Future Power Markets Forum

Market design implications of high penetrations of inverter-based resources

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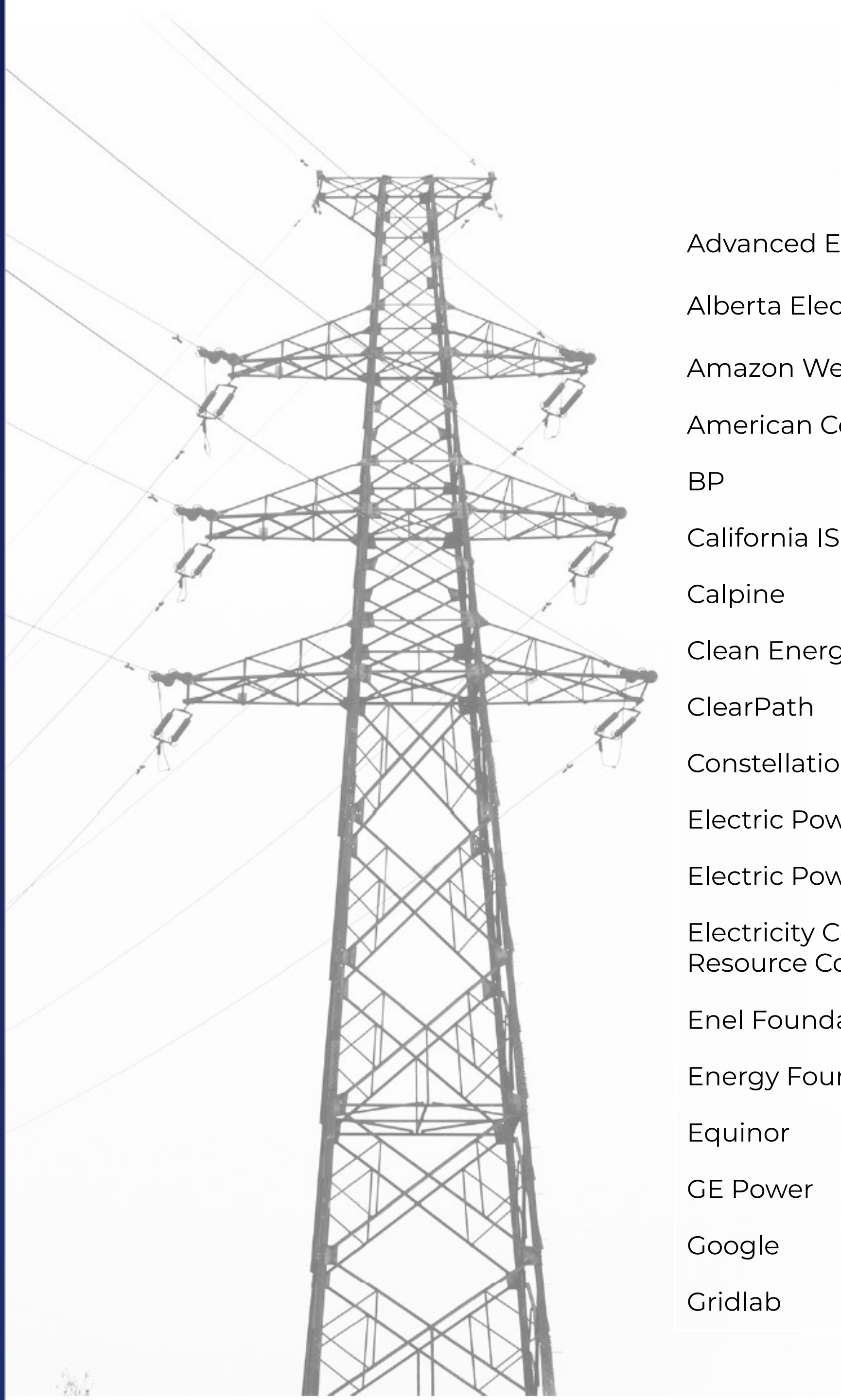

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Inverter challenge for power system operation and control

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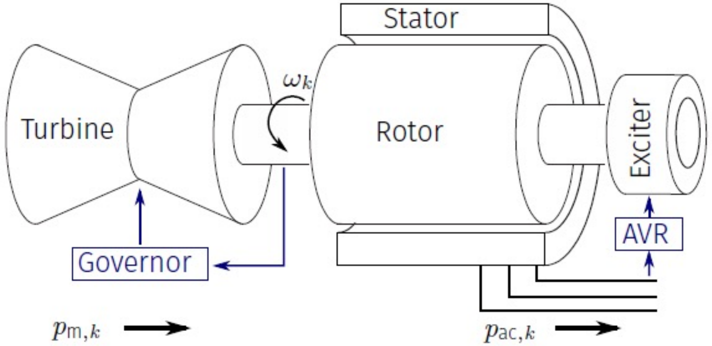
Outline

