Unified Grid-Forming/ Following Converter Control

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Overview

- Energy storage
  - Electric vehicles
  - Grid applications
- Grid-forming/following converters
- Grid modelling
  - Rotating dq-frame references
  - Steady-state conditions
- Examples
- Experiments

Electric vehicles (EVs)

- Around 1 million passenger vehicles are sold in Australia annually.
  - They are designed to last around 10 years, and so are their batteries.
- Average mass of lithium-ion batteries per EV is around 400kg.
- **Moving to 100% EVs would result in disposal of around 400,000 tonnes of batteries per year.**
- No economic “second life” applications (currently).
- Used batteries are crushed into “black mass”.
- No cost-effective process for recycling (currently).

- Current shortages of raw materials are leading to significant price increases.
- No mechanism for tracking whether materials are ethically sourced (e.g. cobalt).
- Given the current generation mix in Australia, EVs may be responsible for more carbon emissions than traditional vehicles.
  - Depending on when they are charged.

Other thoughts on EVs

- EVs are fine for around town but not well suited for long distance travel.
- When fueling a regular vehicle, the energy is delivered at ~5MW.
  - Takes 5 minutes to deliver sufficient energy to drive 700km.
  - The equivalent for an EV would be ~1MW.
- The highest powered “DC fast chargers” are capable of 250kW (currently).
  - Fast charging reduces battery life.

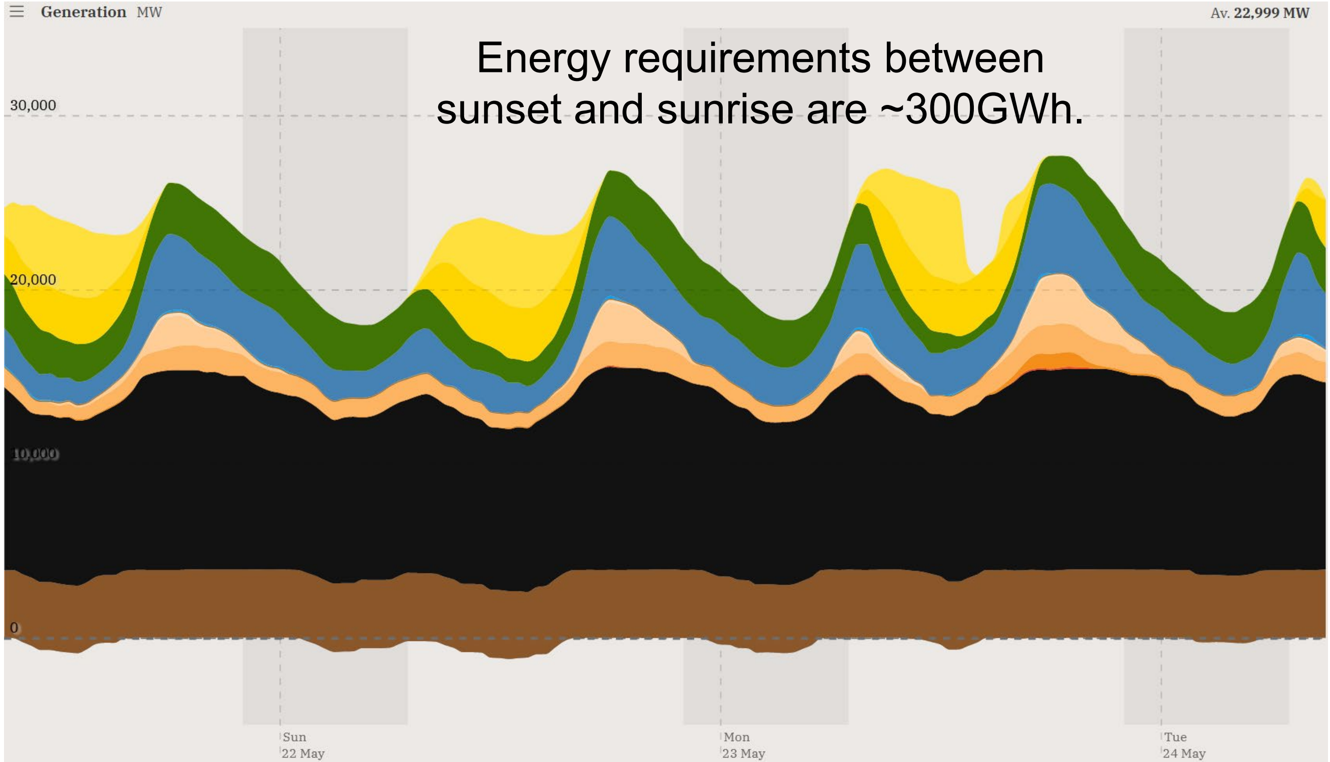
- Large-scale coincident charging of EVs is extremely challenging for the distribution network.

- If EVs are primarily for use around town, why not invest in public transport rather than subsidizing EVs?
- “Range anxiety” is real when venturing into the country.

- Short-term solution: Plug-in hybrid electric vehicles.
- Long-term solution: hydrogen powered fuel-cell vehicles.
  - Storage of hydrogen is challenging.

Renewable generation

- Solar farms require around 1.5 ha to produce 1MW of electricity.
  - A 1000MW solar farm would require 15 sq km.
- Wind farms require around 20 ha to produce 1MW of electricity.
  - The base of each turbine requires around 600 cubic metres of concrete.
  - Gearboxes are vulnerable.
- Significant new transmission will be required to support renewable generation.



Energy requirements between sunset and sunrise are ~300GWh.

