Research Landscape for Grid Forming Inverters

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Chickens and Eggs

Behaviours of Apparatus

Needs of Grids

Historical Perspective

Synchronous generators came first – were they a chicken?

Grids were created exploiting their features.

The entire theoretical base of power systems is aligned with synchronous generators.

(1) Frequency indicates power balance;

(2) Rotor swing governs synchronization;

(3) Short circuit current defines grid strength.

Inverter Based Resources

No intrinsic behavior but some physical limits.

Can be controlled freely within physical limits.

But we need to answer what we want them to do?

Do we want them to look like chickens (virtual synchronous machine)?

OK, but we have to “pay” for it (energy storage/headroom, overcurrent capacity etc.).

Would it be better to rethink from the beginning what are the needs of a secure, stable and well-regulated grid?

Technology Neutral Needs and Services

Need Group	Need Sub-Type	Type of Problem
Frequency Regulation	Containment within Frequency Limits	Loss of load/infeed causing large increase /decrease of frequency to the outside limits defined and causing equipment malfunction or loss of service
	RoCoF Limitation	Loss of load/infeed causing rapid change of frequency and protection malfunction or unwanted triggering of protection
	Frequency Regulation (response)	Power fluctuation of VRE or load causing drift of frequency
	Recovery (reserve)	Reserve services to restore frequency following large disturbance
Angle Stability / Synchronisation	Synchronising torque (or power)	Loss of synchronisation of SM from angle instability in low inertia or low synchronising torque cases
	PLL instability mitigation (increase in system “strength” or reactive power)	PLL instability in GFL IBR arising from high impedance (low strength) at connection point causing loss if IBR
	First-swing mitigation	Loss of synchronisation from large voltage disturbance causing acceleration of SM
	Phase-jump mitigation	Loss of synchronisation from abrupt change of angle from loss-of-infeed or loss of line.
Voltage Regulation	Containment within Voltage Limits	Heavy line loading and/or absence of reactive power sources leading to voltage excursions outside limits.
	Mitigation of unbalance and harmonics	High impedance presented to equipment sourcing distortion leading to power voltage quality.
	Voltage collapse mitigation	Sudden and large increase in line loading or grid impedance due to loss of line causing non-linear behaviour and collapse of voltage beyond bifurcation point.
	Low-voltage ride through (aka fault ride through)	Deep voltage dips leading to tripping of generation and consequent frequency regulation problem
Damping	Sub-synchronous mode/resonance mitigation (power oscillation damping)	Poorly damped local or inter-area mode causing instability

And several more needs exist and a lot more detail lies behind each

Overlaps and Co-actions in Services to meet Needs

- A synchronous machine comes with a consistent set of properties and abilities to deliver services.
- Inverters give us more choice to configure services tailored to each need but there are overlaps
  - one service might meet more than one need,
  - one need might be met by several services.

- Controlling frequency after a sudden loss of in-feed is an example:
  - We need to contain the maximum frequency deviation
  - This helped by limiting the rate-of-change of frequency because it reduces the frequency extreme and provides time over which to provide other services
- The services could be
  - Synthetic inertia (*P* proportional to *df/dt*)
  - Fast frequency response (*P* proportional to (f - f_0) with or without dead-band)
  - Frequency containment (Fixed *P* triggered by (f - f_0) threshold)
  - Blends of these or other relationships not possible with synchronous machines
- Loss-of-infeed may also cause a phase-jump and a voltage sag.
  - If reactive power and synchronising power are need at the same time how is the limited current rating of the inverter prioritised between services.

Grid Forming Inverters

- Grid following inverters provide energy.
- Grid forming inverters provide energy but are also intended to provide many of the services that a grid needs when synchronous machines are stood down.
- A GFM inverter creates something *approaching* an infinite bus
  - Voltage and frequency change little when real and reactive power are drawn,
  - Voltage and frequency are “stiff” (or system “strength” is high).
  - To do this requires a ready supply of power and energy which means a reliance on storage or de-rating a source (operating below MPP etc.). This is both over-provision of capacity and a foregoing revenue. (This is a service that costs.)
  - It also requires capacity for extra current for both reactive power and short-circuit current. (This is also a cost.)
- A synchronous generator also has to de-rate to provide reserve and response and have a larger machine for reactive power – but can provide fault current and inertia for free. Often the short-term rating of the machine is exploited, but IBR do not have a short-term rating.

