Public lecture:

Paradigm change of power system operation and control

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New Paradigm of Power System Operation and Control

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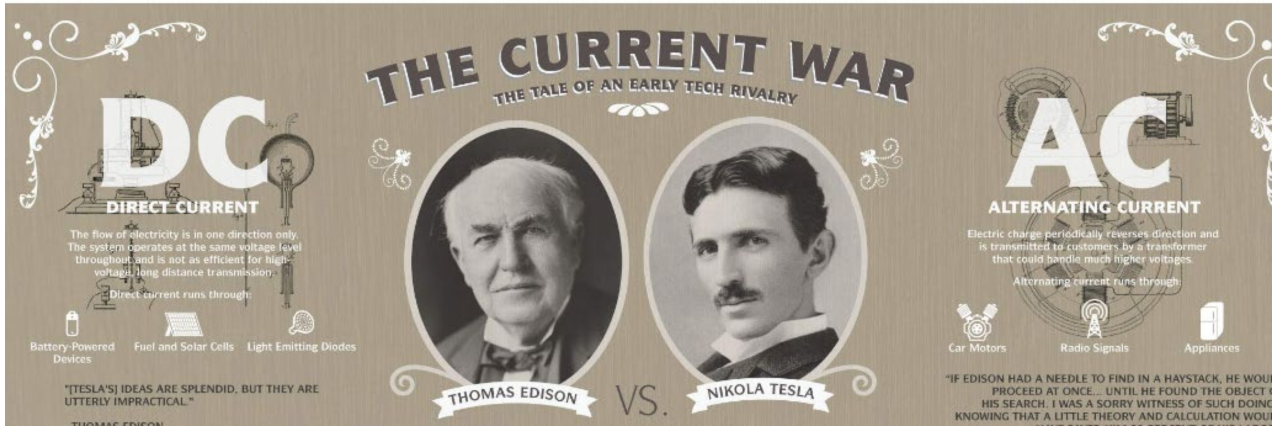
Outline

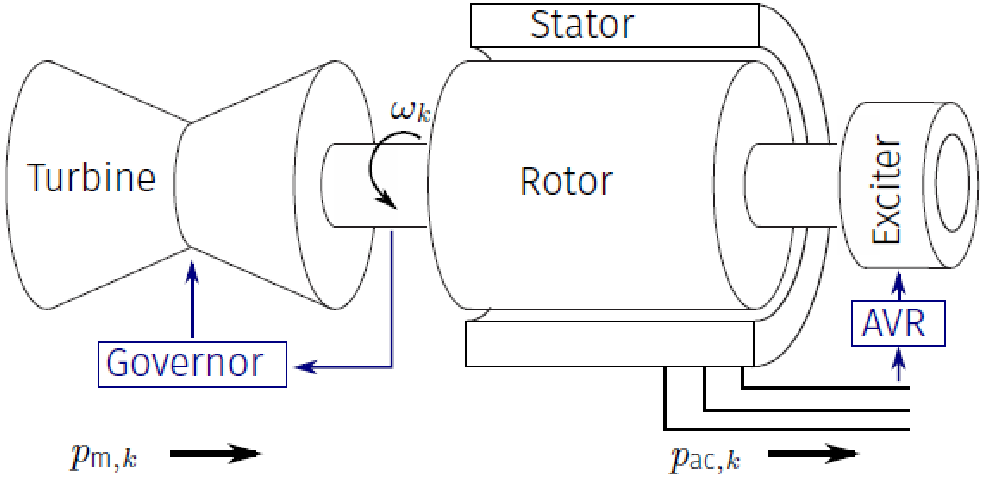
- High-level overview of the challenges posed by high penetration of Inverter-Based Resources (IBRs)
- Can inverters replace synchronous machines?
- Frequency control in IBR-based systems
- Conclusions

- Acknowledgments:
  - many people!
  - F. Doerfler (ETHZ), T. Green (Imperial)

1st revolution, end of 19th Century: The Current War DC vs AC



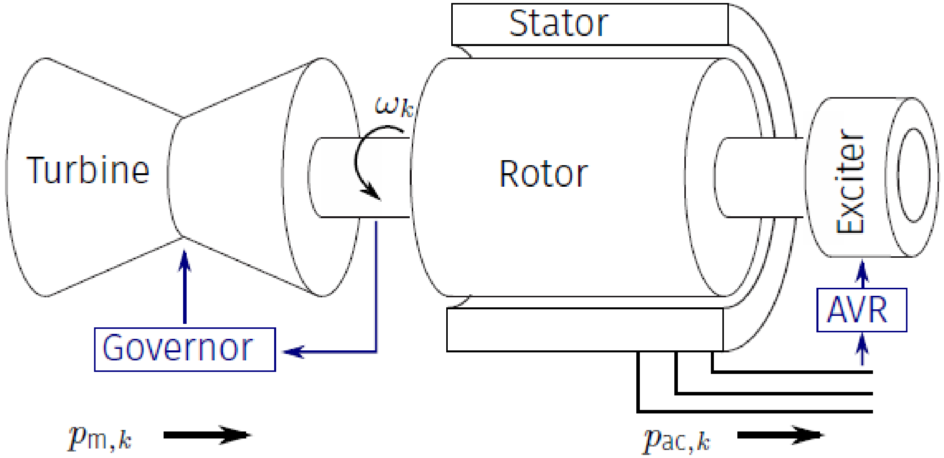
- Tesla won with AC
- Thermal/hydro/nuclear plants used Synchronous Machines (SMs) to convert mechanical energy into AC electricity
- Technical characteristics and controls of the grid determined by the physics of SMs



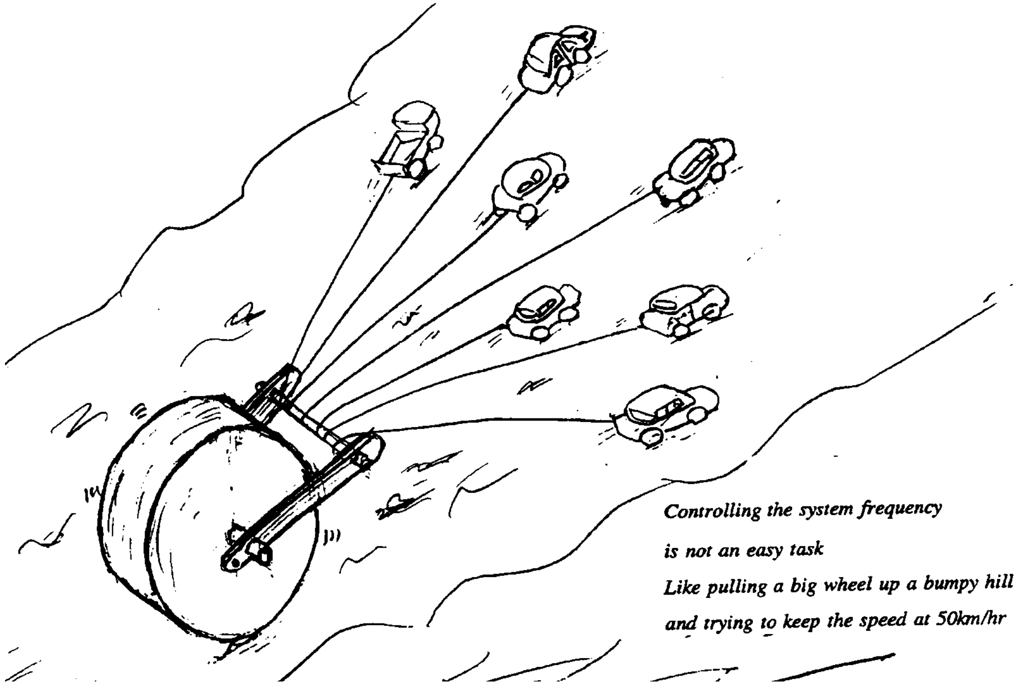
Source: D. Gross

SM: physics-defined behaviour

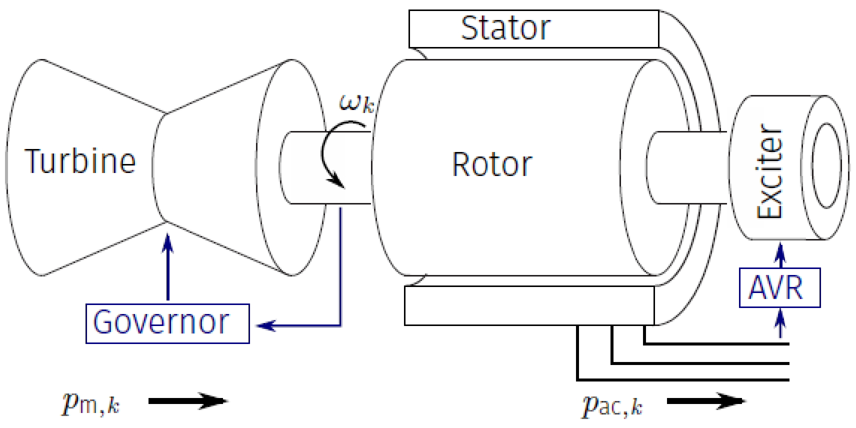
- SM: a turbine rotates an electromagnet (rotor) inducing smooth AC voltage in the stator windings
- Physics dominated by relatively slow phenomena:
  - thermodynamic (turbine/boiler, minutes),
  - electromechanical (rotating masses, seconds),
  - and electromagnetic (windings, sub-second)
- Physics and construction ensure
  - self-synchronisation and common speed (frequency)
  - inherent damping of oscillations around the synchronous speed



Source: D. Gross

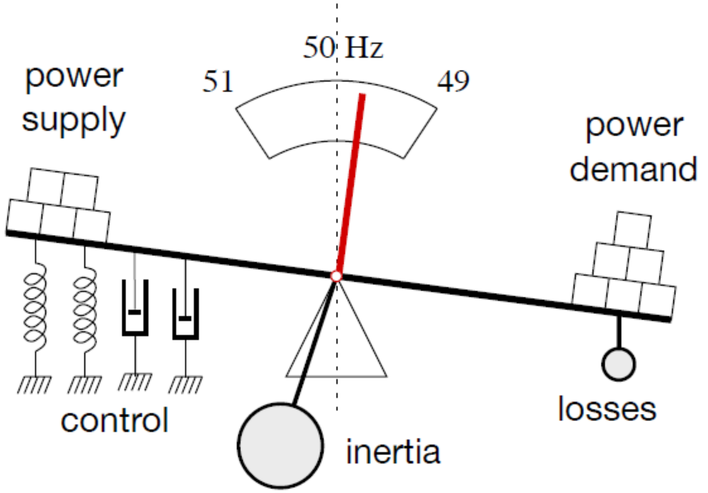


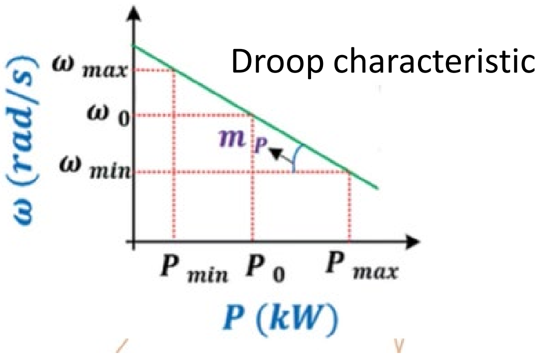
SM: frequency control and maintaining generation-demand power balance