Source: opennem.org.au

Bulk energy storage

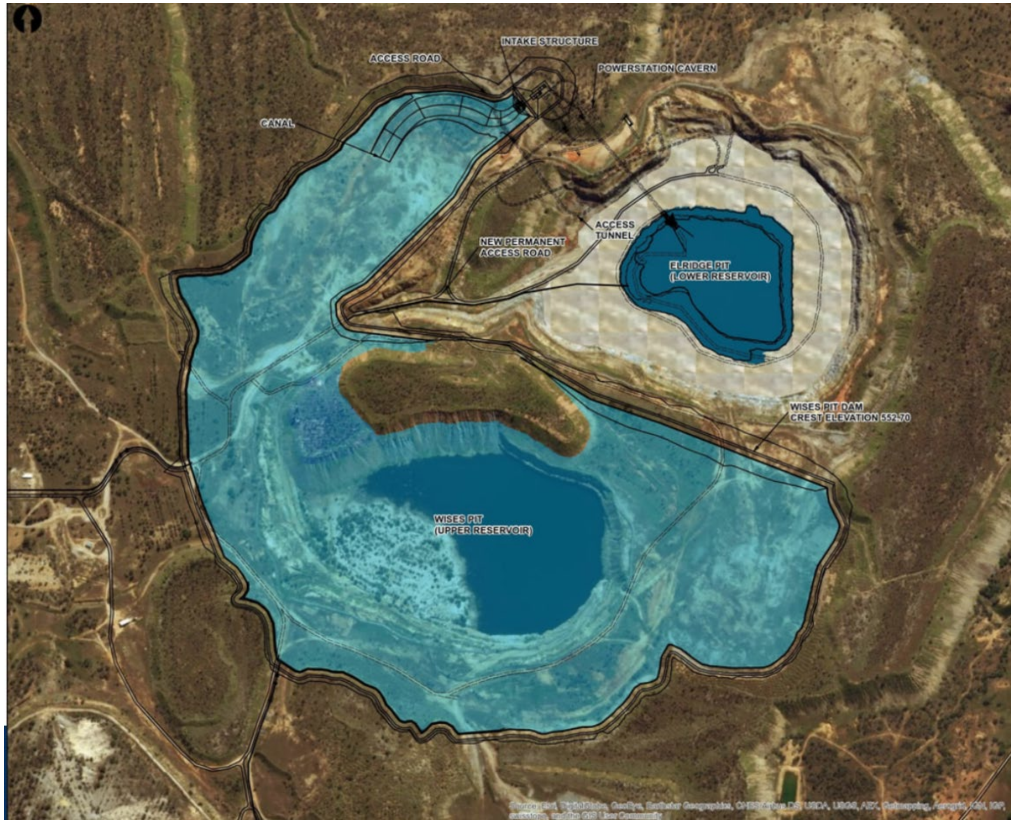
- Energy usage between sunset and sunrise is ~300GWh.
  - That will grow significantly with electrification of cooking and heating, and overnight charging of EVs.
- Presumably a significant amount of that energy will be produced by solar PV during the day and stored.

- Assume solar PV contributes half the overnight energy usage, then storage of ~150GWh is required.
  - Equivalent to ~1500 Hornsdale “Big” batteries.
  - Batteries degrade and must be replaced every 10-15 years.
- What will make up the remainder?
  - Over the period under consideration, wind contributed ~32GWh.

- Pumped hydro storage provides a much more sustainable solution than batteries.
  - Lifespan of 80 years.

Pumped hydro storage

Borumba pumped hydro (proposed)
- Near Gympie, Queensland
- Power, 1500MW
- Energy storage, 30GWh



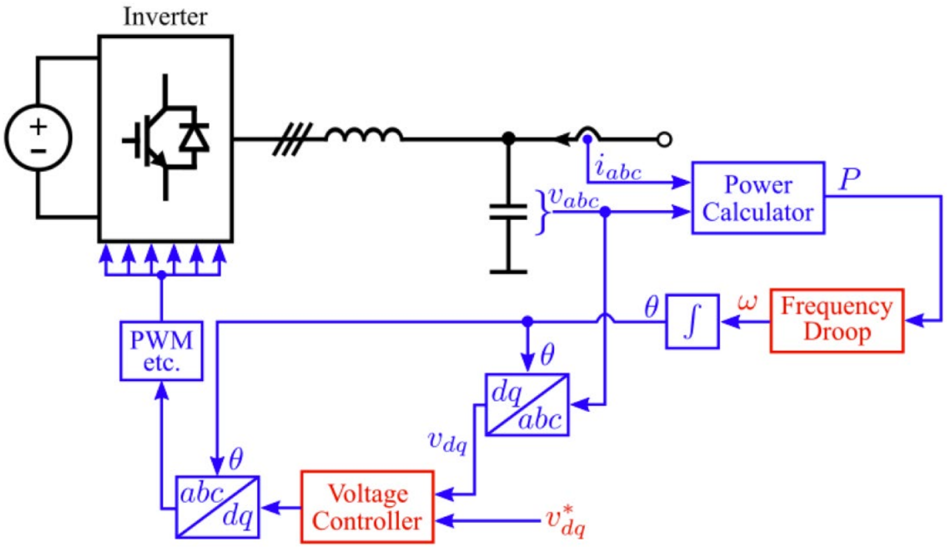
Kidston pumped hydro (under construction)
- Utilizes an old gold mine by transferring water from one pit to the other.
- Power, 250MW
- Energy storage, 2GWh

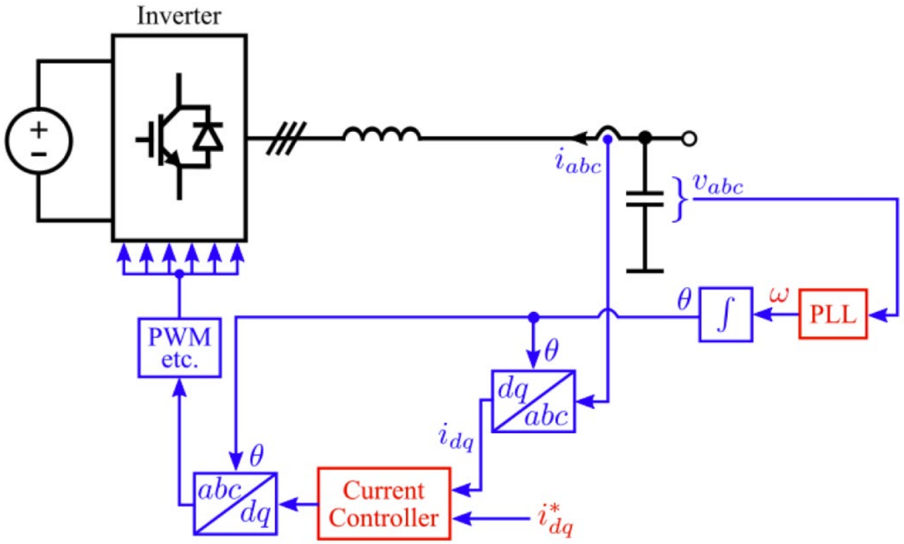
Power system integration of renewables

- Power systems will never be 100% inverter based.
- Inverter-based resources must interact well with synchronous machines.

- Damping of inter-machine and inter-area modal oscillations relies on power system stabilizers (PSSs).
- The damping provided by PSSs is dependent on a phase shift that is system dependent.
- Achieving robustness to huge variations in system conditions (e.g. GW of solar during the day and zero at night) is extremely difficult.