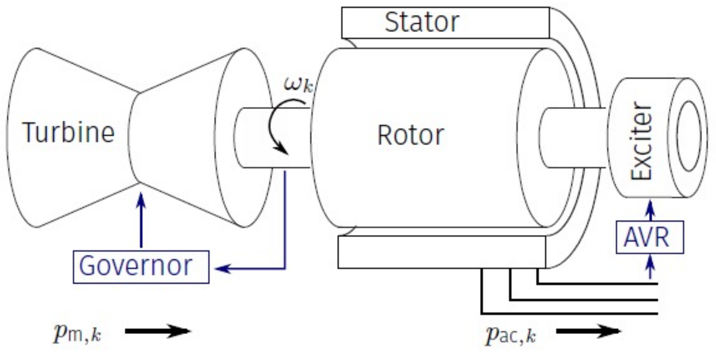
- High-level overview of the challenges posed by high penetration of Inverter-Based Resources (IBRs)
- Understanding Grid Following and Grid Forming Inverters
- Frequency control in IBR-based systems
- New services needed
- Conclusions

Inverter-Based Resources (IBRs)



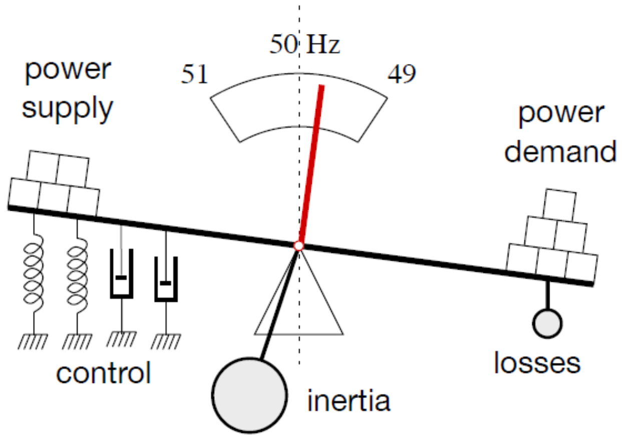
- Traditional thermal/hydro plants used Synchronous Machines (SMs) to convert mechanical energy into AC electricity
  - Technical characteristics and controls of the grid were determined by the physics of SMs
- Wind and solar PV produce DC output so they are connected to the AC system asynchronously using programmable inverters (converters)
- IBRs also include batteries, EV, HVDC terminals, variable-speed motor drives, Statcom, etc
- Replacing SMs by IBRs changes fundamental technical characteristics of the power system and requires new controls
- Inverter challenge: operate the grid efficiently and to the same reliability standard but using IBRs
- Fast pace of change: System Operators are scared

SM: physics-defined behaviour



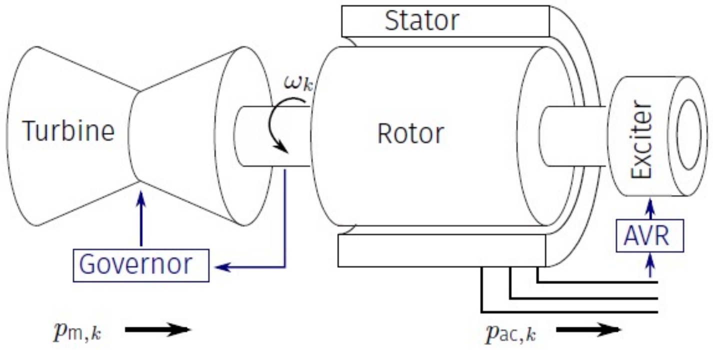
Source: D. Gross

- Physics dominated by slow electromechanical phenomena (seconds) and thermodynamic phenomena (minutes)
- Create 50/60 Hz smooth AC voltage from a rotating electromagnet
- Self-synchronisation and inherent damping of oscillations around the synchronous speed
- Physical link between power balance and frequency
  - Large inertia provides a buffer to absorb generator trips

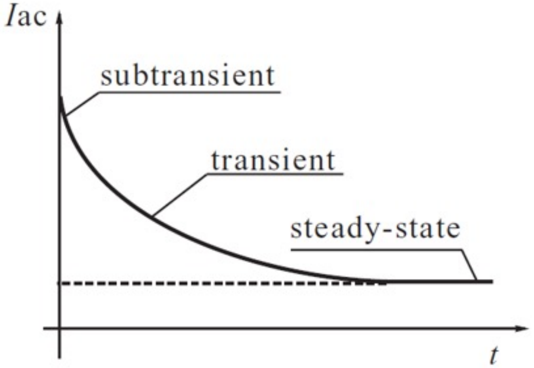


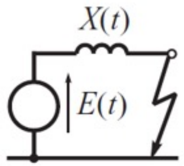
SM: fault currents, grid strength and modelling

- SM produce large 2-4 pu fault (short-circuit) currents that decay with time
  - High fault currents support voltages during a fault (essential for fault-ride-through)
  - Easy to detect, useful for protection
- SMs maintain grid “strength”: voltage and frequency independent of real and reactive power changes