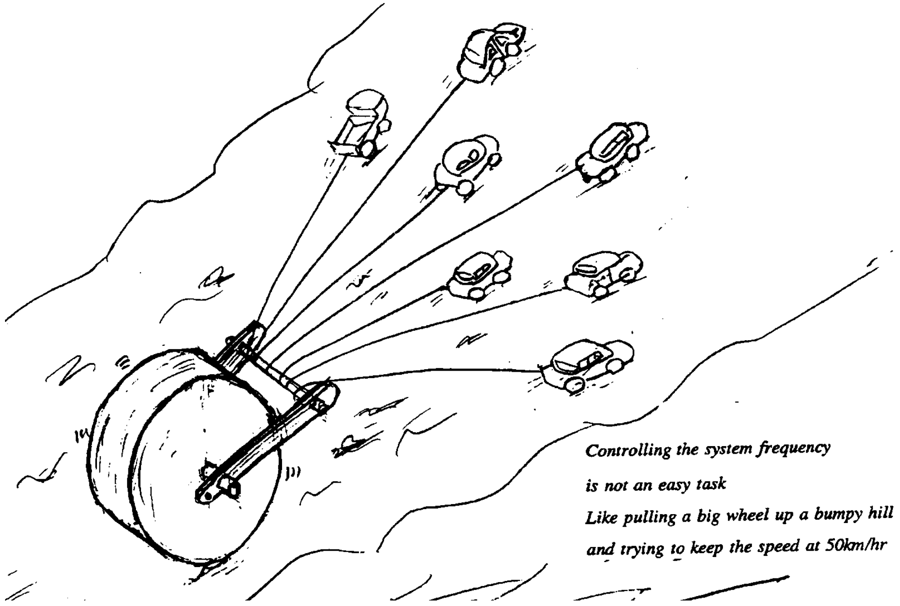


Source: D. Gross

- Physical link between power balance and frequency
  - If a power station trips, the power imbalance is covered initially by kinetic energy of rotating masses
  - Frequency drops
  - Governor droop ensures restoring power balance
  - Large inertia provides a buffer to absorb generator trips







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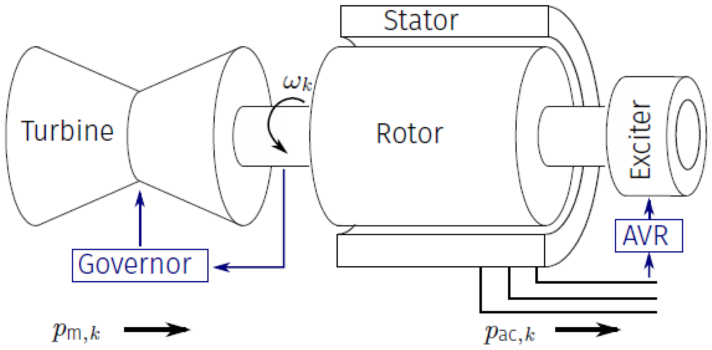
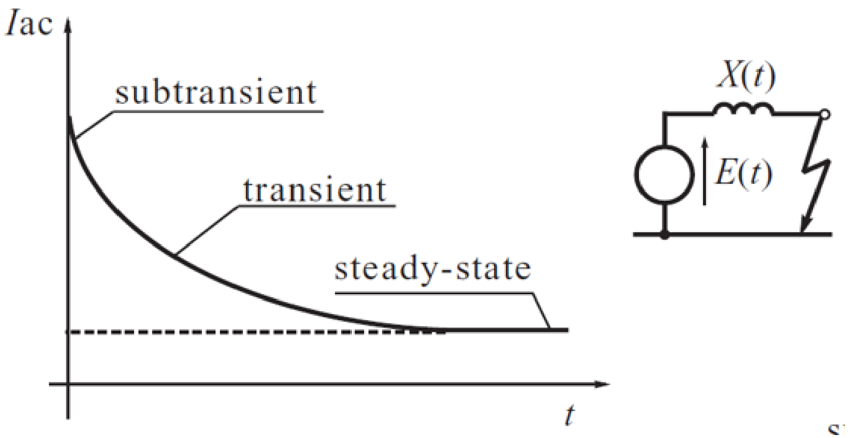
SM: fault currents and grid strength



Source: D. Gross

- Faults (short-circuits) cause SM to produce large (2-4 pu) slowly-decaying (a few seconds) fault currents
  - High fault currents are useful!
  - No damage as high thermal mass of conductors
  - High fault currents support voltages during a fault (essential for fault-ride-through)
  - Easy to detect, useful for protection
- SMs maintain “grid strength”: constant voltage and frequency at a given location
- Fault levels act as a proxy to quantify “grid strength”:
  - a high short-circuit current at a given location indicates that there are many SMs nearby maintaining constant voltage and frequency



2nd revolution happening now: zero-carbon generation

Environmental Targets

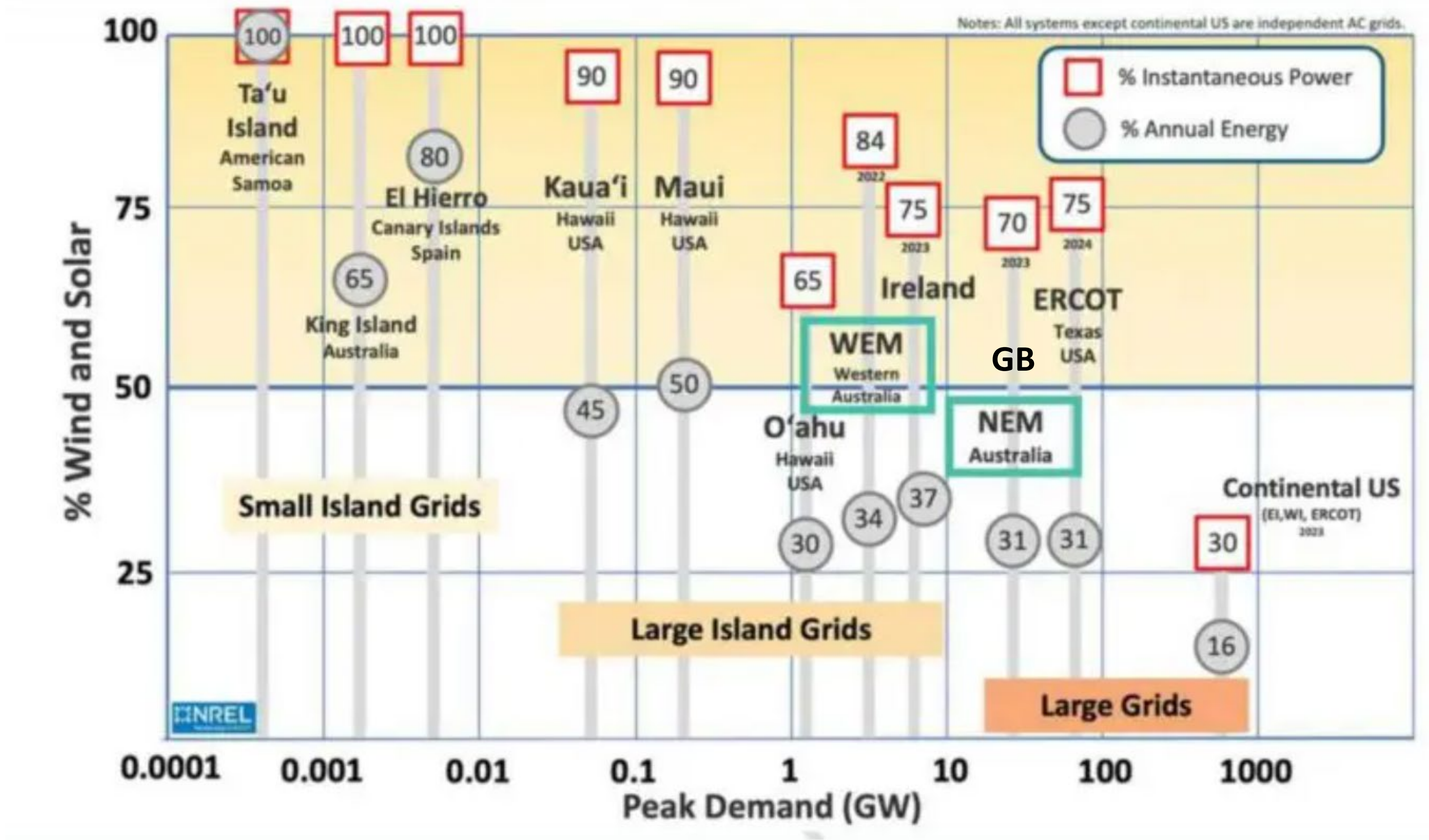
- Clear Government ambition over a sustained period
  - 15% of all generation to be renewable by 2020
  - All coal to be closed by 2024
  - 100% zero carbon 100% of the time by ~~2035~~ 2030
  - 50GW offshore wind by 2030
  - 10GW of H2 by 2030
- ESO ambition to have the ability to operate zero carbon in 2025

nationalgridESO

Mature, slowly-evolving, risk-averse industry must quickly change to manage considerable risks

Fast pace of change: System Operators are scared

Wind and solar PV penetration levels in an entire AC grid



Source: AEMO

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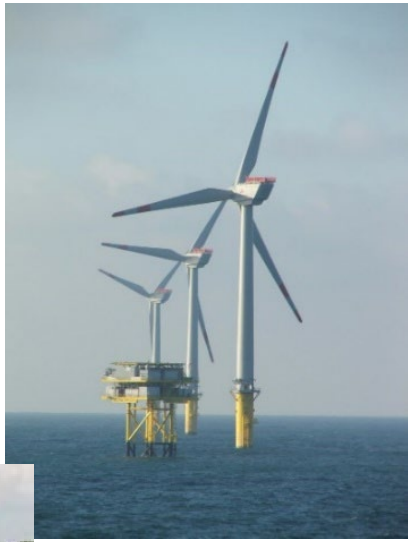
Inverter-Based Resources (IBRs)

- Wind, solar PV and batteries produce DC output so they need power electronics (inverters/converters) to convert DC to AC and connect to the AC grid
- IBRs also include EVs, HVDC, variable-speed motor drives, statcom, etc as they need inverters to connect to the AC grid
- Replacing SMs by IBRs changes fundamental technical characteristics of the power system and requires new controls