Grid forming/following inverters

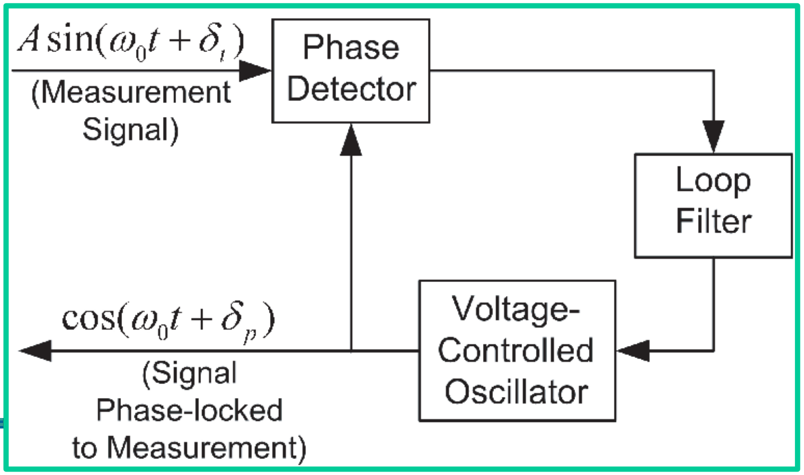




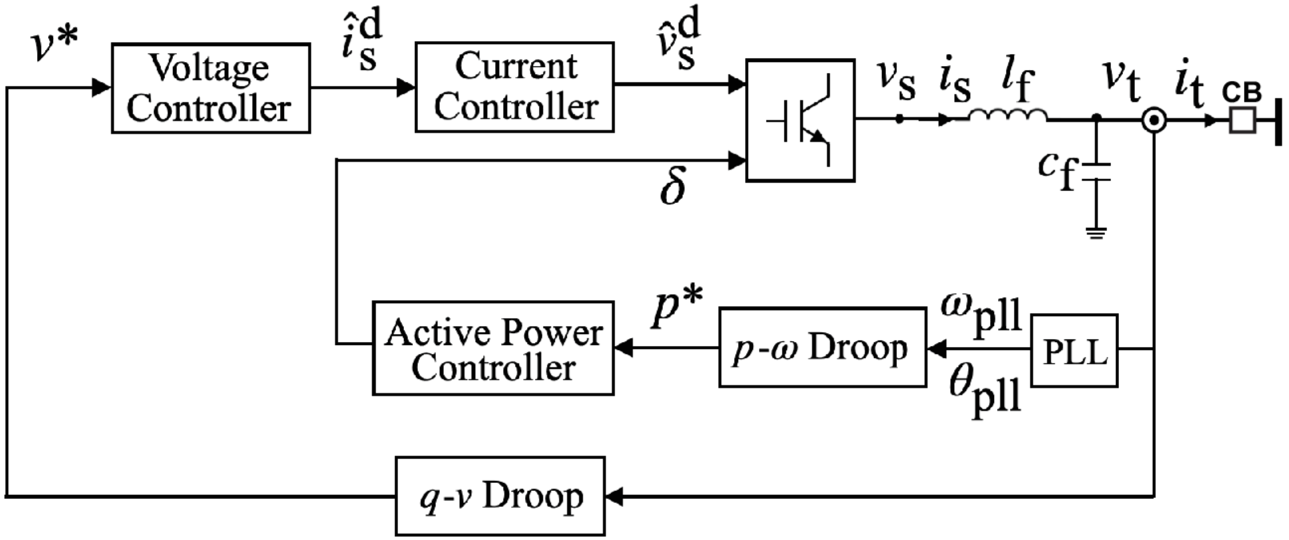
- Grid forming
  - Frequency droop control

- Grid following
  - Phase-locked loop (PLL)

Top two figures are from: Li, Gu, Green, “Revisiting grid-forming and grid following inverters: A duality theory”, IEEE Transactions on Power Systems, 2022.

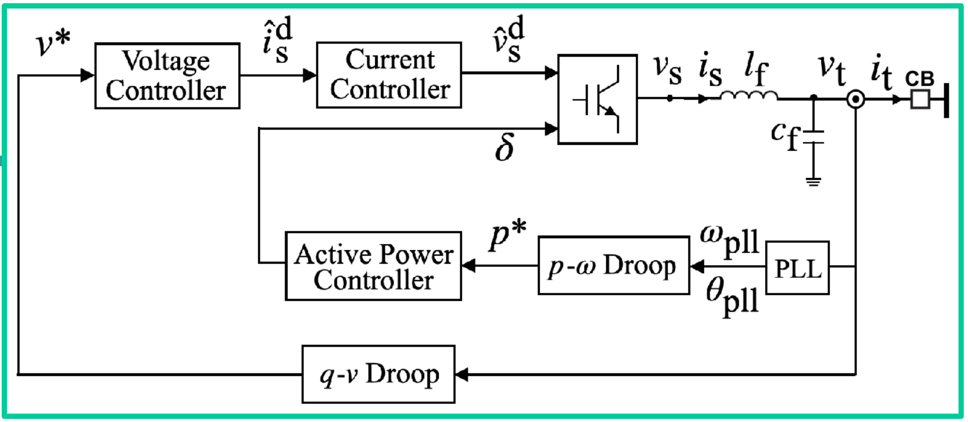


Grid forming with PLL



- The control scheme incorporates both a PLL and power-frequency ($p - \omega$) droop.
  - This hybrid control strategy inherits desirable characteristics of both grid-forming and grid-following inverters.

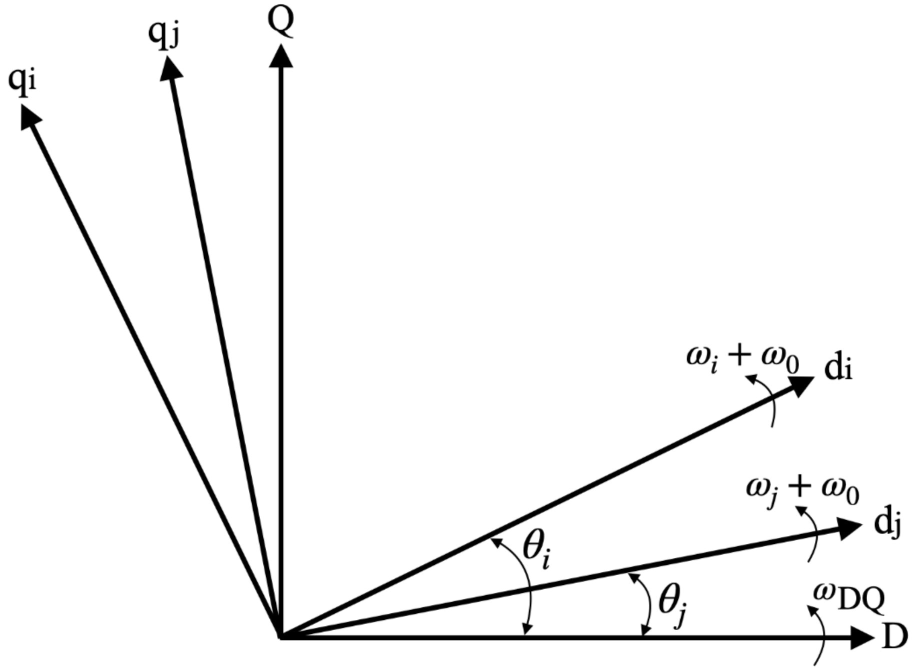
PLL start-up



- Achieving black-start (grid forming) with PLL-based control.