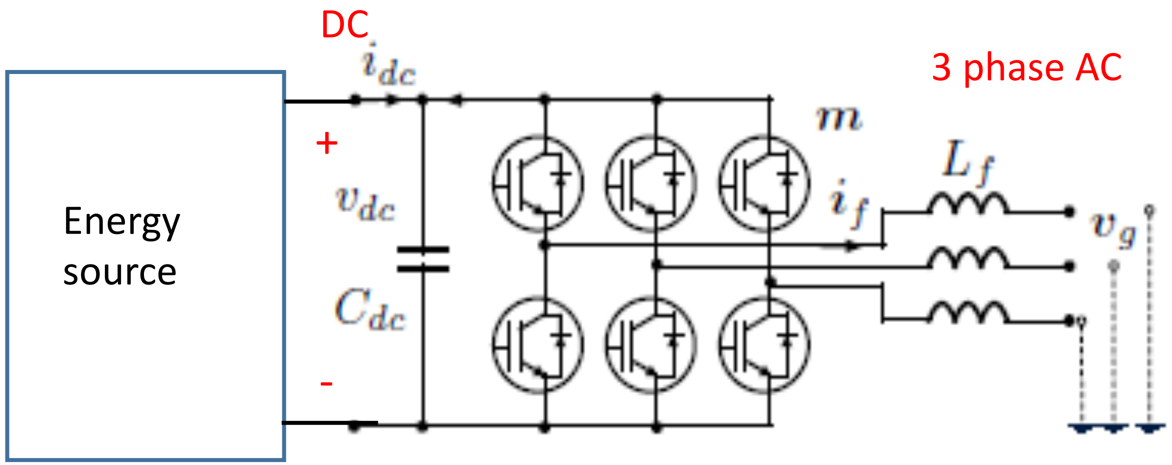
Source: D. Gross

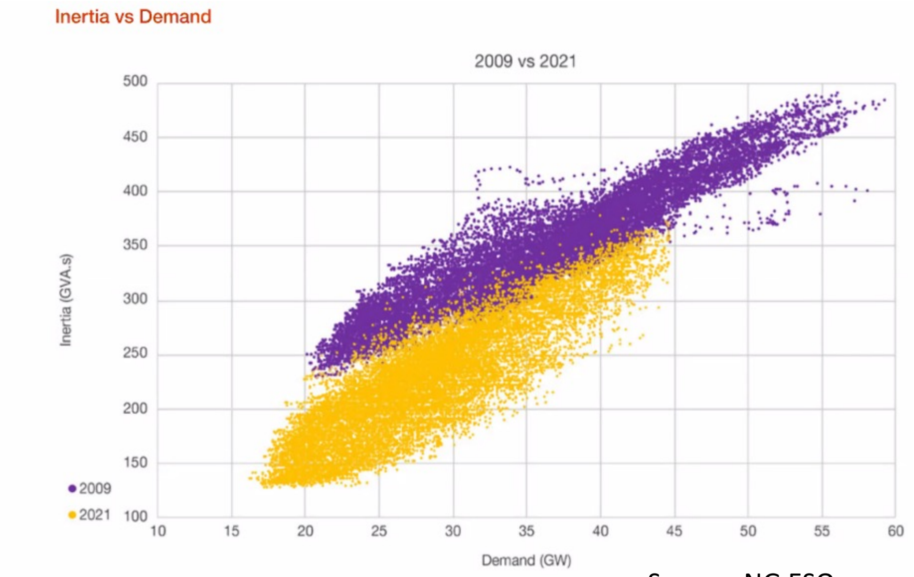




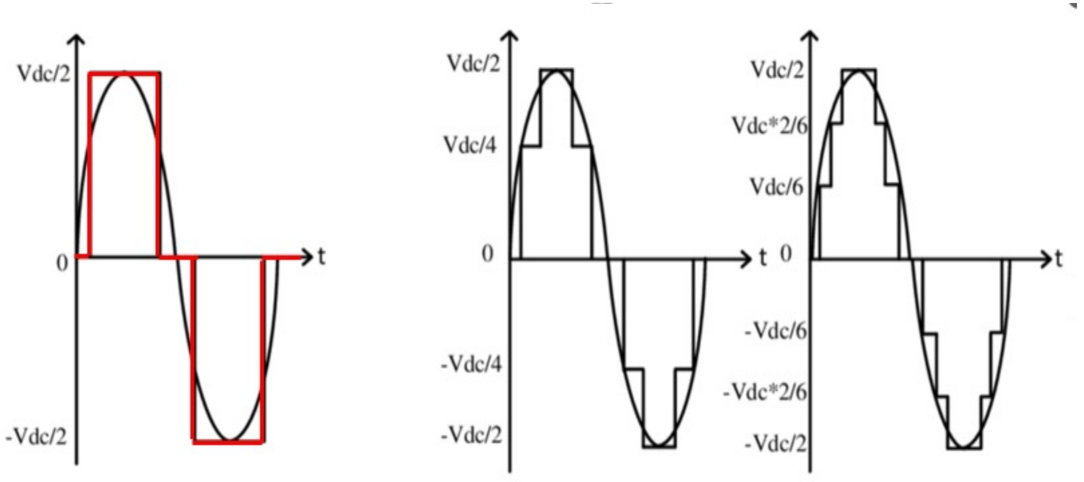
IBRs: software-defined behaviour

- Inverter is essentially a switching device
- Creates a quasi-AC waveform: Pulse-Width Modulation (PWM)
  - Controllable amplitude, frequency and phase shift
  - High flexibility and speed ☺
- Little energy storage– just DC-side capacitor (“electrical inertia”) ☹
- No inherent self-synchronisation, primary frequency response or damping of oscillations – everything must be programmed