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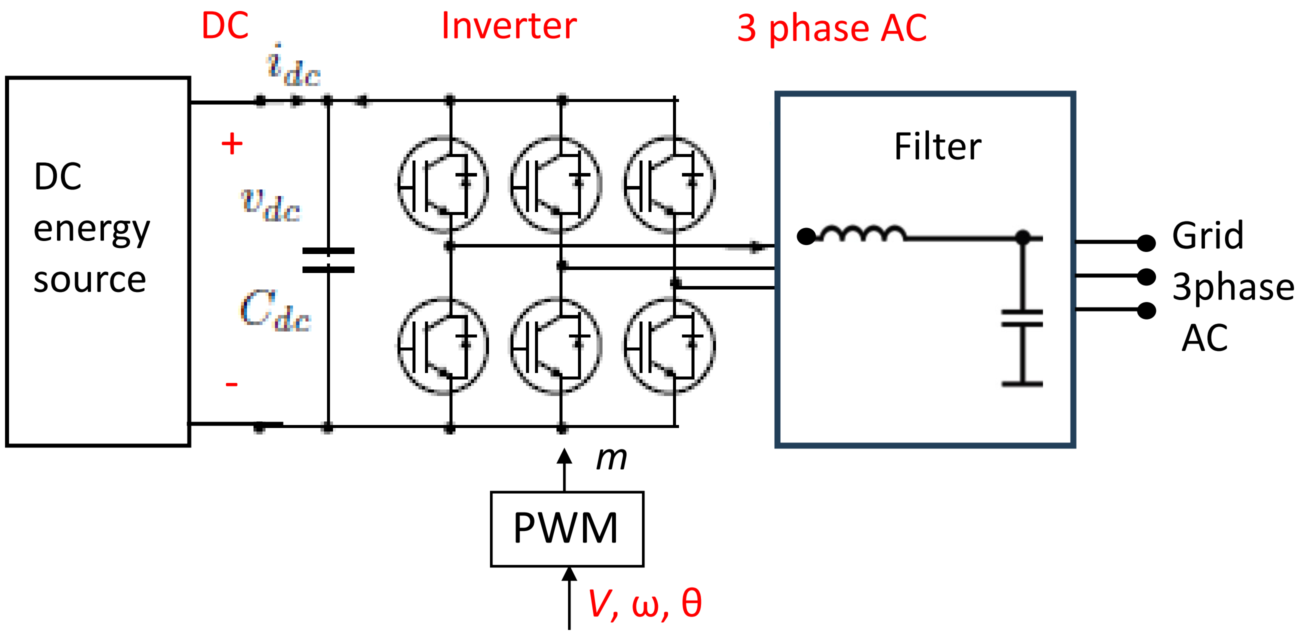
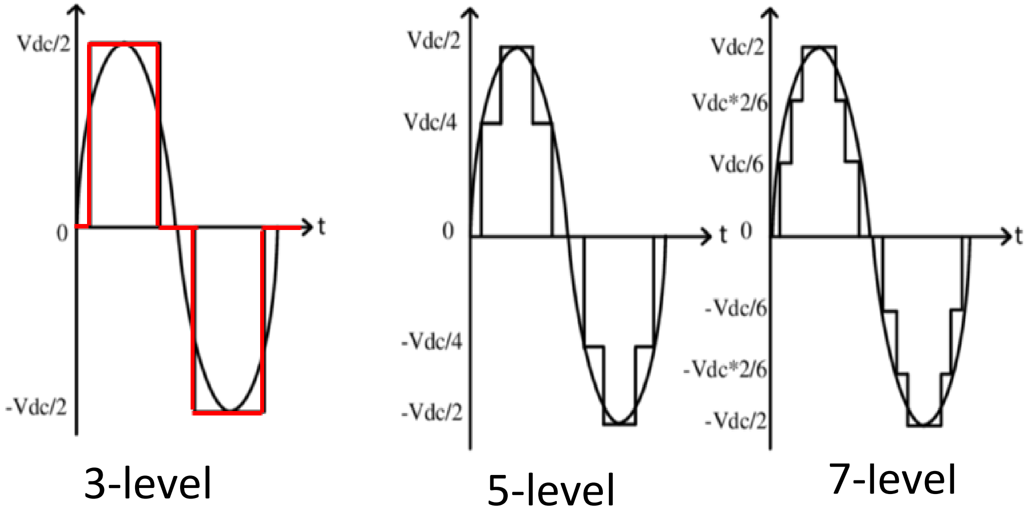
What is an inverter?

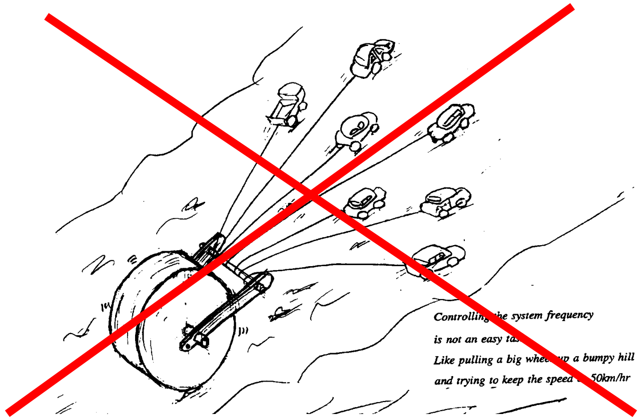


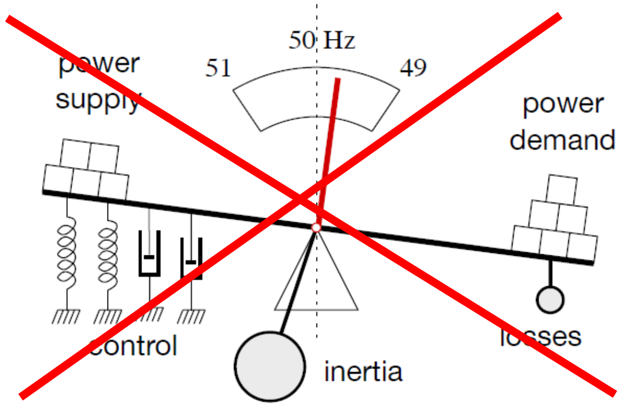
- Converts DC input into 3-phase AC output
- Inverter is essentially a programmable switching device
- Fast switching (kHz) converts DC into a quasi-AC signal: Pulse-Width Modulation PWM
  - Fast actuation (milliseconds) ☺
  - Needs filtering out high-frequency harmonics
- Controllable amplitude (voltage *V*), frequency ω and phase angle θ

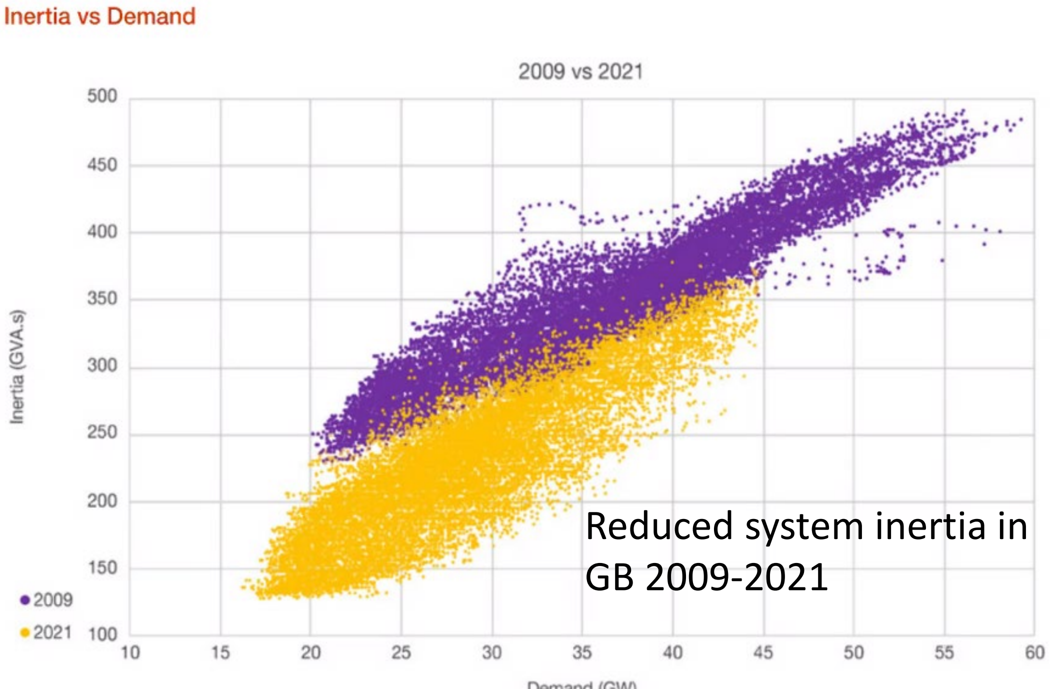


Inverters: control-based behaviour

- No physics-based inherent self-synchronisation, power-frequency mechanism, damping of oscillations etc
- Everything must be programmed and the services provided previously “free” by SMs have to be paid for
- High flexibility but many problems
- No inertia
    - Problems with buffering large generator trips

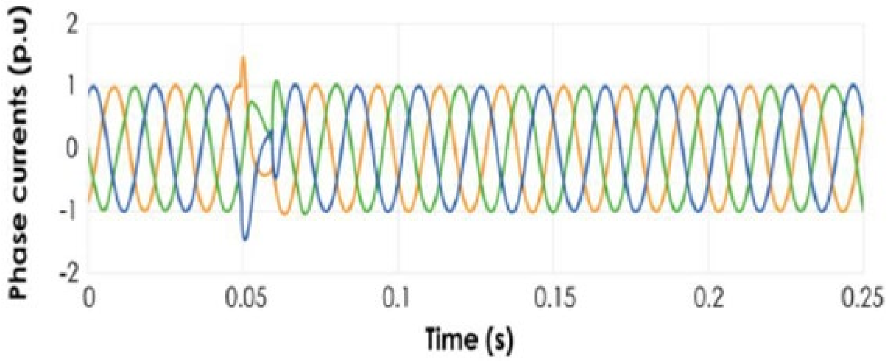






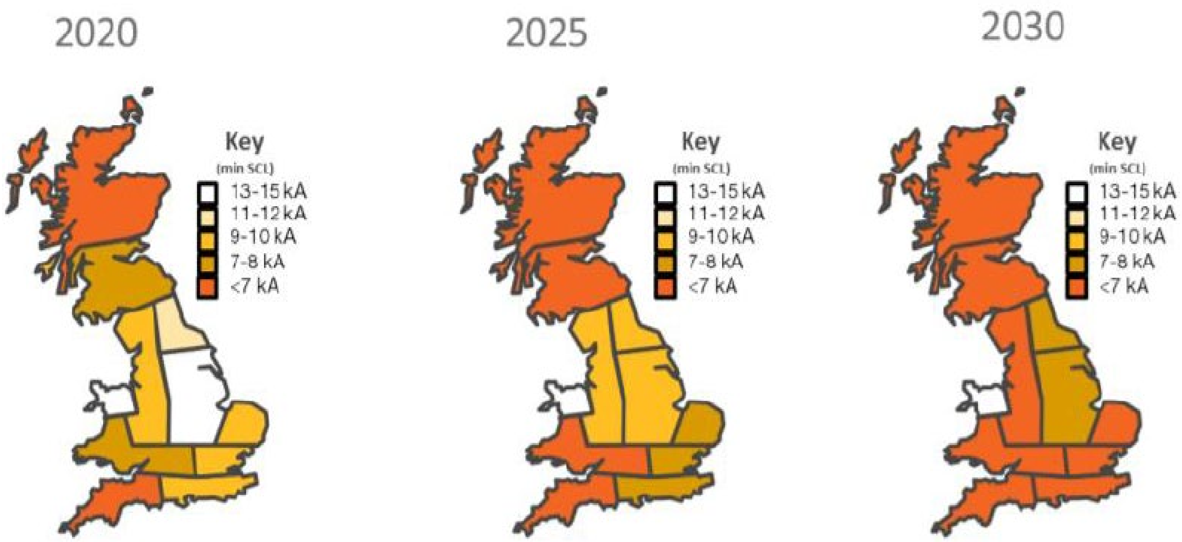
Source: NG ESO

Fault currents and grid strength



- Semiconductors have low thermal mass and cannot be overloaded
- Inverters can only provide small (~1.2 pu) short-duration fault currents
  - Deteriorated fault-ride-through
  - Protection has to be re-thought
- Reduced short-circuit levels indicate a "weak grid"
  - Stability problems

Source: Y. Gu



Regional minimum short circuit level

Source: NG ESO

Stability problems with IBRs

- Two potential modes of instability:
  - weak grid
  - control interactions
- Sub-synchronous oscillation (SSO) events around the world
- SSO are new and poorly-understood phenomena - exact reasons are often not clear and difficult to replicate by simulation
  - West Murray Zone oscillations have been replicated only after 2 years
- Risks to the security of supply
- Additional costs as SOs have to operate the grid more conservatively, e.g. 23 stability constraints in ERCOT

