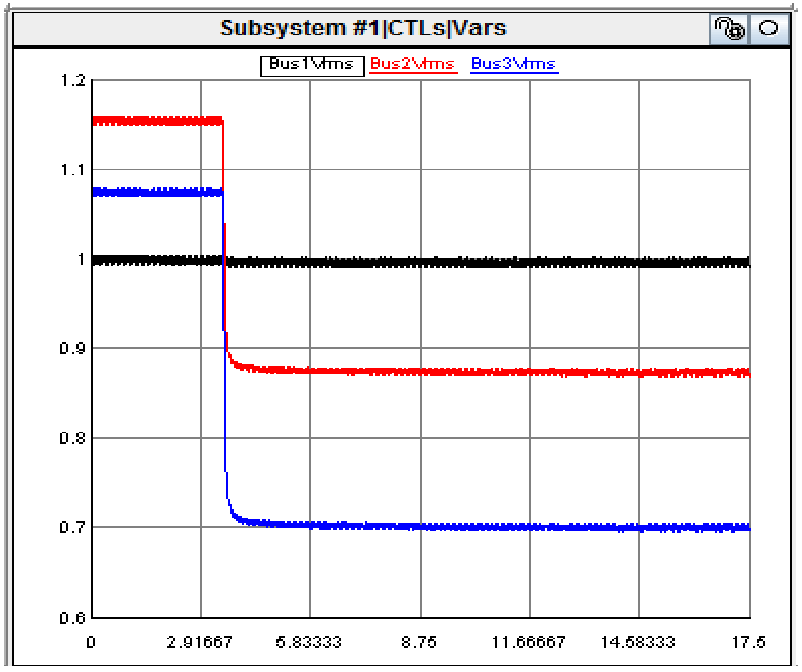
UNIVERSITY OF WATERLOO

Examples: PLL Bandwidth

- The load at bus 3 increased at 3.5 s.
- Control system stability issue.