Source: NG ESO

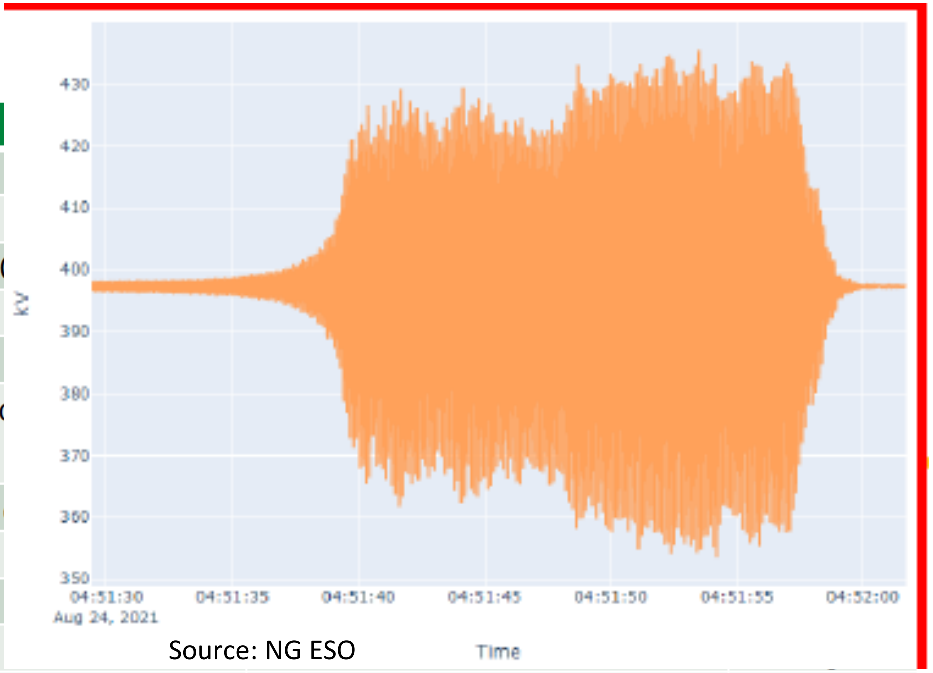


3-level 5-level 7-level

Stability problems of IBRs

- New controls of IBRs create new modes of instability
- Sub-synchronous oscillation (SSO) events around the world
- Scotland events still not fully understood
- Lack of white-box models of IBRs (proprietary concerns)
    - Problems with grid modelling and analysis
- Uncertainty creates additional costs as SOs have to operate the grid more conservatively

Sl #	Date	Location		
1	2007	South Central Minnesota		
2	2009	South Texas		
3	2010	Oklahoma Gas & Electric (		
4	2011	Texas		
5	2011-2014	BPA territory in Oregon		
6	2011-2012	OG&E reported two wind events		
7	2012-2013	58+ oscillation events in N		
8	2014-2015	Xinjiang China		
9	2015	Hydro One, Canada		
10	2016	AEP footprint		
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



Source: NG ESO

S. Dutta "SSO events and Learnings" PES GM 2023

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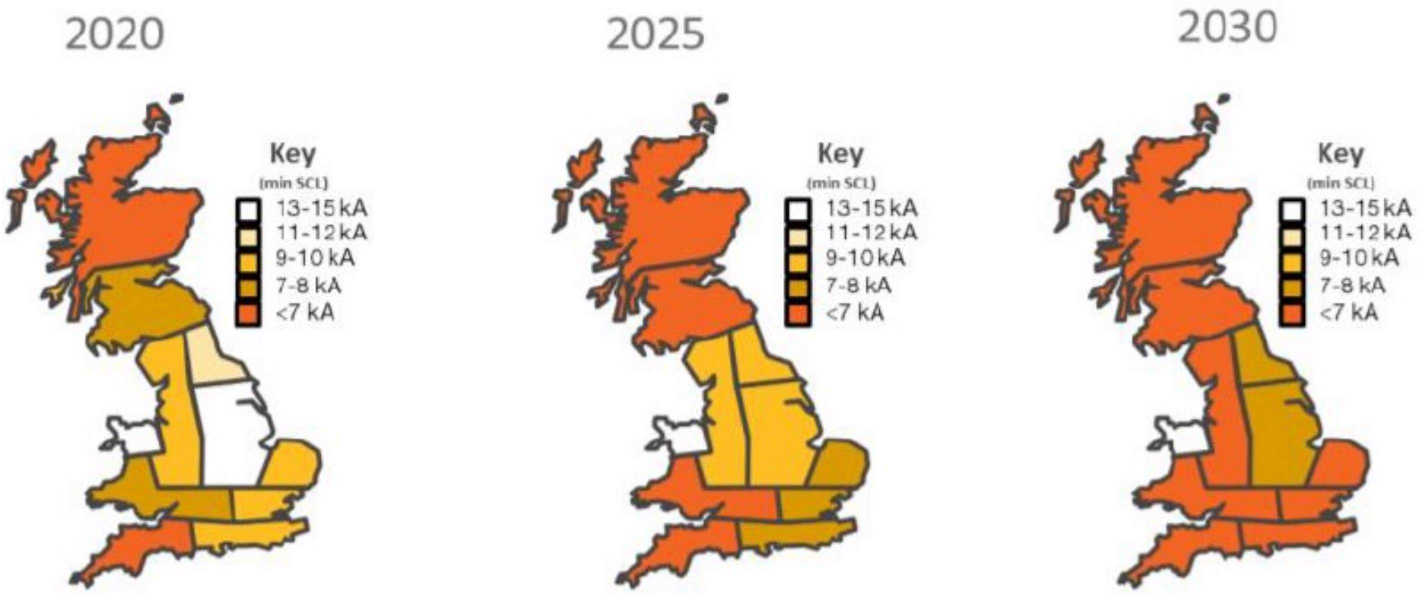
IBRs: fault currents and grid strength

- Inverters do not provide fault currents
  - Cannot be overloaded temporarily due to low thermal mass of semiconductors
  - Deteriorated fault-ride-through