Sl #	Date	Location	Frequency of oscillations	Cause
1	2007	South Central Minnesota	9.44Hz	SSCI
2	2009	South Texas	20-30Hz	SSCI
3	2010	Oklahoma Gas & Electric (OG&E)	13Hz	Weak grid
4	2011	Texas	4Hz	Weak grid
5	2011-2014	BPA territory in Oregon	5-14Hz	Weak grid
6	2011-2012	OG&E reported two wind oscillation events	3Hz	Weak grid
7	2012-2013	58+ oscillation events in North China	6-9Hz	SSCI
8	2014-2015	Xinjiang China	30Hz	Weak grid
9	2015	Hydro One, Canada	20Hz	Weak grid
10	2016	AEP footprint	Not known	Weak grid
11	2017	220-kV grid in northwest China	37Hz in voltage, 63Hz in currents	Weak grid
12	2017	First Solar's solar farm in California	7Hz	Weak grid
13	2017	South Texas	22-26Hz	SSCI
14	2015-2019	Australia's West Murray zone	7Hz	Weak grid
15	2018-2019	Hydro One	3.5Hz	Weak grid
16	2019	Great Britain	9Hz	Weak grid
17	2020	West Murray zone in Australia	17-19Hz	Weak grid
18	2021	Eastern USA (Dominion Energy territory)	22Hz	Weak grid
19	2021	Scotland	8Hz	Weak grid
20	2021	Kauai, Hawaii	19Hz	Weak grid
21	2009-2023	7+ events in AEP territory in USA	21Hz	SSCI
22	2023	Scotland	8Hz	Weak grid

S. Dutta "SSO events and Learnings" PES GM 2023.
SSCI- Sub-Synchronous Control Interactions

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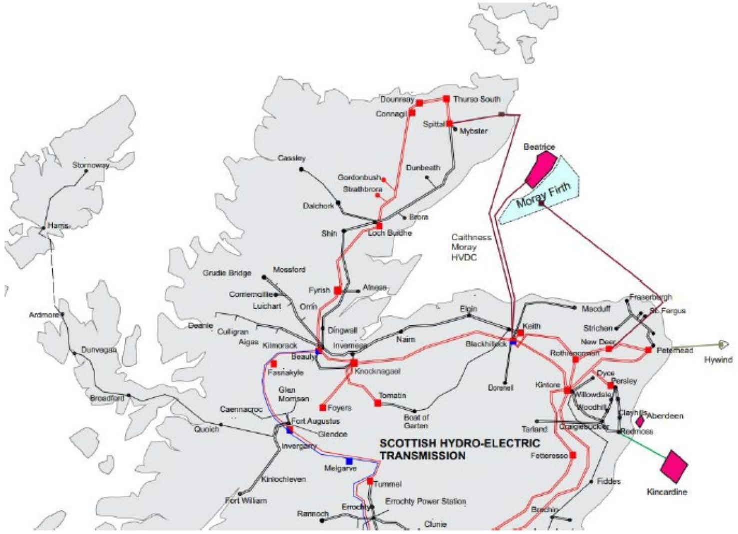
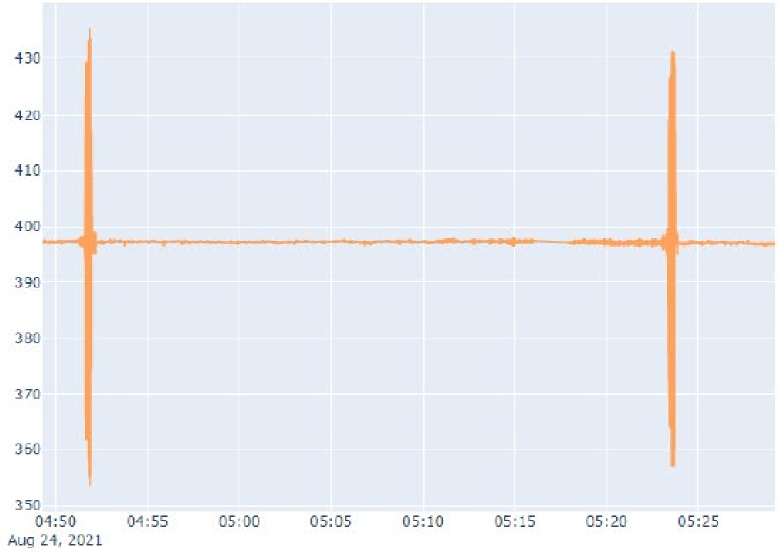
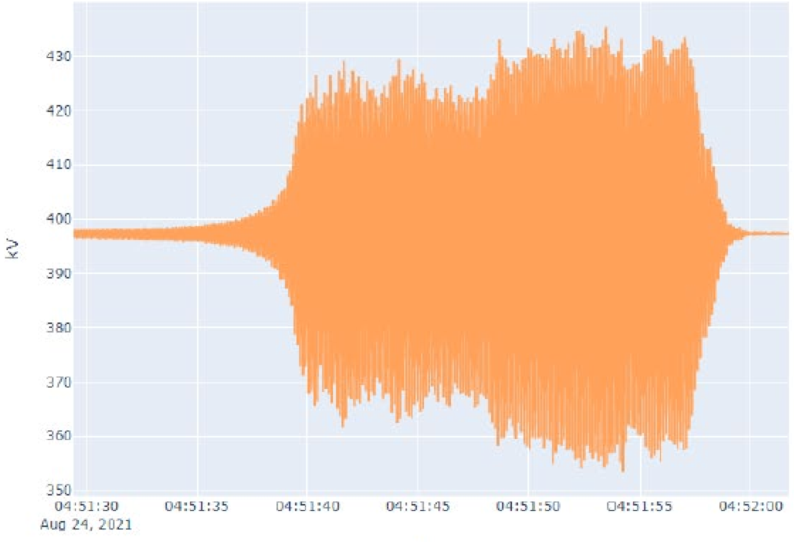
A case study of SSO: Scottish "wobbles"

- Northern Scotland: only wind, no SMs
- 8 Hz spontaneous oscillations in Northern Scotland 2021, 2023, 2024
- 2023: 5 days, tripping of assets (generation, HVDC link, transm. line)
- A mystery: no link to levels of inertia, fault levels, demand, wind levels, generation mix and system flows
- ESO still not sure about the causes
  - Simulation could not replicate the events due to a lack of models of IBRs







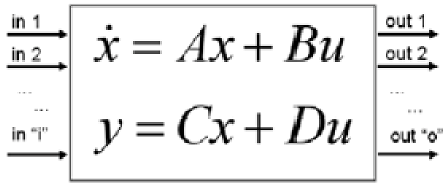
Glasgow traffic light faults due to power spike

1 day ago

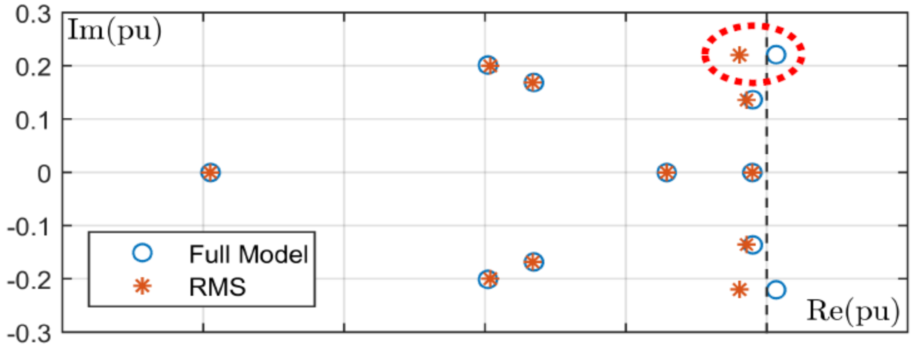
Share

At least 68 traffic signals in the city have been affected by the power spike

Stability analysis

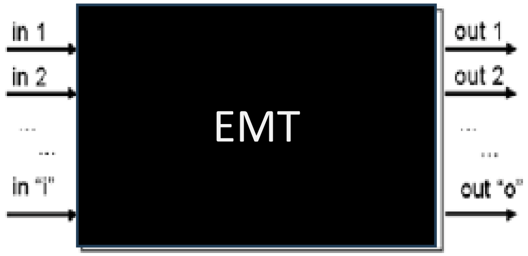


- SM: white-box models available (state-space, block diagrams) as physics is well-known
  - Can use simulation and/or analytical methods, e.g. eigenvalue analysis



Source: T. Green

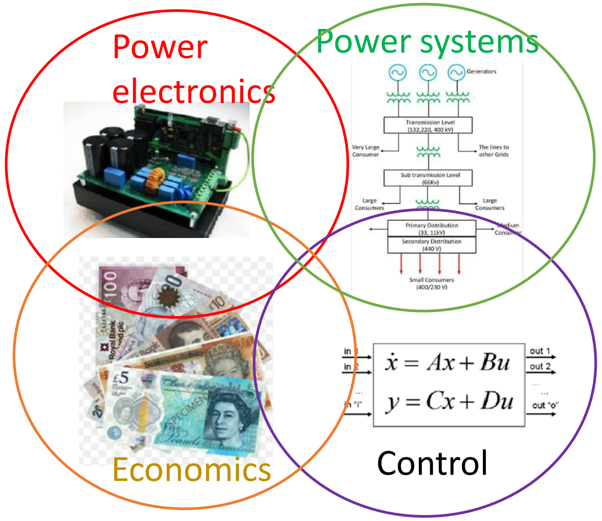
- IBR: freedom of control design
- Due to proprietary reasons, manufacturers usually release only black-box models: compiled Electromagnetic Transients EMT code
  - Only simulation possible but can't use model-based analytical methods
  - In GB mandated only in 2022
  - EMT is poorly scalable due to a short-time step (μs)
  - running multiple black-box EMT simulations to assess stability is infeasible

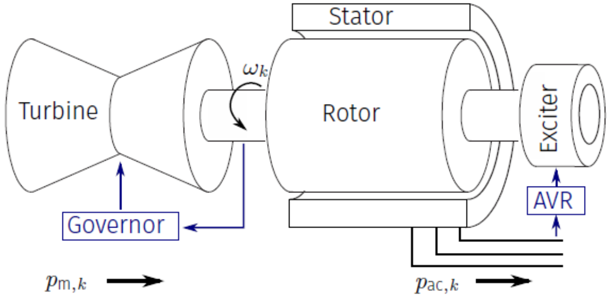


- Analytical, but black-box based, stability analysis methods are urgently needed

IBR research challenge

- SM-based system: slow but robust as physics-based, well-understood
- IBR-based system: agile but fragile as control-based, poorly-understood
- Inverter challenge: operate the grid efficiently and to the same reliability standard but using IBRs
- Turn a threat of IBRs into an opportunity to remove the shackles imposed by slow and bulky SMs
- Exciting times for power systems research!
- Lack of full understanding how the future IBR-based power system will work
- Rethink power system control
- Multidisciplinary approach needed