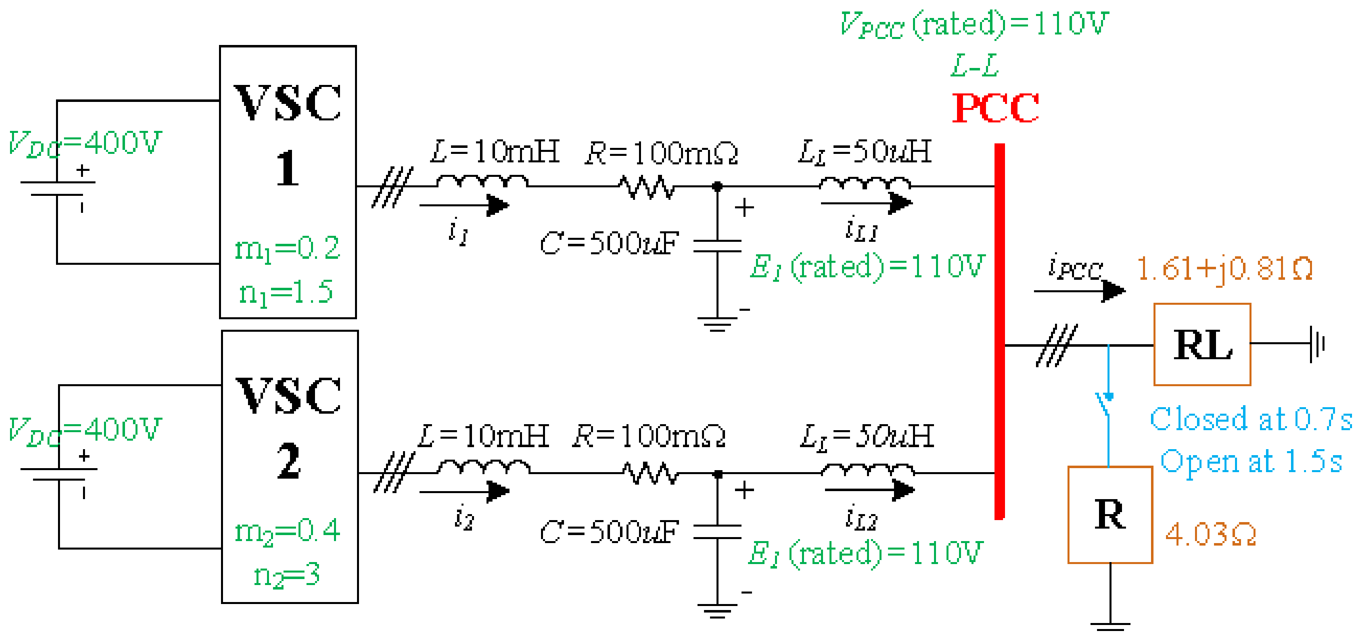
5.7 Hz PLL



20 Hz PLL

Examples: Droop Controls

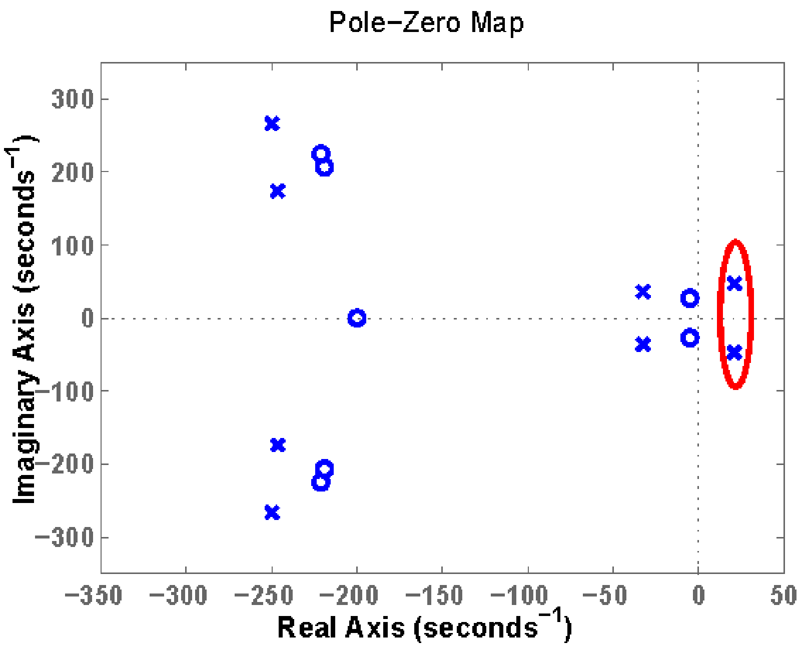
- Oscillations can occur in parallel converters with V-I droop control.
- Such oscillations do not occur if converters are modelled as an aggregated converter, or if droop coefficients be re-tuned.
- Example of Power Supply and Balance Stability.



UNIVERSITY OF WATERLOO

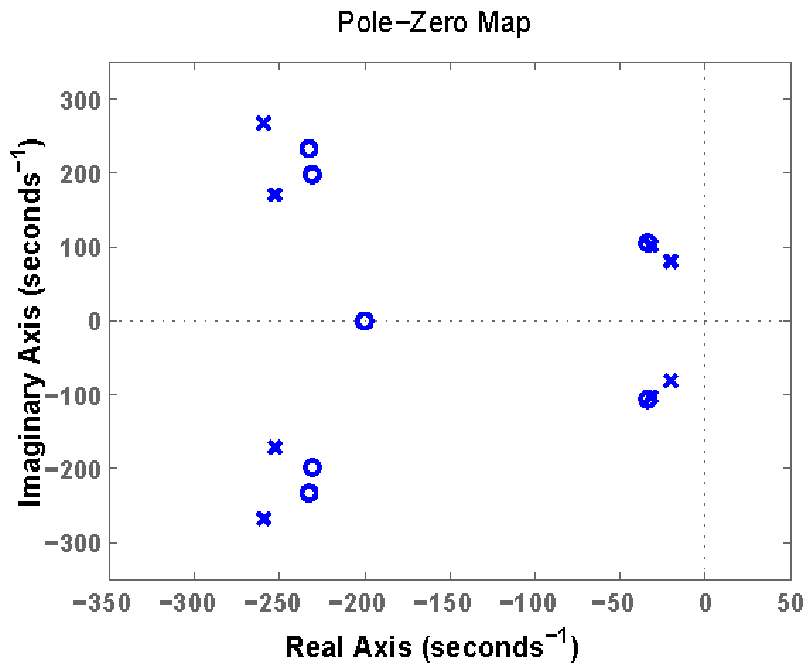
Examples: Droop Controls

- Small droop coefficients introduces stability issues, while increasing those values and/or choosing the same values makes the system stable:



m1=0.004, m2=0.008

n1=0.01, n2=0.02



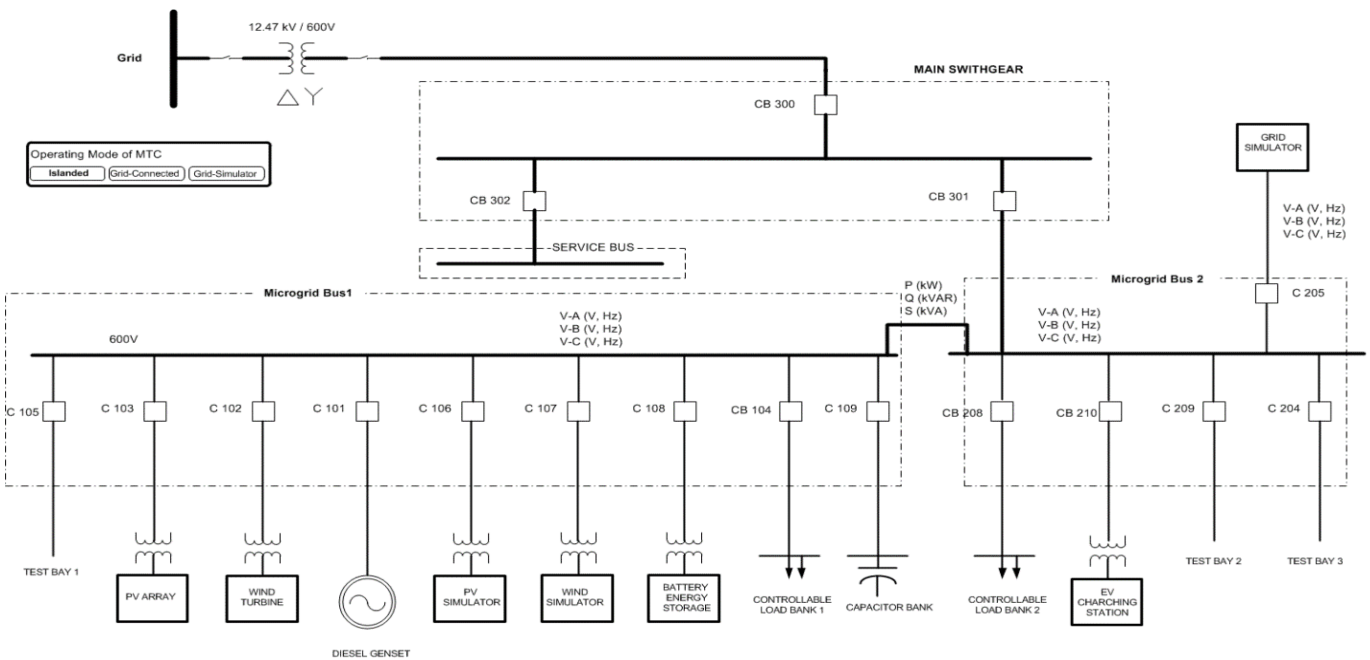
m1=m2=0.04

n1=n2=0.04

UNIVERSITY OF WATERLOO

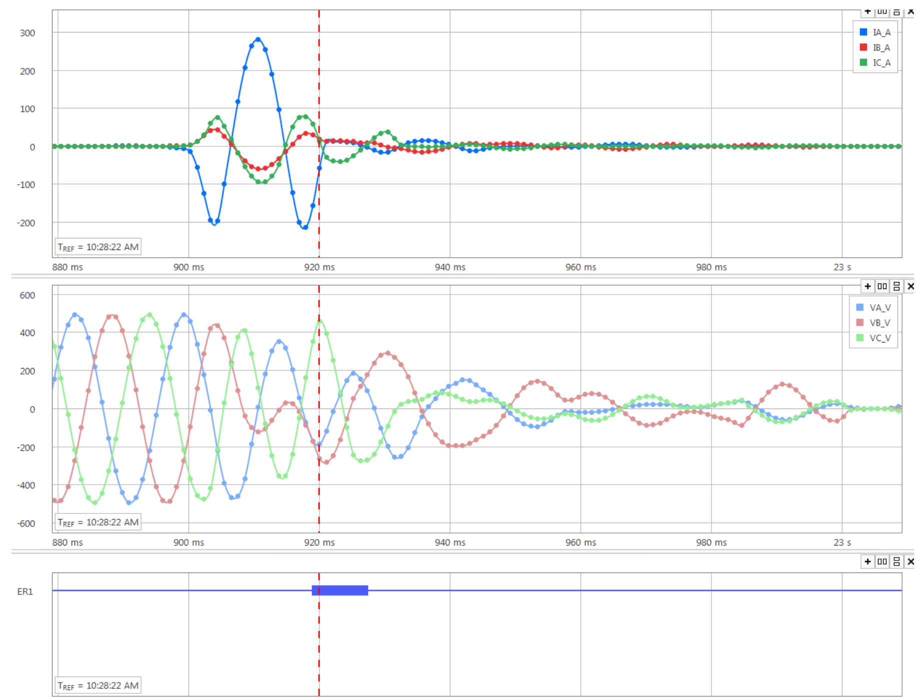
Examples: Transformer Energization

- Test on Canadian Solar's Canadian Renewable Energy Laboratory (CanREL) show that transformer inrush current in inverter-based microgrids may lead to system loss.
- Example of Power Supply and Balance Stability.



Examples: Transformer Energization

- 200 kW battery energy storage is in grid-forming mode with no load.
- Breaker of wind turbine simulator transformer (112.5 kVA, 480V/600V) is then closed, tripping overcurrent protections of the battery inverter.



UNIVERSITY OF WATERLOO

Conclusions

- A classification and definitions of stability in microgrids has been proposed in:
  - IEEE-PES Task Force on Microgrid Stability Analysis and Modeling, “Microgrid Stability Definitions, Analysis, and Examples,” *IEEE Transactions on Power Systems*, preprints, July 2019, 17 pages.
  - “Microgrid Stability Definitions, Analysis, and Examples,” IEEE-PES Microgrid Stability Analysis and Modeling TF, Technical Report PES-TR-66, May 2018, 120 pages.
- Example of various voltage stability problems in microgrids were also shown, providing solutions and controls.
- Stability modeling and analysis techniques an tools were not discussed due to lack of time, but can be found in the TF report, together with other examples of microgrid stability problems, solutions, controls, and modeling.
- From the TF work, it has been concluded that microgrid component models significantly impact the simulation and associated results of dynamic events. Thus, a TF is being proposed to study and determine the validity and types of applications of detailed and approximate models for microgrid dynamic studies and simulations.