1) With the circuit breaker (CB) open, energize the power electronic inverter at a fixed frequency determined by an internal oscillator. This will energize the LC filter (which is disconnected from the grid).
2) Synchronize the PLL to the filter voltage v_t and switch inverter voltage control from the fixed-frequency oscillator to the PLL.
3) Close the circuit breaker to energize the network. As with black-start of any source, the load on the network must be compatible with the capability of the inverter-based source.
   - If connecting to an energized network, use a synchronism-check relay.

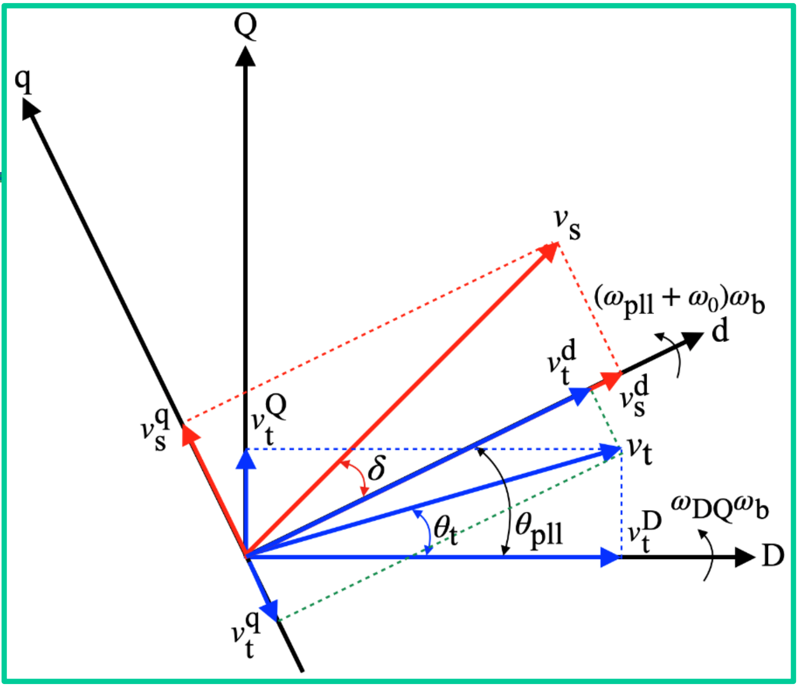
Rotating reference frames



Local (rotating) dq reference frames

Global (rotating) DQ reference frame

Active power dynamics



- PLL dynamics

$$\dot{\xi} = \theta_t - \theta_{pll}$$

$$\omega_{pll} = K_{pll,p}(\theta_t - \theta_{pll}) + K_{pll,i}\xi$$

$$\dot{\theta}_{pll} = (\omega_{pll} + \omega_0 - \omega_{DQ})\omega_b$$

  - The last equation expresses the difference in the rotational velocities of the dq-frame and the DQ-frame.
  - Driving $\theta_t - \theta_{pll}$ to zero is equivalent to aligning the d-axis of the local dq-frame with the terminal voltage v_t .

- Active power droop characteristic

$$p^* = p^0 - m_p\omega_{pll}$$

where p^0 is the active power set-point at nominal frequency ω_0 .

- Active power control

$$\dot{\delta} = K_{p,i}(p^* - p_t)$$

where δ is (effectively) the phase difference across the filter inductance.

Transforming to a common reference

- Each inverter is described relative to its own (local) dq-frame.
  - This is conceptually the same as for synchronous generators.
- Assembling the complete system requires all inverters (and generators) to be referenced to the global DQ-frame.
- Define the rotation matrix,

$$\mathcal{R}(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$$

  where θ denotes the angle of the local dq-frame with respect to the global DQ-frame.
- The angle of the inverter local dq-frame is specified by the PLL angle θ_{pll} giving,

$$\begin{bmatrix} v_{\mathrm{t}}^{\mathrm{D}} \\ v_{\mathrm{t}}^{\mathrm{Q}} \end{bmatrix} = \mathcal{R}(\theta_{\mathrm{pll}}) \begin{bmatrix} v_{\mathrm{t}}^{\mathrm{d}} \\ v_{\mathrm{t}}^{\mathrm{q}} \end{bmatrix}, \qquad \begin{bmatrix} i_{\mathrm{t}}^{\mathrm{D}} \\ i_{\mathrm{t}}^{\mathrm{Q}} \end{bmatrix} = \mathcal{R}(\theta_{\mathrm{pll}}) \begin{bmatrix} i_{\mathrm{t}}^{\mathrm{d}} \\ i_{\mathrm{t}}^{\mathrm{q}} \end{bmatrix}$$

Dynamic line modelling

- Consider a three-phase RL branch,

$$\boldsymbol{v}^{\mathrm{abc}} = L\frac{d}{dt}\boldsymbol{i}^{\mathrm{abc}} + R\boldsymbol{i}^{\mathrm{abc}}$$

  where $\boldsymbol{v}^{\mathrm{abc}} = [v_a \; v_b \; v_c]^{\mathsf{T}}$ is the vector of voltages across the branch and $\boldsymbol{i}^{\mathrm{abc}} = [i_a \; i_b \; i_c]^{\mathsf{T}}$ is the vector of currents.

- This can be viewed from a DQ rotating reference frame using the transformation $\boldsymbol{v}^{\mathrm{DQ0}} = T_\theta \boldsymbol{v}^{\mathrm{abc}}$ and $\boldsymbol{i}^{\mathrm{DQ0}} = T_\theta \boldsymbol{i}^{\mathrm{abc}}$, where

$$T_\theta = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

- The resulting model in the DQ-frame,

$$\dot{i}^{\mathrm{D}} = \frac{\omega_{\mathrm{b}}}{l_{\mathrm{pu}}} v^{\mathrm{D}} + \omega_{\mathrm{DQ}}\omega_{\mathrm{b}} i^{\mathrm{Q}} - \frac{r_{\mathrm{pu}}\omega_{\mathrm{b}}}{l_{\mathrm{pu}}} i^{\mathrm{D}}$$
$$\dot{i}^{\mathrm{Q}} = \frac{\omega_{\mathrm{b}}}{l_{\mathrm{pu}}} v^{\mathrm{Q}} - \omega_{\mathrm{DQ}}\omega_{\mathrm{b}} i^{\mathrm{D}} - \frac{r_{\mathrm{pu}}\omega_{\mathrm{b}}}{l_{\mathrm{pu}}} i^{\mathrm{Q}}$$

  where $\omega_{DQ}\omega_b = d\theta/dt$ is the frequency (rotational velocity) of the DQ-frame.