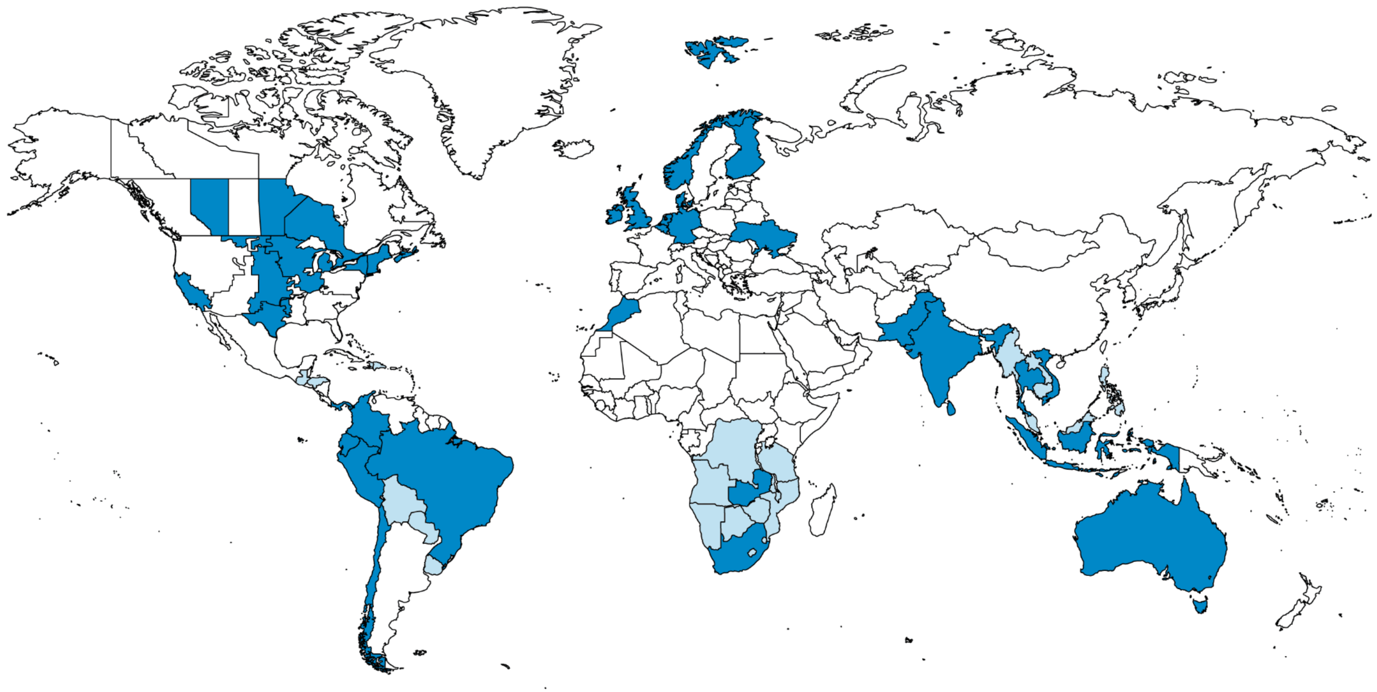




Acknowledgement: Yunjie Gu

THE GLOBAL POWER SYSTEM TRANSFORMATION CONSORTIUM

Rapidly accelerating transitions to advanced low emission power systems in collaboration with power system operators in all regions



G-PST's network of system operator partners represent approximately 30% of global electricity generation.

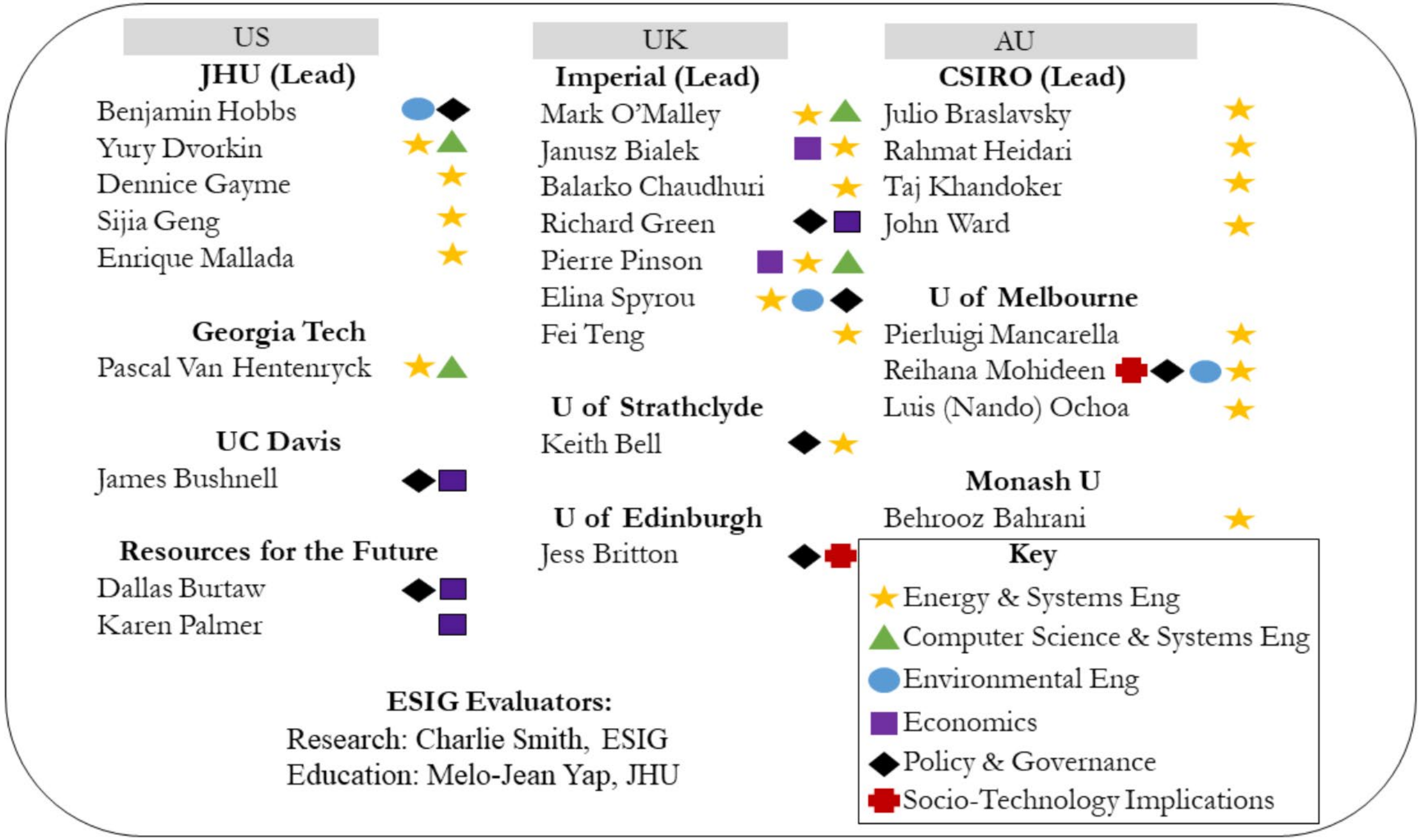
Set up by System Operators and research community (including CSIRO and Melbourne University) in 2019 to address the scale and urgency of the IBR challenge

Goal: ability to operate 100% IBR transmission system by 2025 and share the learnings

Global Centre: Electric Power Innovation in a Carbon Free Society (EPICS)

- Funded jointly by NSF, UKRI and CSIRO in Global Centres in Clean Energy and Climate Change call
- CSIRO, Melbourne and Monash
- Main task: address the technical, economic and societal aspects of the inverter challenge

EPICS: Global Academic Team and Expertise

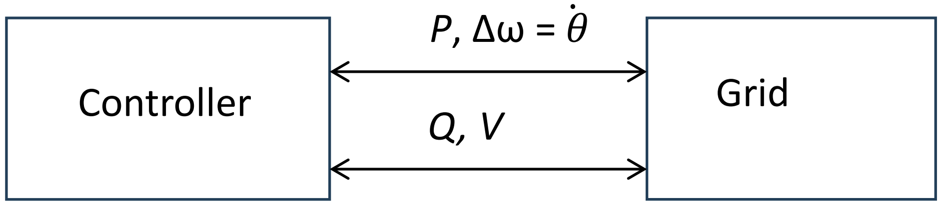


Outline

- High-level overview, from the power system point of view, of the challenges posed by high penetration of Inverter-Based Resources (IBRs)
    - (almost) no equations or complicated circuit diagrams
- Can inverters replace synchronous machines?
- Frequency control in IBR-based systems
- Conclusions

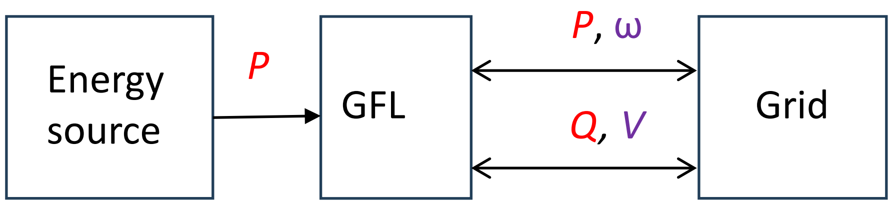
Grid Following Inverters (GFL) and Grid Forming Inverters (GFM)

- A lot of discussion and disagreement in power electronics and control communities about defining GFL and GFM
- Here: high-level explanations about their *functionality* (signal causality) without going into power electronics or control details
- Fundamental question: which are the main variables that a grid controller can control?
- Two weakly-linked pairs of strongly-linked variables
  - Real power *P* strongly related to the phase angle θ and frequency $\Delta\omega = \dot{\theta}$
  - Reactive power *Q* strongly related to voltage *V*
- 2 degrees of freedom:
  - only 1 variable from each pair can be independently controlled
  - the other one depends on grid operating conditions

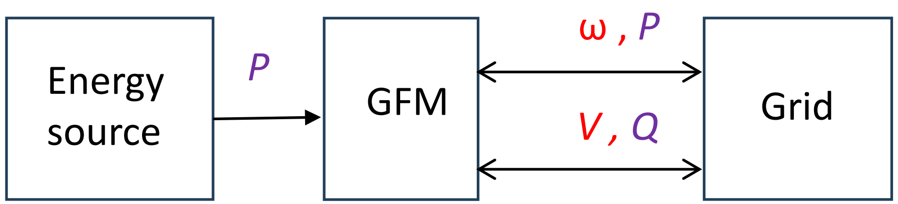


Grid Following Inverters (GFL) vs Grid Forming Inverters (GFM)

- Grid Following Inverter GFL:
  - Controllable set-points *P* and *Q*
  - *V* and ω set by the grid - GFL "follows" the grid

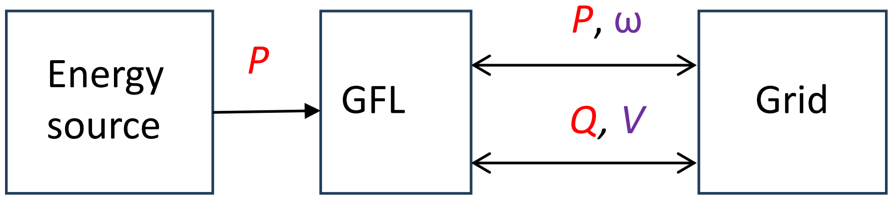


- Grid Forming Inverter GFM:
  - Controllable set-points *V* and ω
  - GFM "forms" the grid like SM