Regional minimum short circuit level

Source: NG ESO

- Reduced system strength
  - Related to short-circuit levels
  - See Scotland - problems with operation of inverters that require fixed voltage and frequency

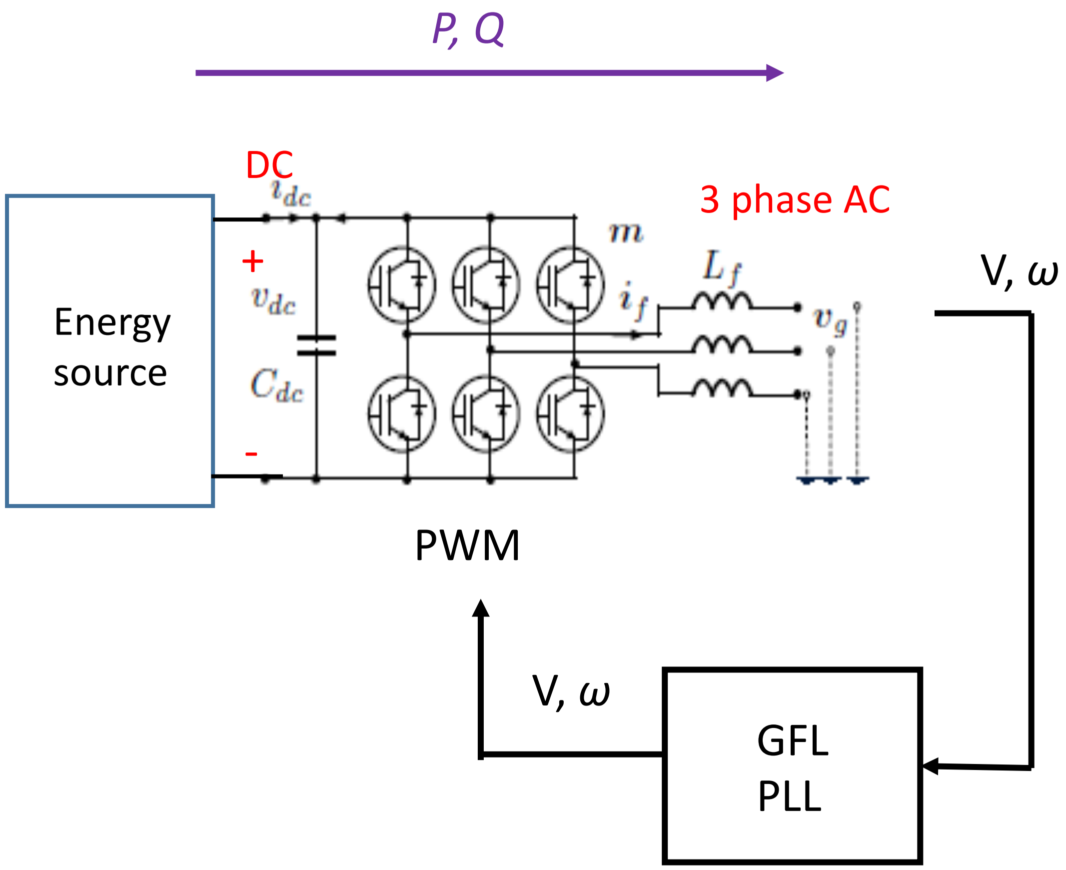
Understanding Grid Following and Grid Forming Inverters

- Fundamental question: which variables can a grid controller control?
    - Power *P*, reactive power *Q,* voltage *V*, frequency ω
- Two pairs:
    - Power *P* strongly related to frequency ω
    - Reactive power *Q* strongly related to voltage *V*
    - Weak link between the pairs
- 2 degrees of freedom:
    - only 1 variable from each pair can be independently controlled
    - the other one depends on grid operating conditions

- 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
    - (*P, Q*) output depends on the grid conditions – cannot be set
- Not a binary divide: a spectrum with many types and flavours, crossovers etc.

Grid Following Inverter (GFL)