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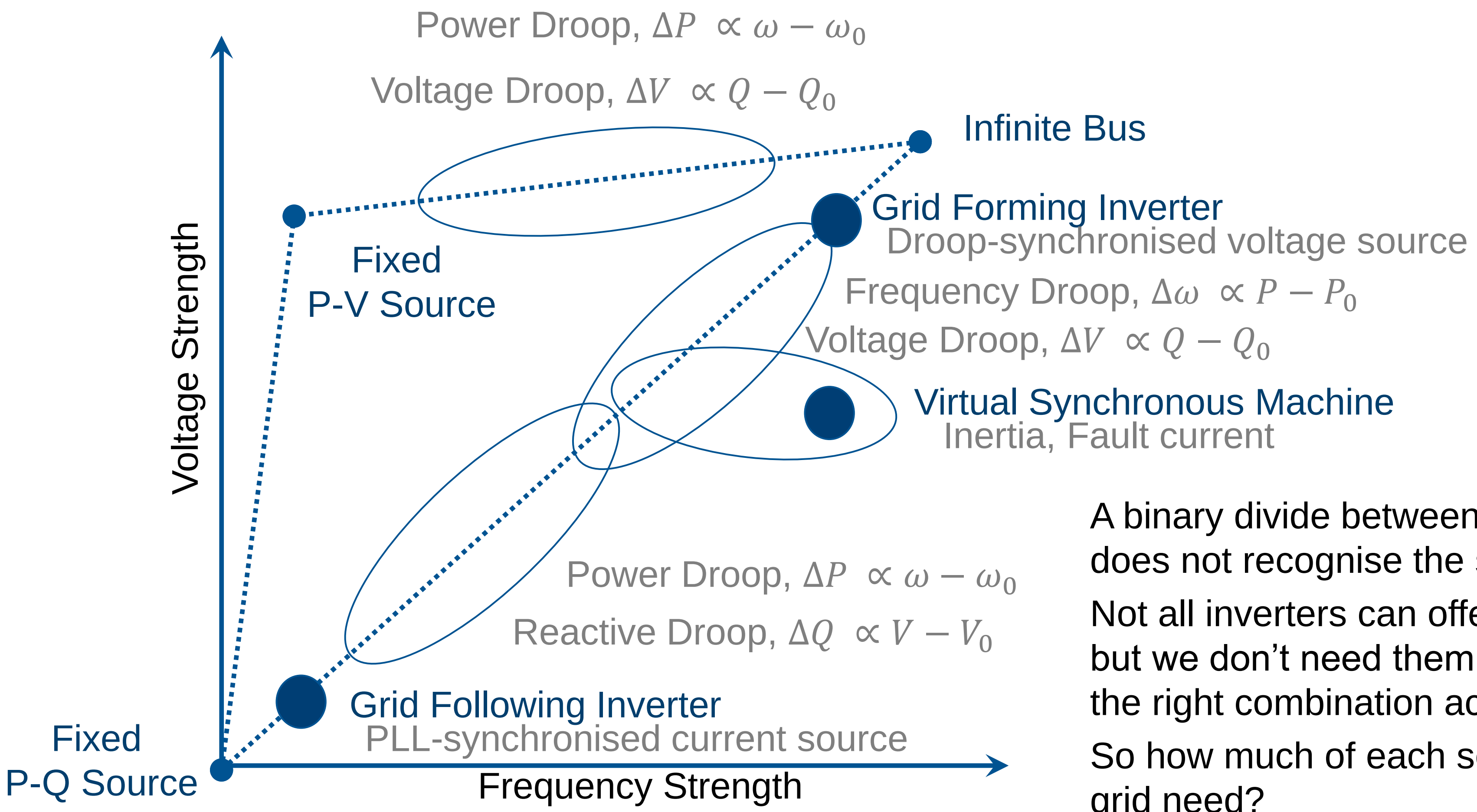
Inverter Types

We are interested in stiffness of frequency and stiffness of voltage: we could plot those separately.



A binary divide between GFM and GFL does not recognise the subtleties.

Not all inverters can offer all services; but we don't need them to. We just need the right combination across the grid.

So how much of each service does a grid need?