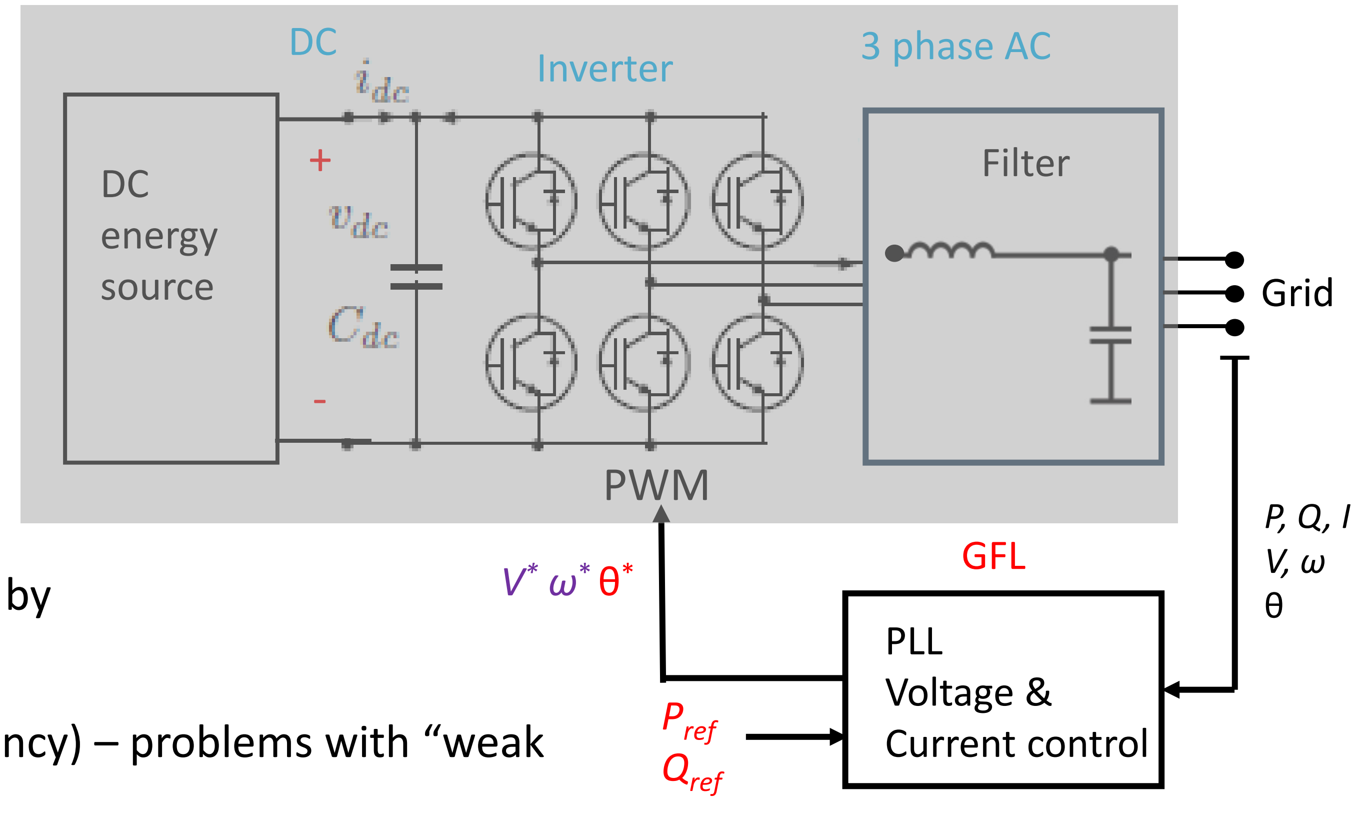


- Not a binary divide: a spectrum with many types and flavours, crossovers etc.

Grid Following Inverter (GFL)

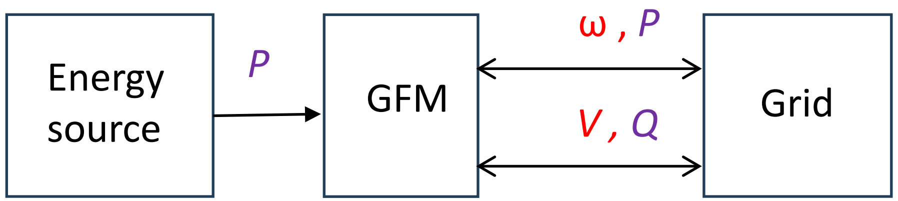


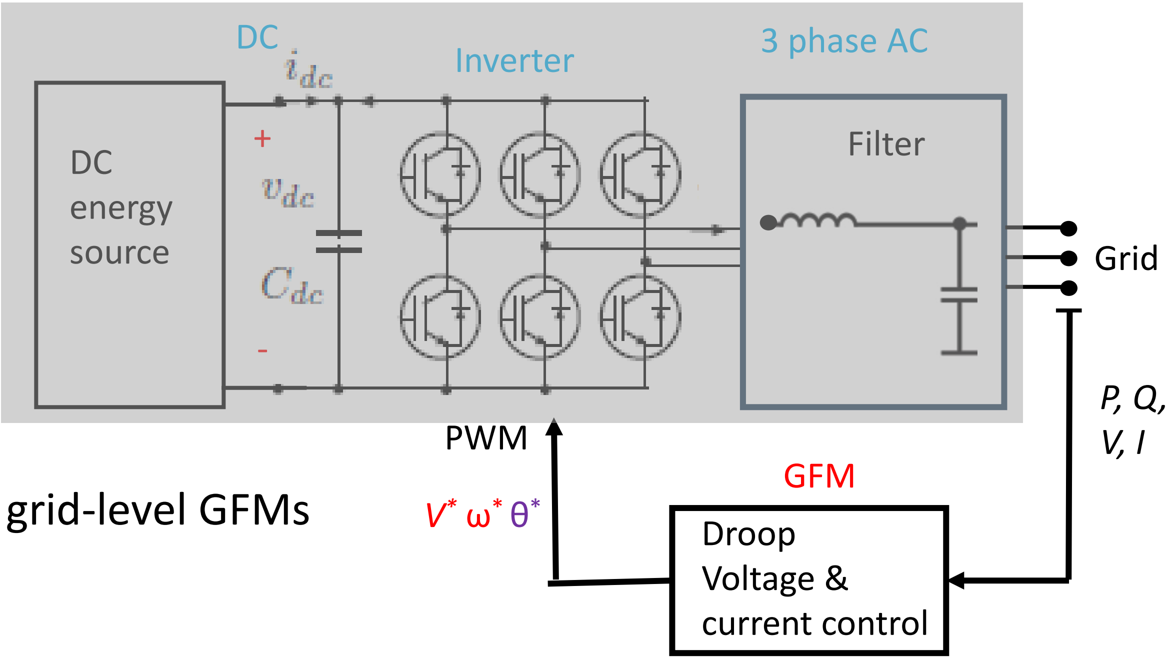
- Practically all IBRs now use GFL – allow to send to the grid all power *P* produced by the energy source (wind/PV/battery)
- A mature technology
- GFL can contribute to voltage control by controlling *Q*
  - Pure power-electronics, does not require an energy source
- Conceptual model neglecting details
- PWM needs $V^* \omega^* \theta^*$
- Voltage *V* is measured directly while frequency ω^* is set by Phase-Lock-Loop (PLL)
  - PLL requires a strong grid (fixed voltage and frequency) – problems with "weak grids"
  - 100% GFL grid is not possible
- The current and voltage controller ensure the desired (θ^*, P_{ref}, Q_{ref})



A conceptual model of GFL

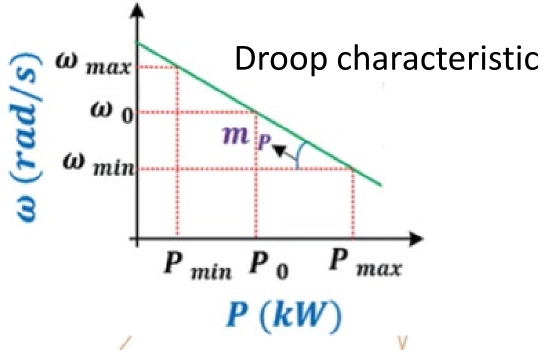
Grid Forming Inverter (GFM)





A conceptual model of GFM

- Known for 30+ years in microgrids but only a few experimental grid-level GFMs
  - A subject of intensive R&D
- GFM controls voltage *V* and frequency *ω* similarly as SM
- 100% IBR grid must have some GFMs
- Many GFM voltage/frequency control schemes proposed
  - the simplest: droop control
- GFM measures grid (*P, Q*) to calculate (ω*, *V**) from the droop characteristics
  - As in SM but the other way around
- Voltage and current controllers ensure the desired V^* ω^* θ^*



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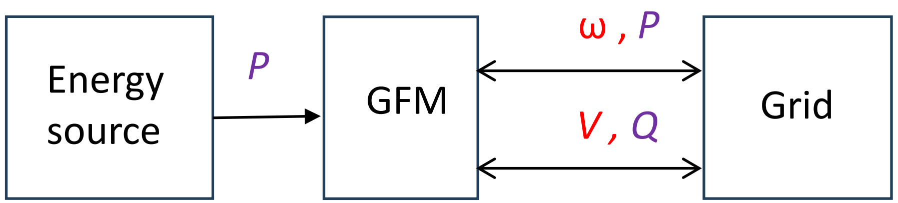
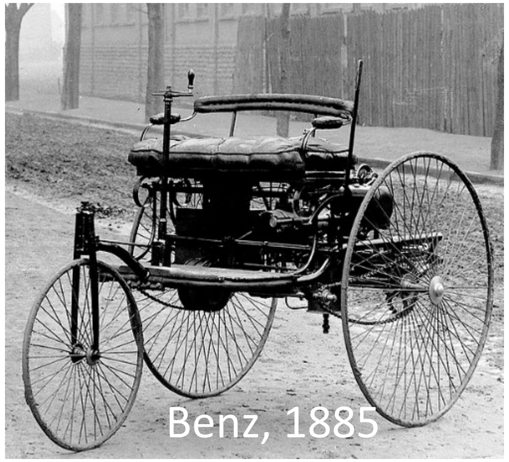
Features of GFM





- The GFM output (*P, Q)* cannot be set as it depends on grid conditions and (*V*, ω)
  - The energy source must have a headroom to deliver *P* required by GFM
  - Battery a natural energy source as a headroom for wind/PV means a revenue loss
- GFM can provide additional services: blackstart, damping of oscillations
- Droop control is the simplest but GFM can emulate SM (Virtual Synchronous Machine VSM) with controllable inertia and damping
- Is it a good idea to emulate SM?
- Many other control methods have been proposed: Virtual Oscillator Control (VOC), matching control and duality, optimal multi-variable control
- The future will tell which one will win

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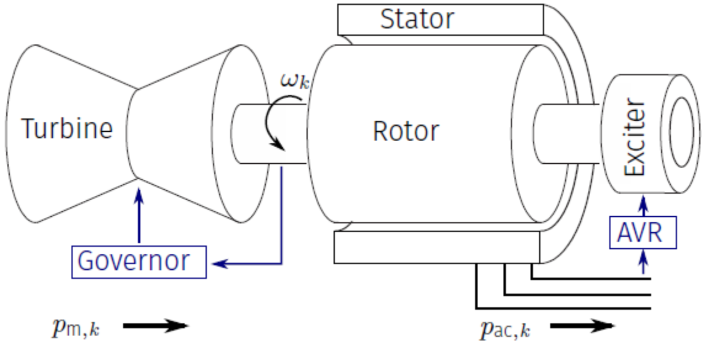
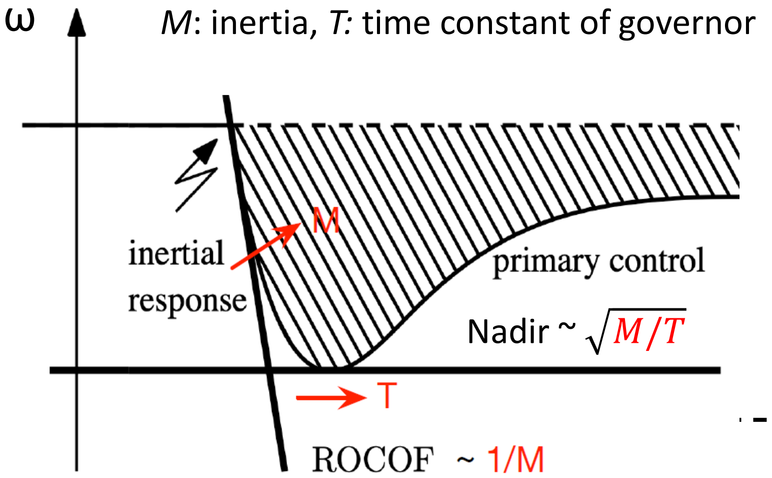
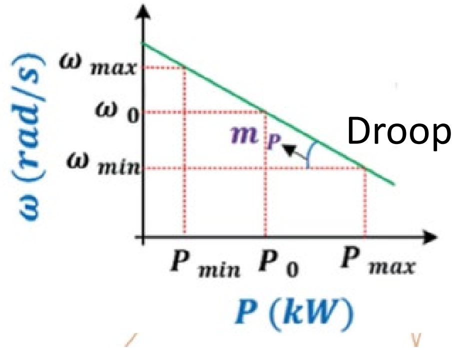
Primary frequency response: SM