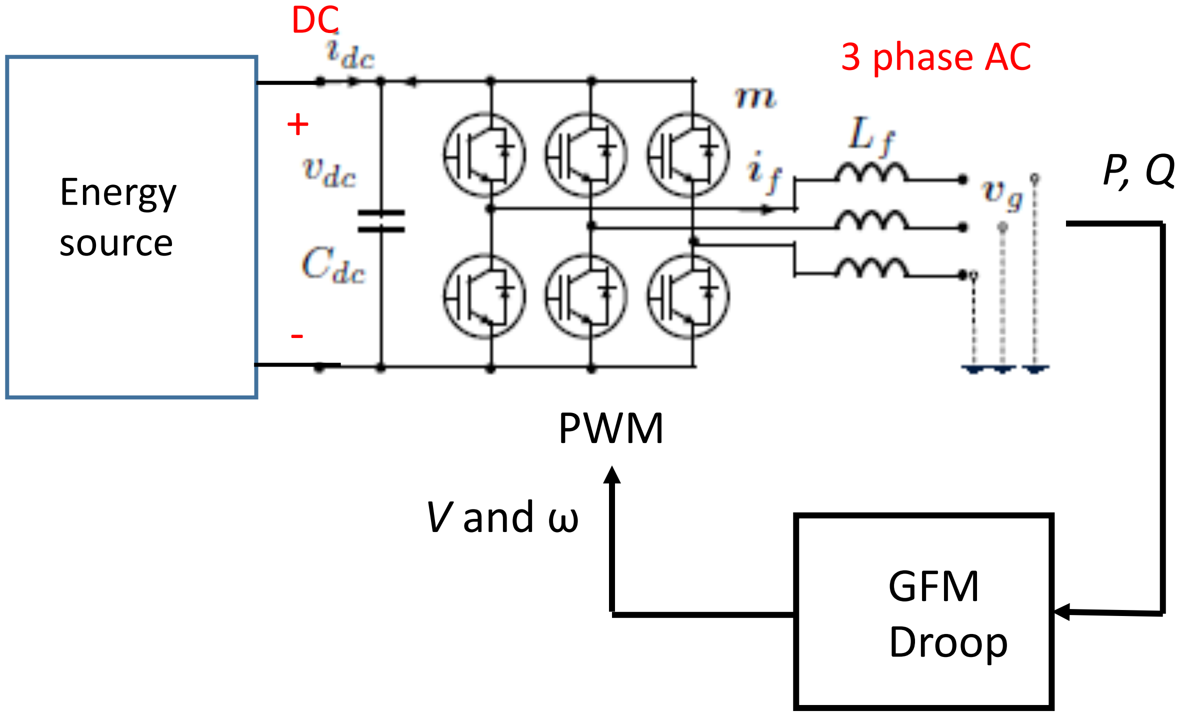
- Delivers to the grid power *P* produced by the energy source (wind, PV or battery) at the voltage and frequency set by the grid
    - practically all IBRs now use GFL - a mature technology
- Frequency for PWM is set by the grid: Phase-Lock-Loop (PLL)
    - PLL requires a strong grid (fixed voltage and frequency)
- GFL can provide Fast Frequency Response (FFR)
    - change quickly output power *P* in response to frequency changes
- Can contribute to voltage control

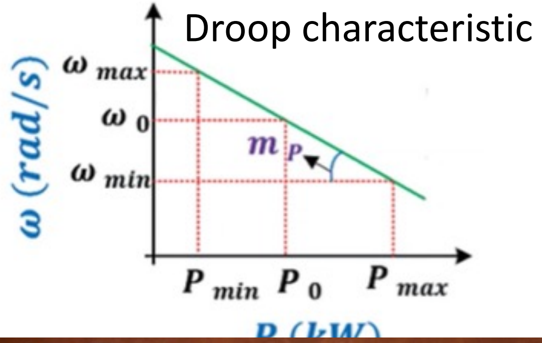


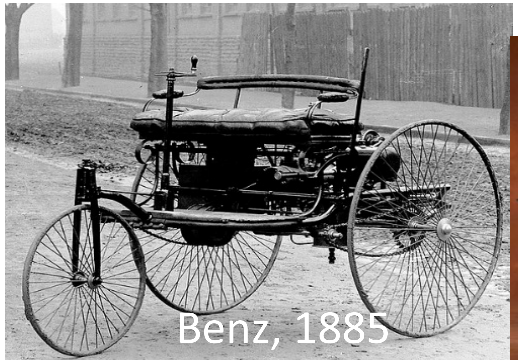
set-points: *P* and *Q*
V and ω set by the grid

Grid Forming Inverter (GFM)

- GFM provides a controllable voltage *V* and frequency *ω* similarly as SM
- Frequency for PWM set by the droop characteristic *ω(P)*
  - Similarly as for SM but the other way around
  - GFM measures *P* and sets *ω*
- The output *P, Q* depends on grid conditions
  - Battery a natural energy source as for wind/PV a headroom would be needed
- GFM may provide additional services (blackstart, damping of oscillations)
- Just a few experimental GFM installations worldwide
- The grid-level technology is not mature - subject of intensive research
  - Should GFM ape SM (Virtual Synchronous Machine VSM)?