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Classification of Inverter Controls

Space	Controlled Output	P	Q	V	f	Grid-side control of DC link	Diagram	Context
DQ	PQ	Fixed	Fixed	Free	Free	No	4-5	most wind/PV in DG grid connected
						Yes	9	
		Droop $P=f(\omega)$	Droop $Q=f(V)$	Free	Free	No	2	wind turbine under some regulations (E.ON grid code, Germany, 2006)
						Yes	10	
	Vf	Set by network	Set by network	Fixed	Fixed	No	3	standby UPS islanded
				Droop $V=f(P)$	Droop $\omega=f(Q)$	No	1-6	line interactive UPS
	PV	Fixed	Set by network	Fixed	Free	No	12-13	Grid connected, voltage support
						Yes	16	
		Droop $P=f(\omega)$	Set by network	Droop $V=f(Q)$	Free	No	14	
						Yes	15	
abc	Vf	Set by network	Set by network	Droop $V=f(P)$	Droop $\omega=f(Q)$	No	7	

Model Types

- Most synchronous machines have consistent physical form:
  - Models are open (white-box) in state-space format.
  - Models can be used for time-domain simulation – EMT or Phasor.
  - Models can also be used for eigenvalue analysis and participation factors used to find root-causes of instabilities.
- Inverters take very many forms and with wide range of design choices in control loop format and tuning:
  - Inverter control systems are proprietary and are not disclosed.
  - Manufacturer’s models are black-box as either binary code or impedance spectrum.
  - Models can be used for time-domain simulation – EMT or Phasor.
  - Models can also be used impedance stability test but limited further analysis.

Representing Inverters Like Traditional Machines

Inverters as Source Behind and Impedance

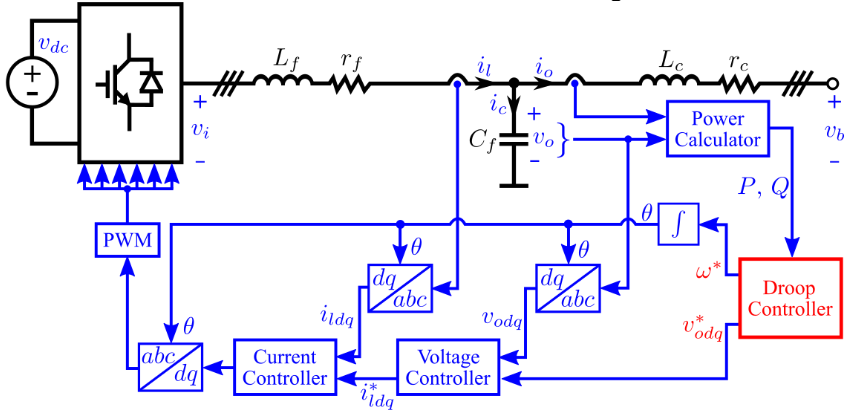
An inverter has:

- Physical resistance, inductance, capacitance,
- Variation of voltage with current because of imperfect inner control loops
- Deliberate droop of voltage with reactive power

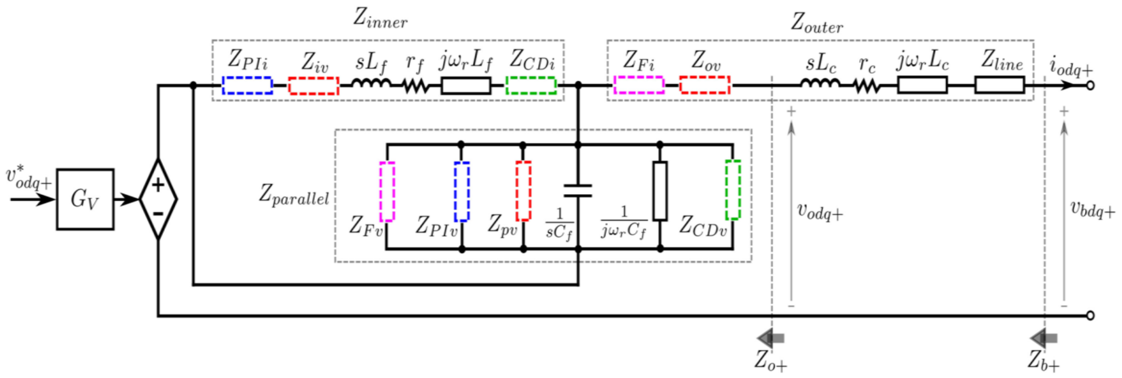
Each property can be expressed as a relationship between voltage and current.