- Maintaining the power balance: the most important grid control
- Following a generation or interconnector loss, the power deficit is initially covered by stored kinetic energy (inertial response) so frequency ω drops
- Turbine governors sense ω↘ and increase output *P* as per the droop characteristic
- Large inertia *M* needed to buy time for slow governors (large *T*) to act
- Two important parameters:
  - Nadir: avoid inadvertent activation of under-frequency load shedding (48.8 Hz in GB)
    - Nadir ~ $\sqrt{M/T}$: large *T* is counterbalanced by large *M* ☺
  - Rate of Change of Frequency ROCOF
    - Fear of catching too late a rapid frequency decline
    - Some countries including UK: DG loss-of-mains ROCOF relays
    - ROCOF ~ 1/M : ROCOF is small ☺





Adapted from F. Dorfler



Primary frequency response: IBR

- Reduced inertia *M* but much faster than SM (smaller *T*)
- Nadir ~ $\sqrt{M/T}$: small *M* counterbalanced by small *T* ☺
- ROCOF ~ 1/M : small *M* means large ROCOF ☹
- ROCOF a contributing factor to GB 2019 disturbance and Australia 2016 blackout

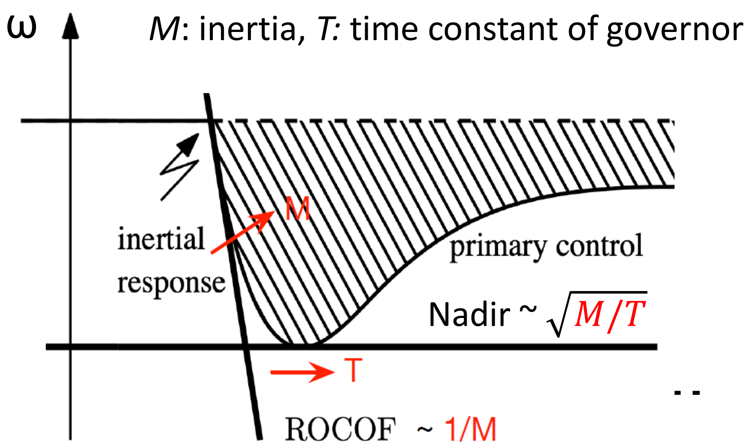
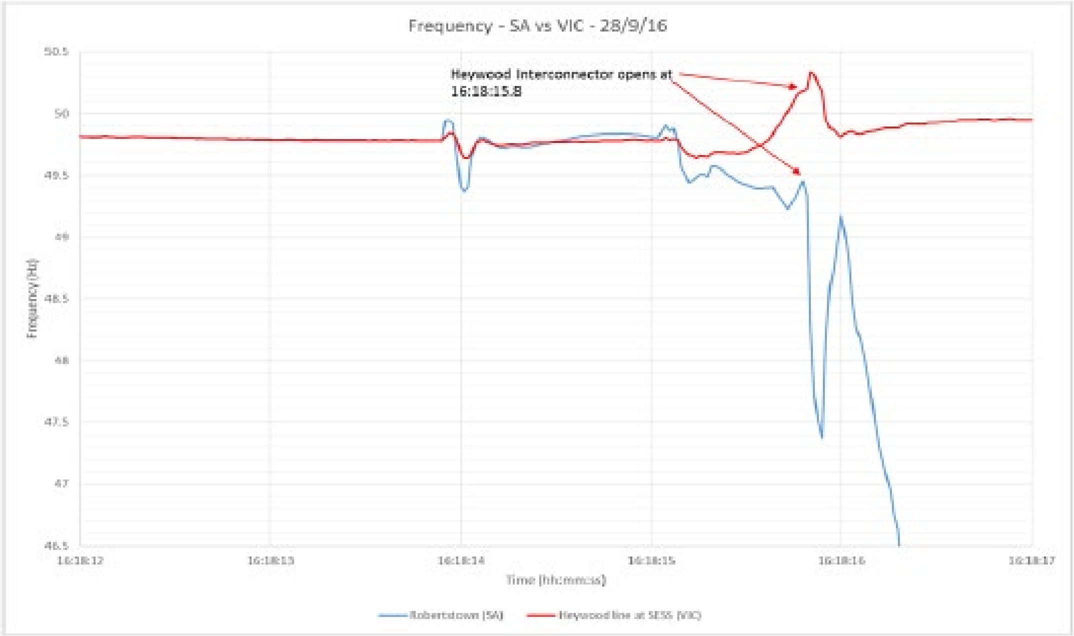
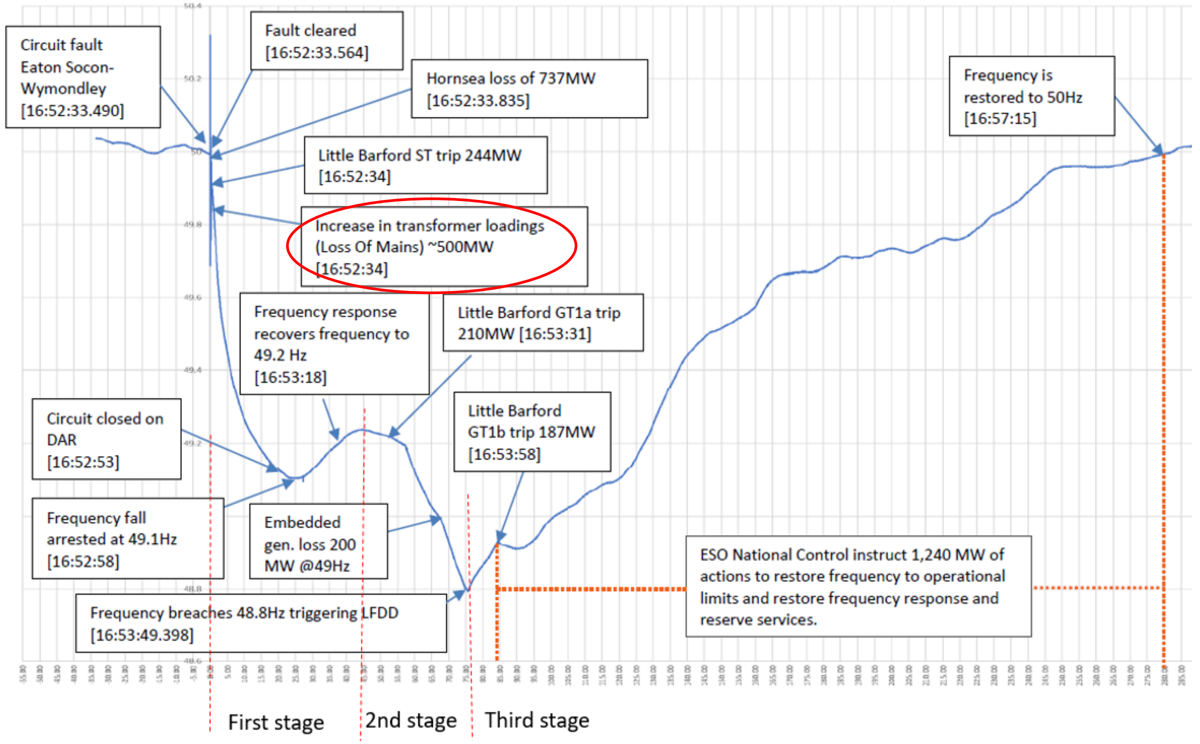


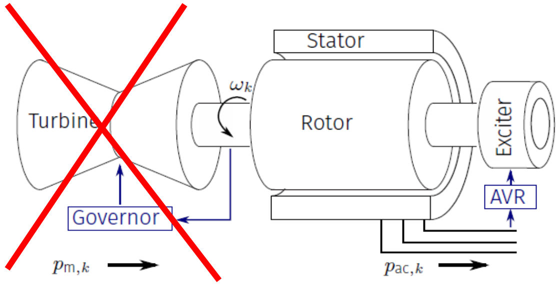
Figure 5 SA frequency compared to Victoria during event



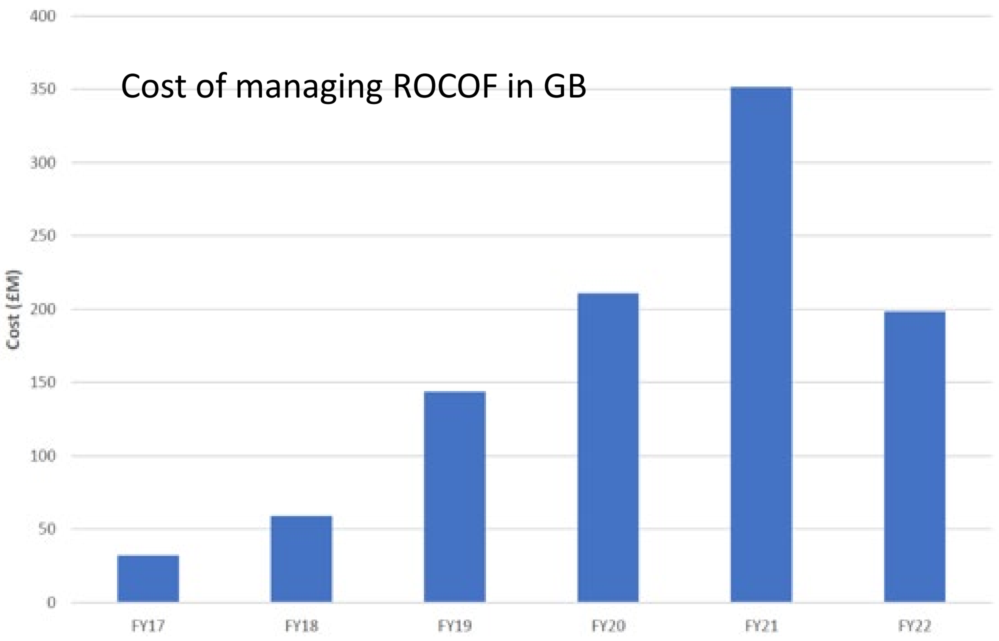


How to deal with reduced inertia

- Planning countermeasures
  - Installing synchronous condensers (syncon)
    - Popular because it is simple, well-understood and also helps with fault currents, but costly
  - GB: increasing ROCOF settings of loss-of-mains relays (0.125 Hz/s to 1 Hz/s)
- Operation (dispatch)
  - Limiting % penetration by wind/PV - “spilling”
  - Increases operating costs



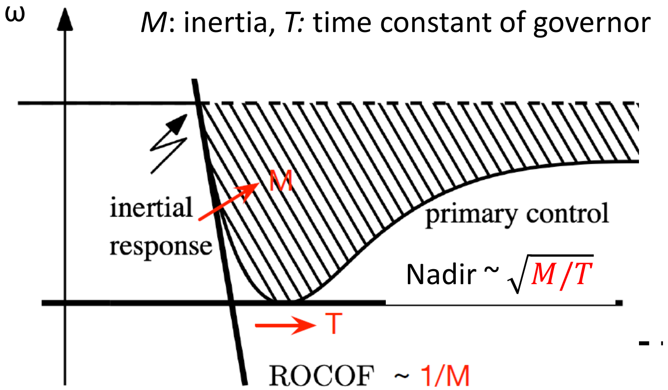
Source: D. Gross

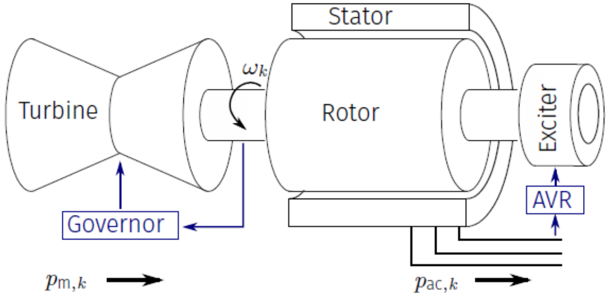


Do we *really* need large physical inertia in IBR-dominated systems?