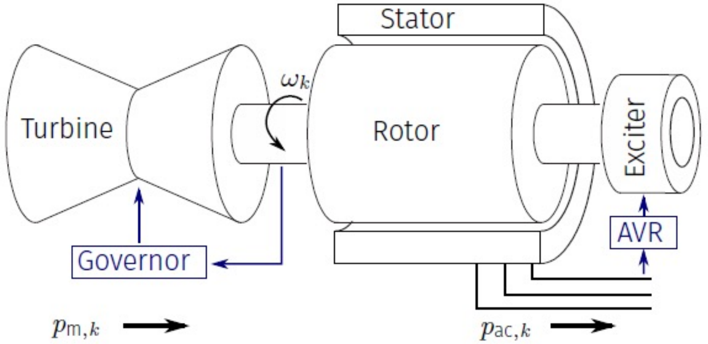




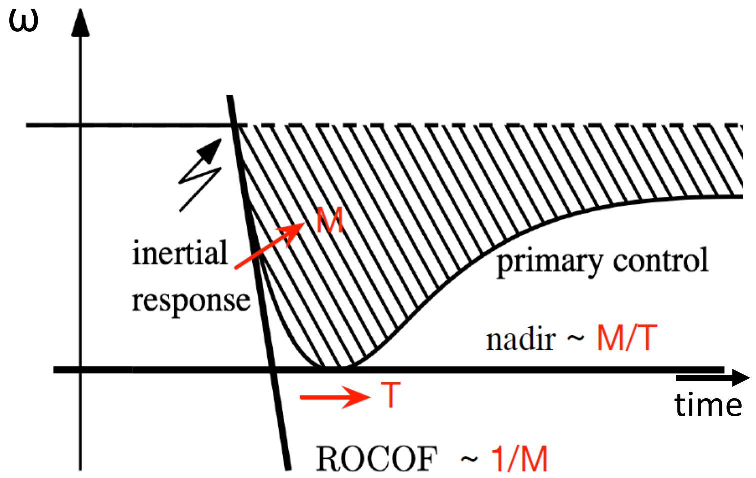

Benz, 1885

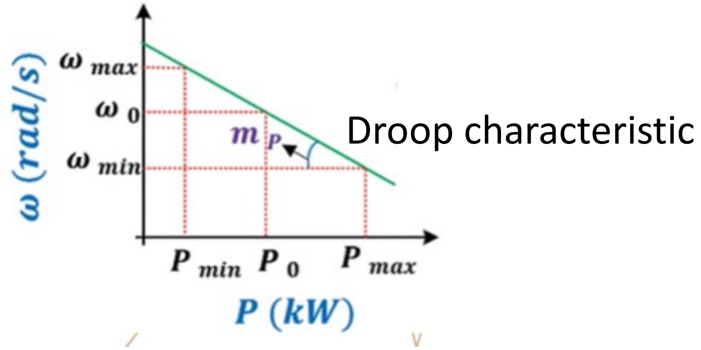

1905, Panhard

Primary frequency response: SM



- Following an infeed (generation or interconnector) loss, power deficit is initially covered from stored kinetic energy (inertial response) and 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)
    - Rate of Change of Frequency ROCOF
        - many units have ROCOF relays – e.g. loss-of-mains relays in DG
- Nadir ~ *M/T* : large *T* is counterbalanced by large *M* ☺
- ROCOF ~ 1/M : ROCOF is small ☺





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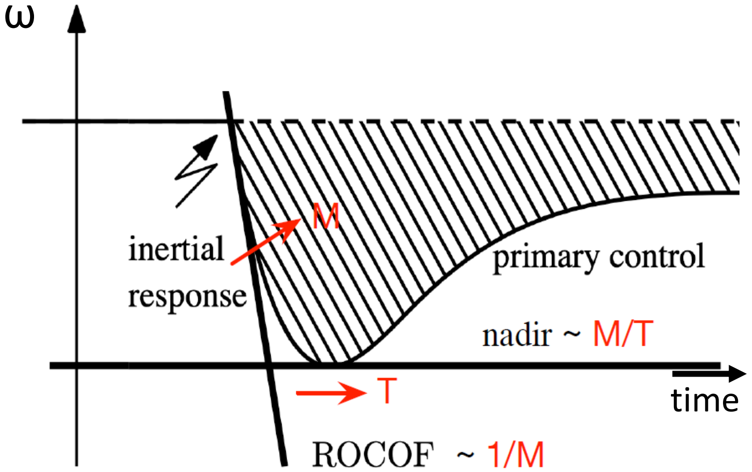
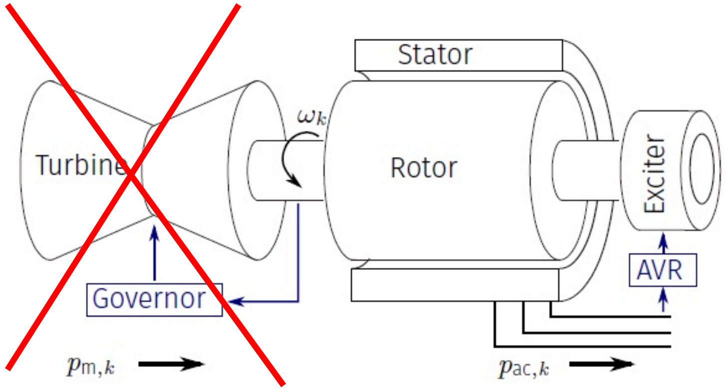
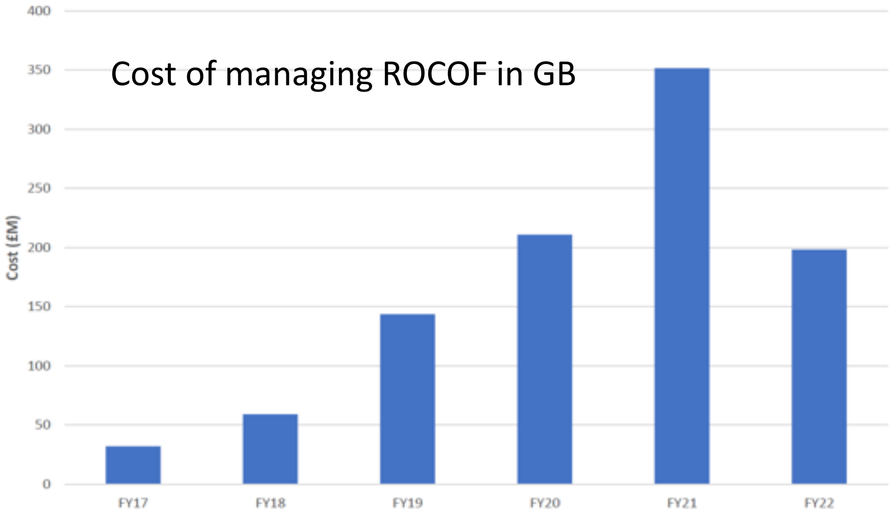
Primary frequency response: IBR