Steady state

- From previous slide,

$$\dot{i}^{\mathrm{D}} = \frac{\omega_{\mathrm{b}}}{l_{\mathrm{pu}}} v^{\mathrm{D}} + \omega_{\mathrm{DQ}}\omega_{\mathrm{b}} i^{\mathrm{Q}} - \frac{r_{\mathrm{pu}}\omega_{\mathrm{b}}}{l_{\mathrm{pu}}} i^{\mathrm{D}}$$
$$\dot{i}^{\mathrm{Q}} = \frac{\omega_{\mathrm{b}}}{l_{\mathrm{pu}}} v^{\mathrm{Q}} - \omega_{\mathrm{DQ}}\omega_{\mathrm{b}} i^{\mathrm{D}} - \frac{r_{\mathrm{pu}}\omega_{\mathrm{b}}}{l_{\mathrm{pu}}} i^{\mathrm{Q}}$$

$$(\omega_{DQ}\omega_b = d\theta/dt)$$

- If ω_{DQ} is chosen equal to the steady-state frequency ω_{ss} then at steady state $\dot{i}^D = \dot{i}^Q = 0$ giving,

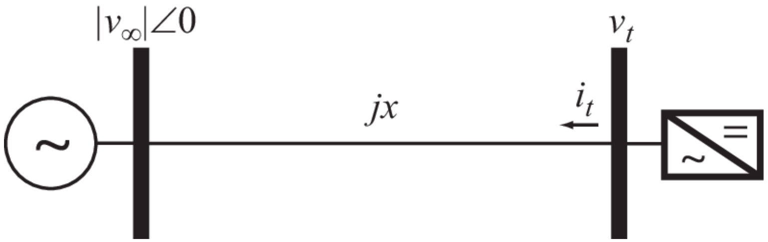
$$v^{\mathrm{D}} = r_{pu} i^{\mathrm{D}} - \omega_{\mathrm{ss}} l_{pu} i^{\mathrm{Q}}$$
$$v^{\mathrm{Q}} = r_{pu} i^{\mathrm{Q}} + \omega_{\mathrm{ss}} l_{pu} i^{\mathrm{D}}$$

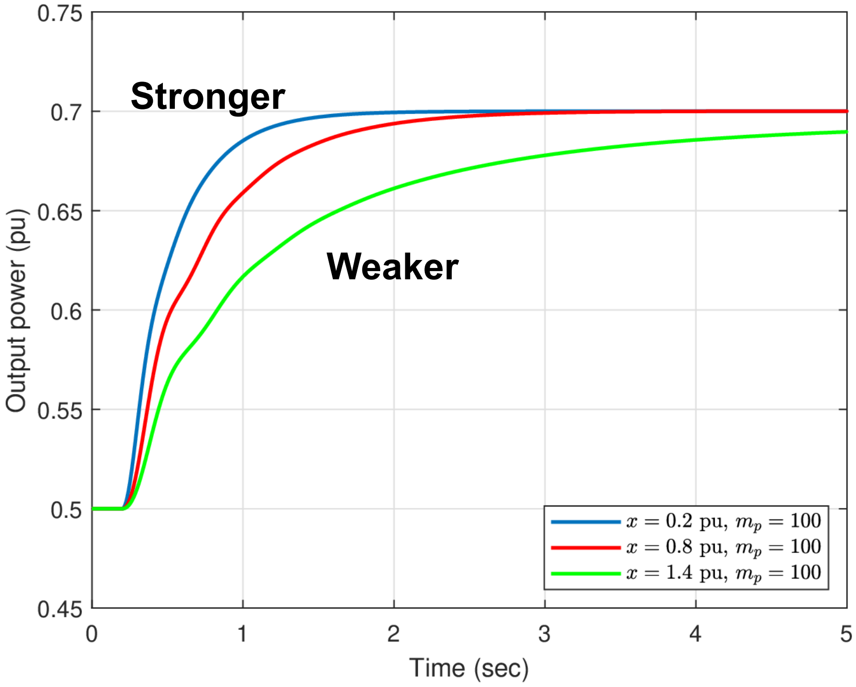
$$(*)$$

- If $\omega_{DQ} \neq \omega_{ss}$ then an oscillatory (limit cycle) steady-state results with $\dot{i}^{\mathrm{D}} = -(\omega_{\mathrm{ss}} - \omega_{\mathrm{DQ}})\omega_{\mathrm{b}} i^{\mathrm{Q}}$ and $\dot{i}^{\mathrm{Q}} = (\omega_{\mathrm{ss}} - \omega_{\mathrm{DQ}})\omega_{\mathrm{b}} i^{\mathrm{D}}$.
- Substitution and manipulation again gives $(*)$, which can be rewritten, $(v^{\mathrm{D}} + jv^{\mathrm{Q}}) = (r_{pu} + j\omega_{\mathrm{ss}} l_{pu})(i^{\mathrm{D}} + ji^{\mathrm{Q}})$
- This is exactly the phasor representation, but with frequency ω_{ss} rather than the nominal frequency ω_0 .

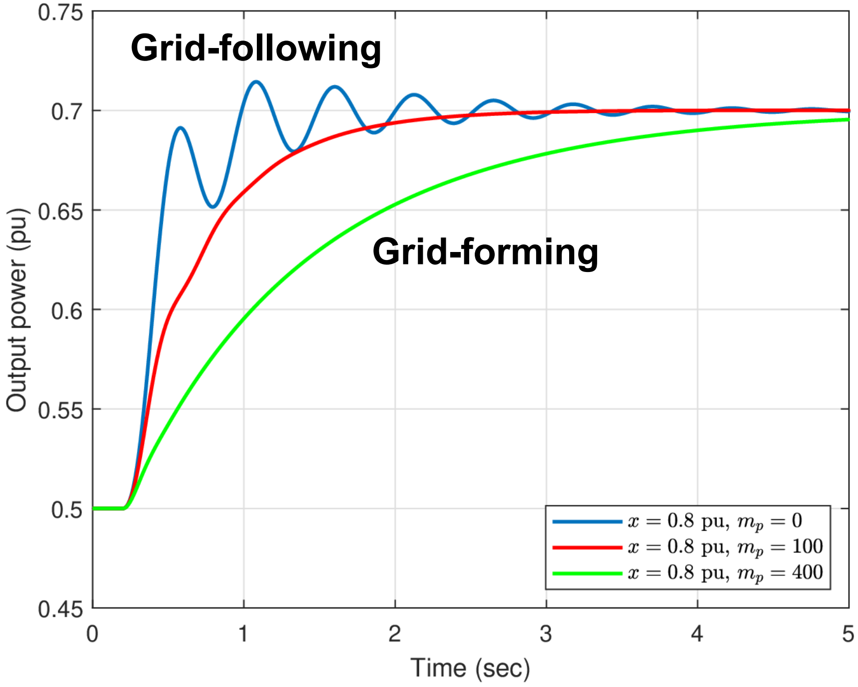
Example: single inverter

- Consider a single inverter connected to a Thevenin equivalent network.