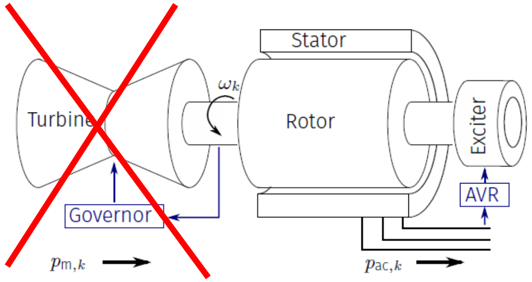
Inertia was needed to buy time for slow turbine governors to act
but inverters are quick
Do syncons make sense?

Can IBRs deliver "synthetic inertia"?





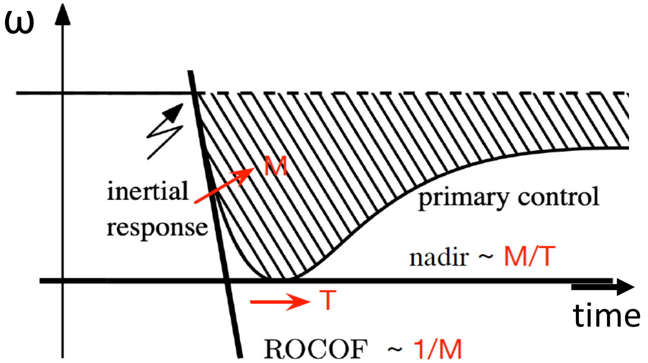
Synchronous condenser

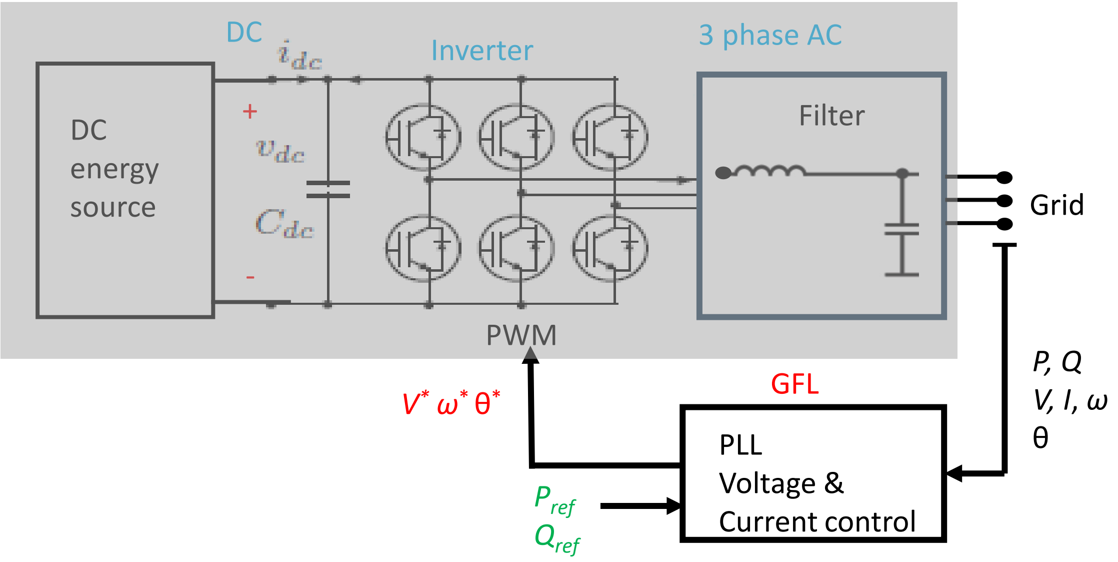


Source: D. Gross

Can GFL provide "synthetic inertia"?

- Inertia is an **instantaneously-acting** energy buffer:
  - energy is released proportionally to dω/dt (rather than just frequency deviation Δω) and without a delay
- GFL are fast but not instantaneous:
  - Measurement delays (PLL) as frequency cannot be measured directly: wait for zero-crossing of AC wave
  - Frequency is a noisy signal, measuring ROCOF requires waiting for a few periods
- GFL can provide Fast Frequency Response proportional to Δω but the delay too big to affect inertial response proportional to dω/dt

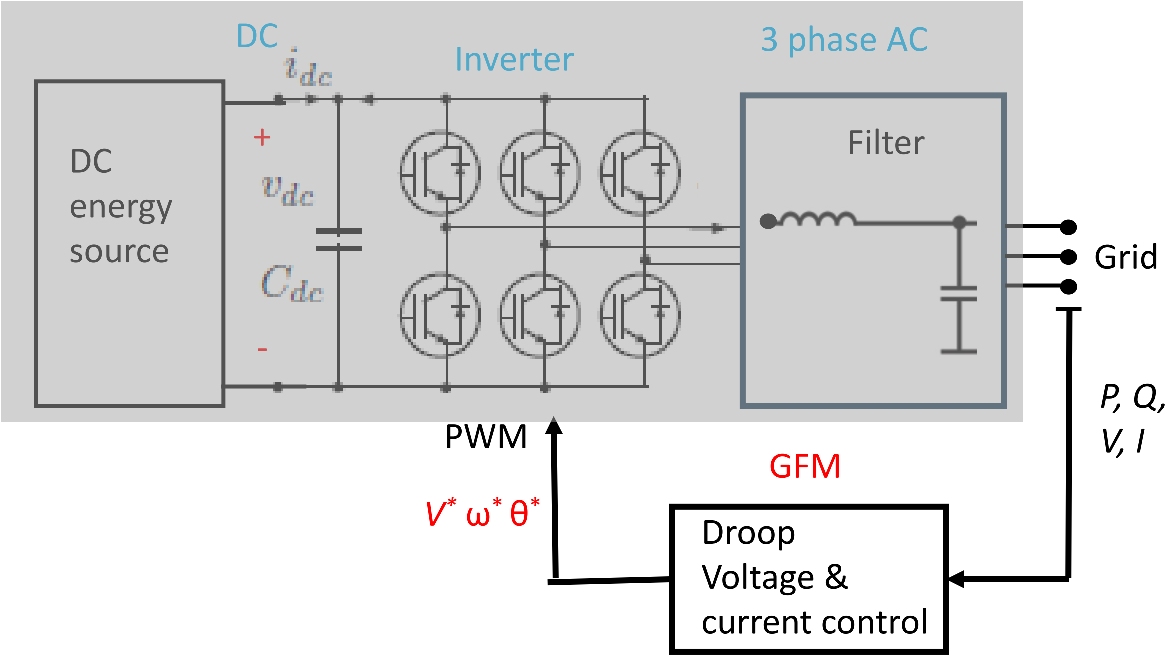


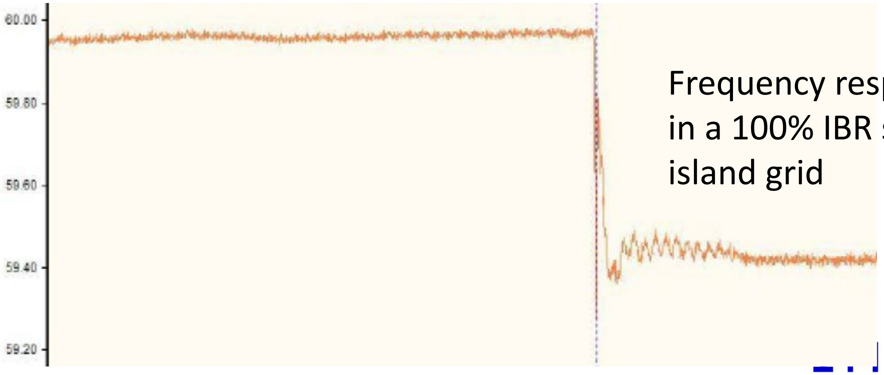


A conceptual model of GFL

Can GFM provide “synthetic inertia”?

- GFM measures *P* and derives ω from the droop
    - *P* can be measured directly – reduced measurement delays ☺
    - But there are still some small unavoidable delays: processing, activating the energy source ☹
    - Smaller delays can be buffered using a large DC-side supercap (“electrical inertia”)
- Can 100% IBR system with GFMs operate without inertia?
    - Possible but large ROCOF
    - Maybe in the future when everything is connected via inverters



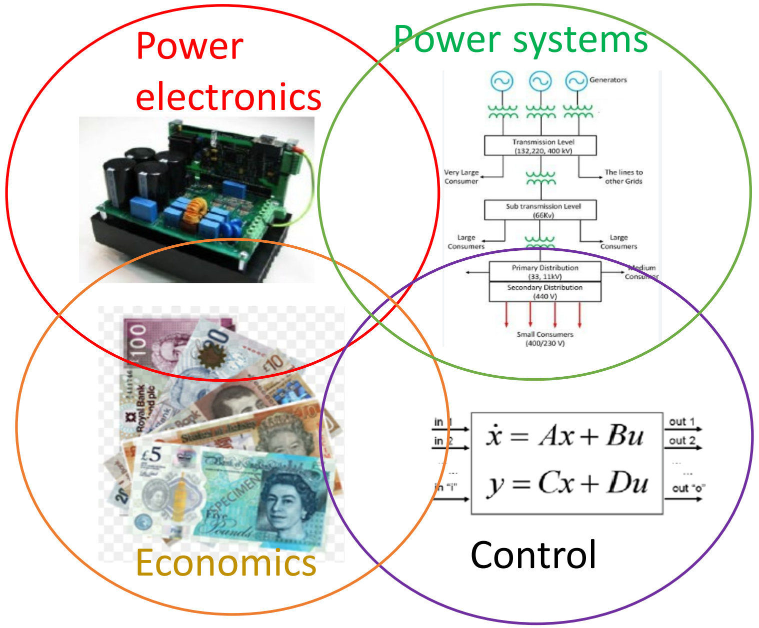


Frequency response in a 100% IBR small island grid

Source: F. Doerfler

Summary

- Power system technical characteristics are changing rapidly due to replacement of SMs by IBRs
- SM: Physics-based, robust, well-understood but slow
- IBRs: software-based, fast, agile but fragile and poorly-understood
- Inverter challenge: operate the system efficiently and to the same reliability standard but using IBRs
- Great time to do power system research!
- Need for interdisciplinary effort



Q & A

Thank you

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