Virtual Impedance	$Z_{iv} = (R_{iv} + jX_{iv})G_{del}$ $Z_{pv} = \frac{(R_{pv}//jX_{pv})}{G_I}$ $Z_{ov} = (R_{ev} + jX_{ev})G_V$
PI Controller	$Z_{PIi} = PI_i G_{del} = (K_{pi} + \frac{K_{ii}}{s})G_{del} = (K_{pi} + \frac{1}{s\frac{1}{K_{ii}}})G_{del}$ $Z_{PIv} = \frac{1}{PI_v G_I} = \frac{1}{(K_{pi} + \frac{K_{iv}}{s})G_I} = \frac{(\frac{1}{K_{pv}}//s\frac{1}{K_{iv}})}{G_I}$
Cross Decoupling	$Z_{CDi} = -j\omega_0 L_f G_{del}$ $Z_{CDv} = \frac{1}{-j\omega_0 C_f G_I}$
Feedforward	$Z_{Fv} = -\frac{Z_{inner}}{F_v G_{del}}$ $Z_{Fi} = -(Z_{inner}//Z_{parallel})F_i G_I$
Loop Gain & Delay	$G_{del} = e^{-1.5T_s s}$ $G_I = \frac{Z_{PIi}}{Z_{inner}}$ $G_V = \frac{Z_{inner}//Z_{parallel}}{Z_{PIv}}$

Inverter with control algorithms



Impedance circuit model

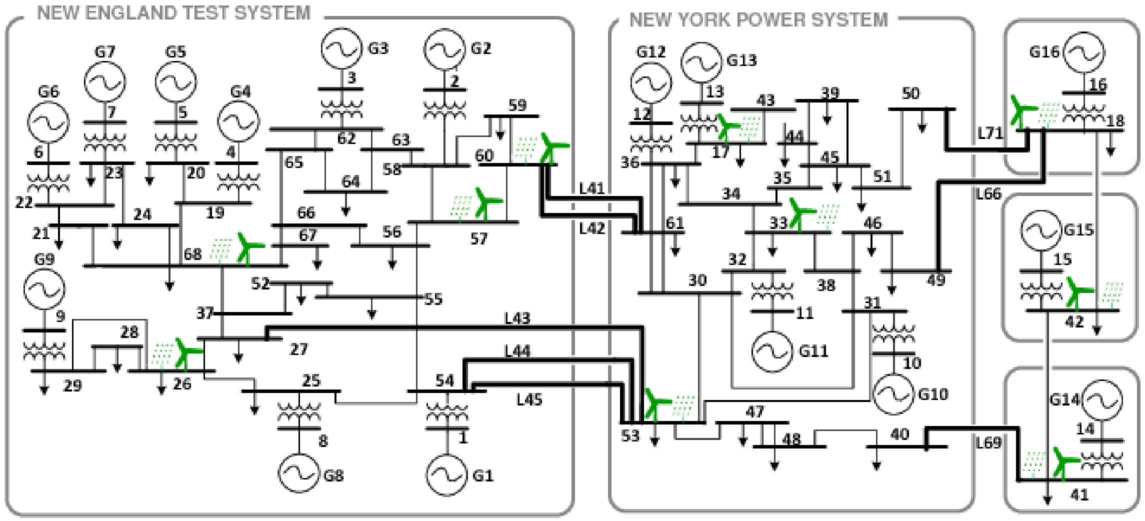


Simulation and Analysis

Running time-domain simulations (EMT etc.) of case-study networks can generate data on how much of a certain service is need, even how much GFM capacity is needed.

Answers will be system-specific, operating-point specific and may not generate much insight into fundamentals.

State-space models might provide more information but insights are difficult in large systems.

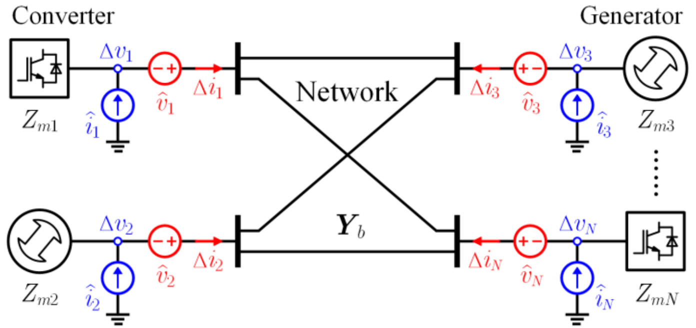


We need an analytical approach that can pinpoint what features of a network determines

- need for each GFM service,
- threats to synchronization and stability

Simple test networks are probably the best way to explore this and develop indices.

This is a research topic in strong need of new approaches and new theories.



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Tools

Power systems are reliant on a huge range of tools for planning, protection setting, dispatch, control-room decision support etc.

- Are we confident that our EMT and Phasor simulation models accurately capture GFM behaviours?
- Do we have acceptable ways to reduce the order of the models to run large system studies quickly?
- How do we achieve systematic tuning of, say, power-oscillation damping at system level if the system configuration changes widely?
- How do do we identify root-cause of an instability if our equipment models are black-boxes from manufacturers?
- With the system getting fast and more complex, what can we provide as new real-time decision-support or situational-awareness tools for a control room?