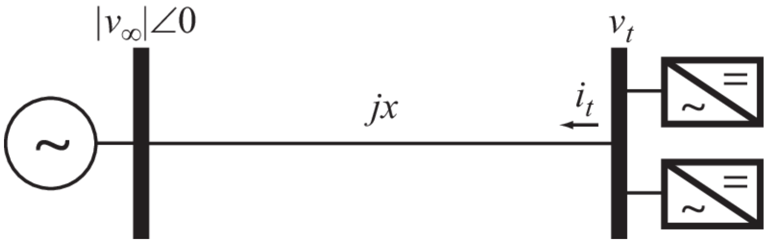
Variation of x (system impedance)

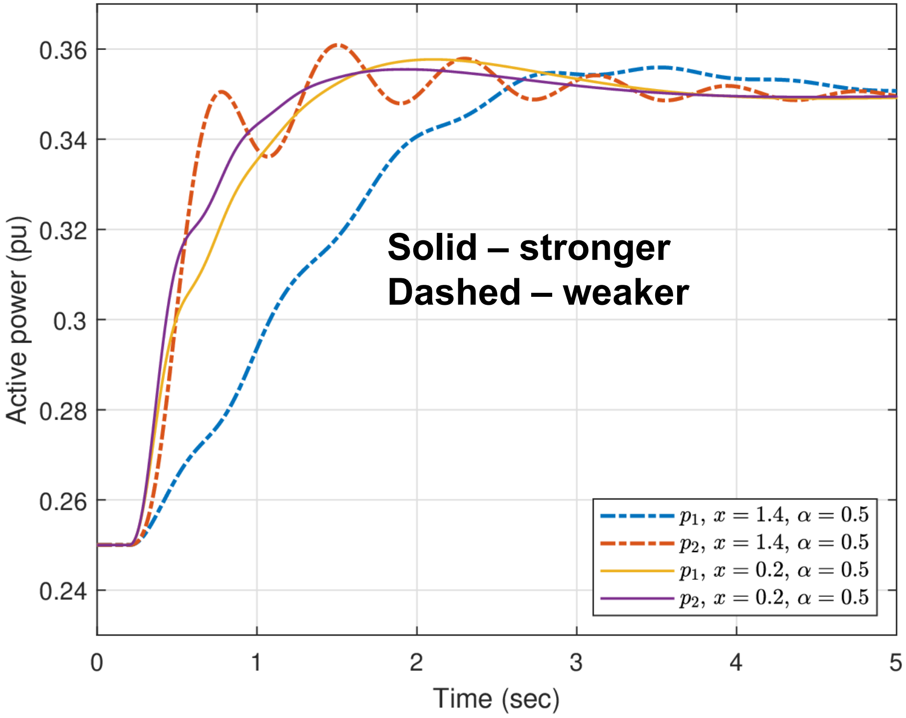


Variation of m_p (droop parameter)

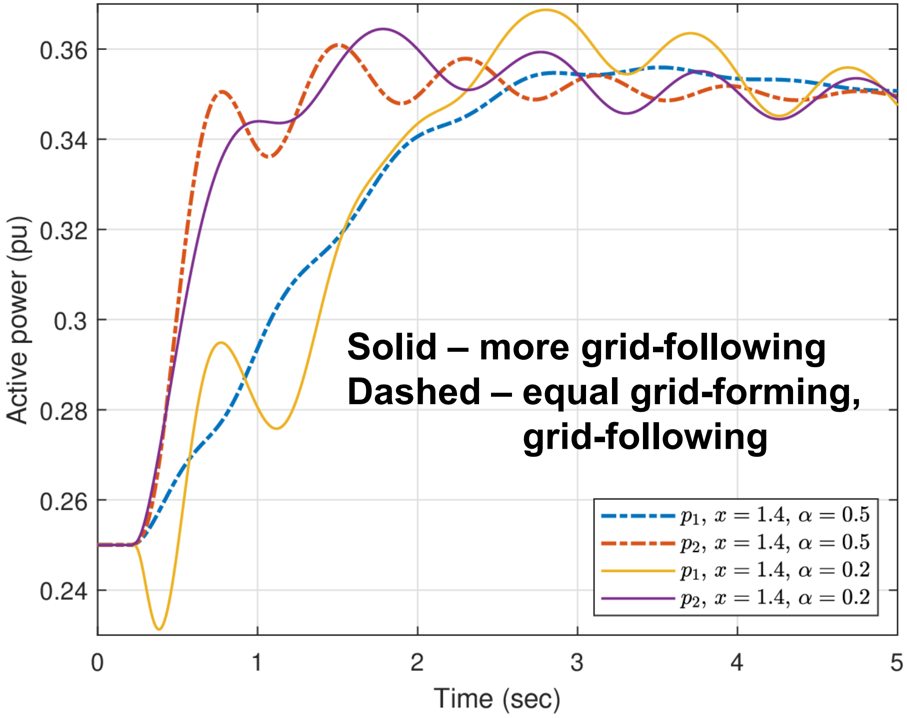
Two inverters at a common bus

- The proportion of grid-forming and grid-following is weight by α and $(1-\alpha)$ respectively.





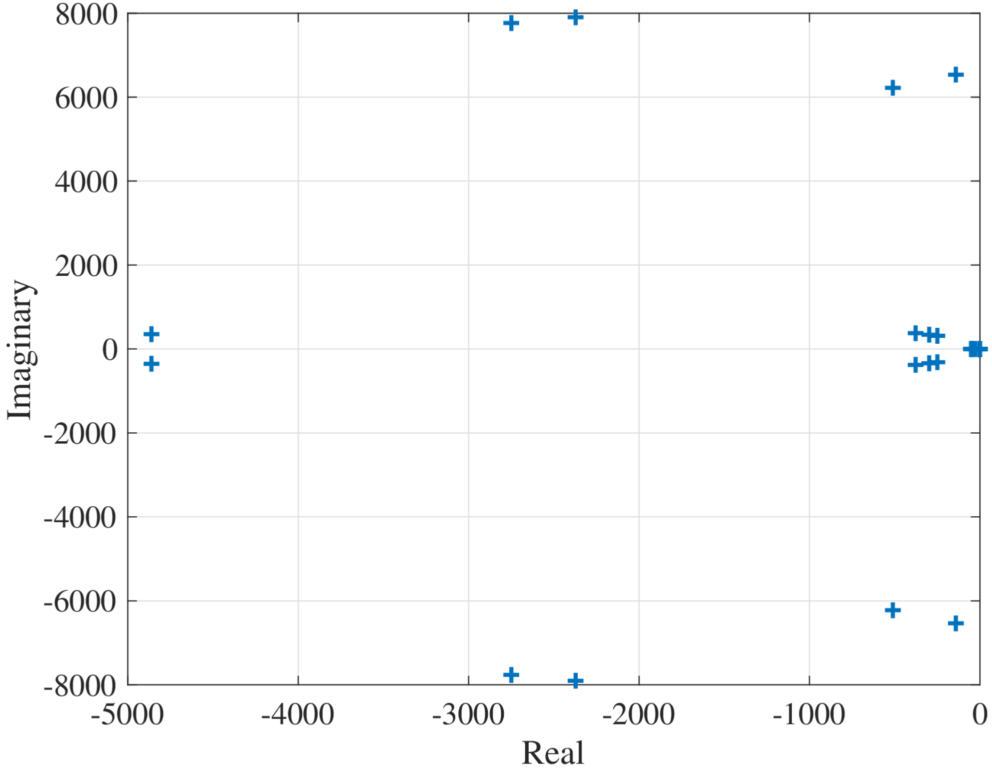
Solid – stronger
Dashed – weaker

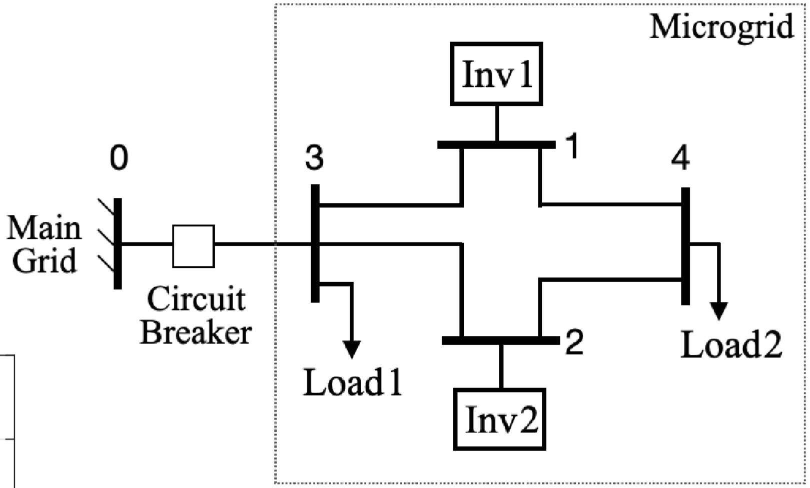


Solid – more grid-following
Dashed – equal grid-forming, grid-following

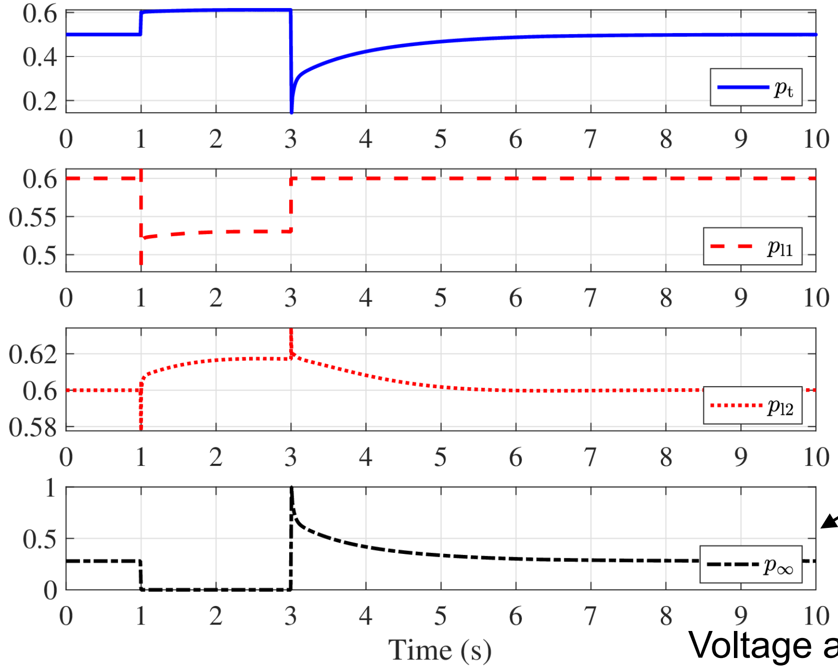
Microgrid dynamics

- Four-bus microgrid connected to the main grid via a synchronism-check relay/breaker.
- Eigenvalue analysis:





Disconnection/reconnection

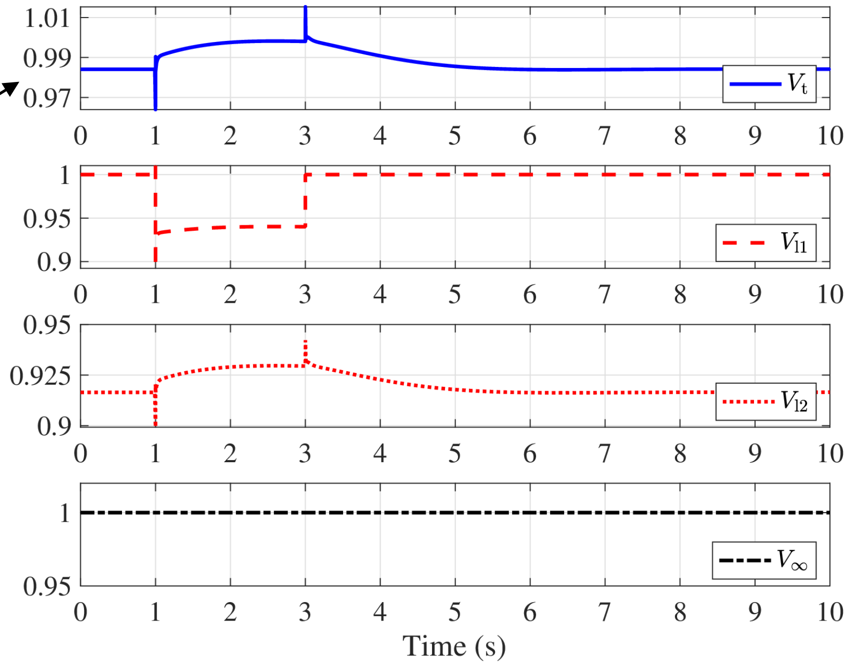


Active power generated by inverters

Active power consumed by load 1

Active power consumed by load 2

Active power supplied by the grid

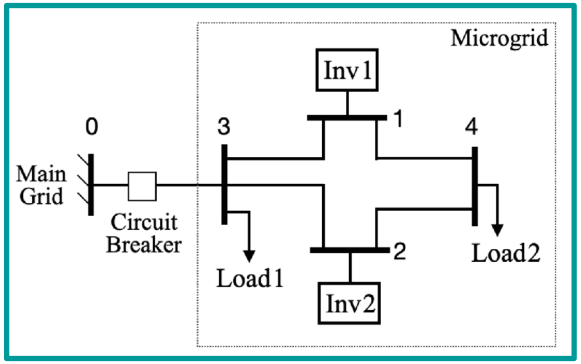


Voltage at inverters

Voltage at load 1

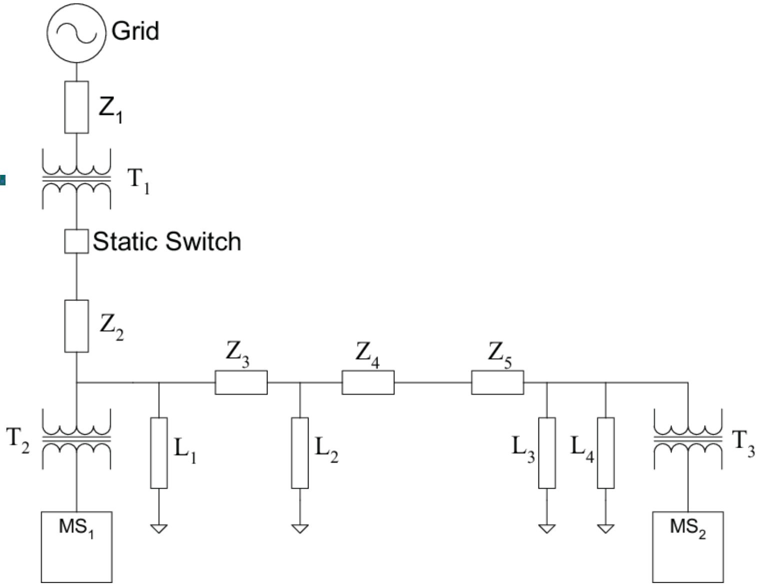
Voltage at load 2

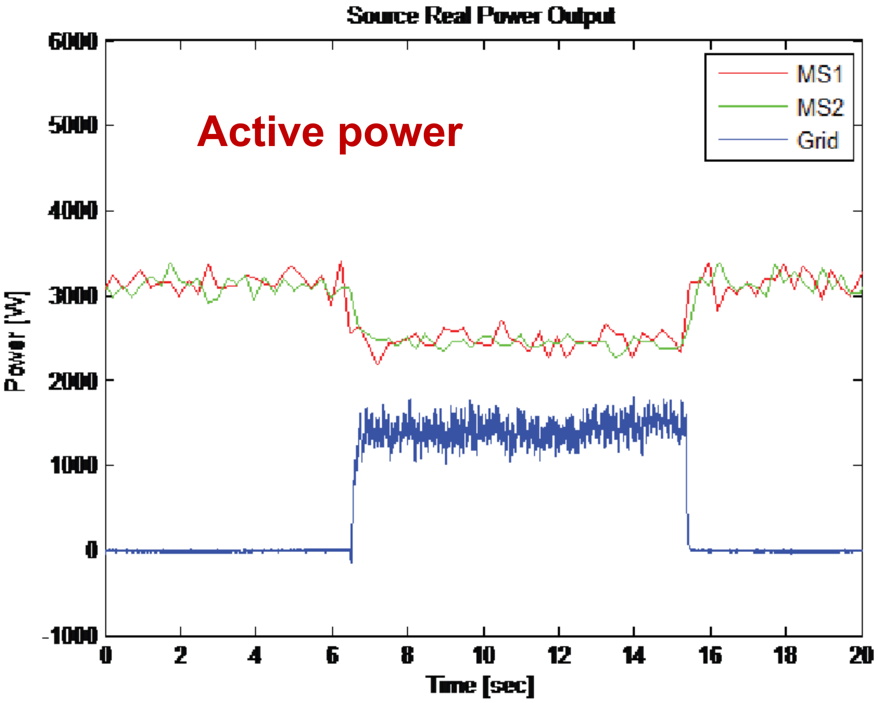
Voltage at the grid

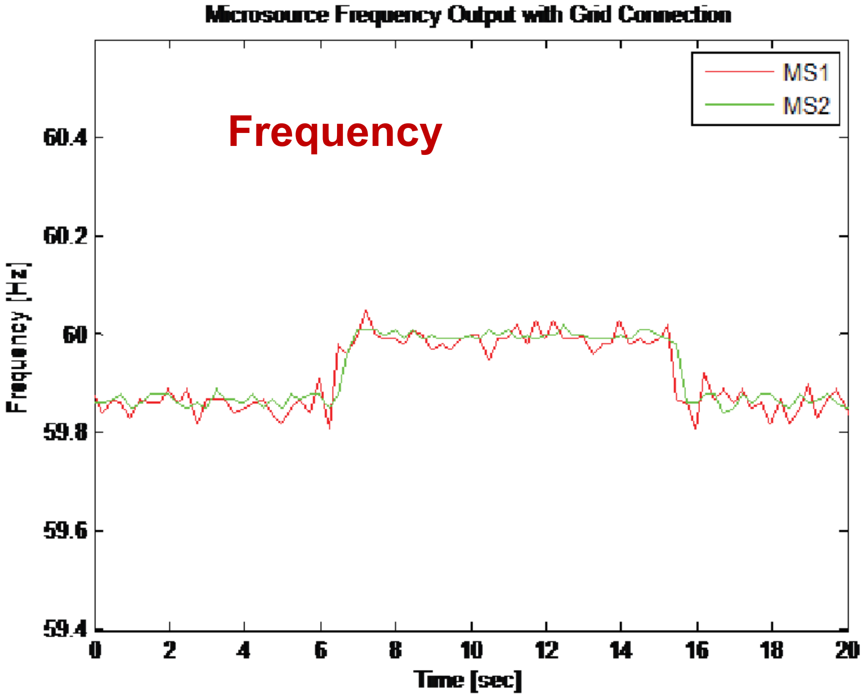


Laboratory experiment

- Microgrid started autonomously.
- Subsequently connected to the grid, and then disconnected from the grid.
- (Experiments undertaken in 2008.)







Conclusions

- The proposed hybrid inverter control scheme incorporates both power-frequency droop and a phase-locked loop (PLL).
- It inherits beneficial characteristics from both grid-forming and grid-following controls.
  - Achieves robust operation over a wide range of system conditions.

- There is still much to discover:
  - Impact of inverter-based resources on modal oscillations.
  - The role of the network in sustaining/destabilizing oscillations.
  - Modelling large aggregations of small inverters.