- Little "electrical inertia" *M* but much faster than SM (smaller *T*)
  - Nadir ~ *M/T* : small *M* counterbalanced by small *T* ☺
  - ROCOF ~ 1/M : small *M* means large ROCOF ☹
- Planning counter-measures:
  - Installing synchronous condensers – very popular, also helps with fault currents, but costly
  - GB: changing ROCOF settings of loss-of-mains relays (0.125 Hz/s to 1 Hz/s)
- Operation (dispatch): replacing wind and interconnectors by SM-based plants

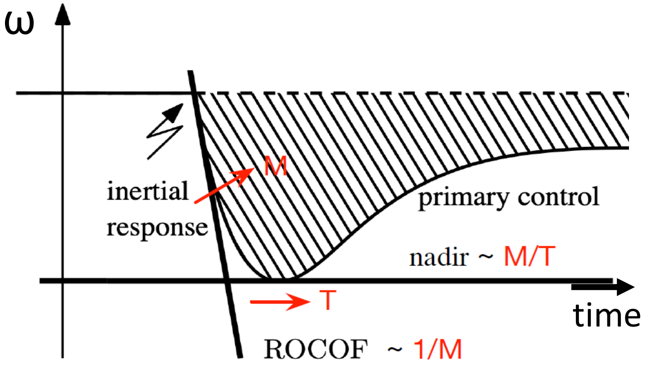




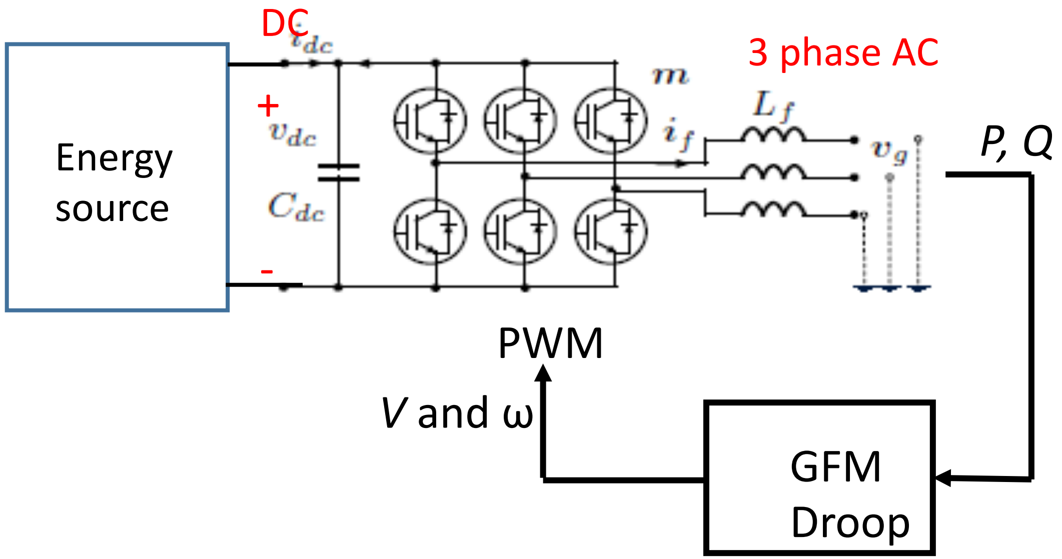
Source: D. Gross

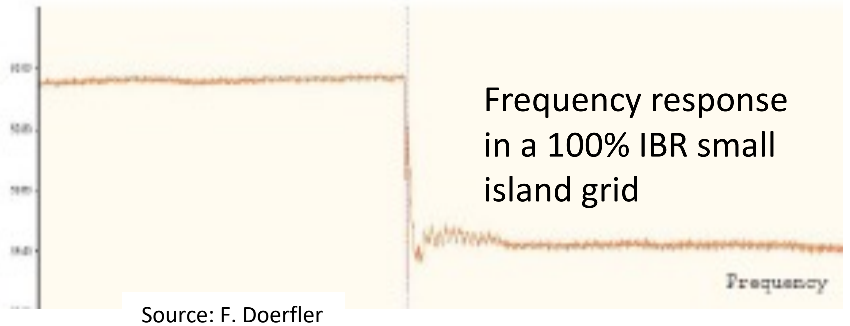


Why can't Fast Frequency Response (FFR) of IBRs reduce ROCOF?



- Reduction of ROCOF must commence immediately after a disturbance occurs
- GFLs are fast but still introduce 0.1-0.5s sec delays
    - Measurement delays as frequency cannot be measured directly (zero-crossing of AC wave)
    - GFLs need inertia of SMs to buffer the delays
    - The term "synthetic inertia" is misleading
- GFM measures *P* instead of ω
    - *P* can be measured directly – reduced measurement delay ☺
    - But there are other unavoidable delays: processing, activating the energy source (20- 40 ms for batteries) ☹
    - 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

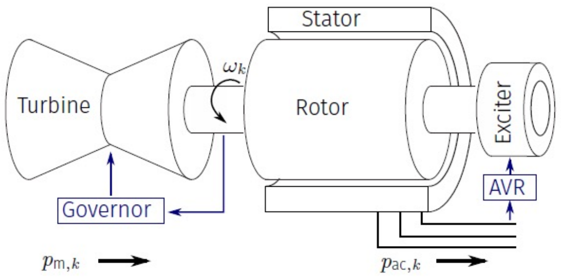




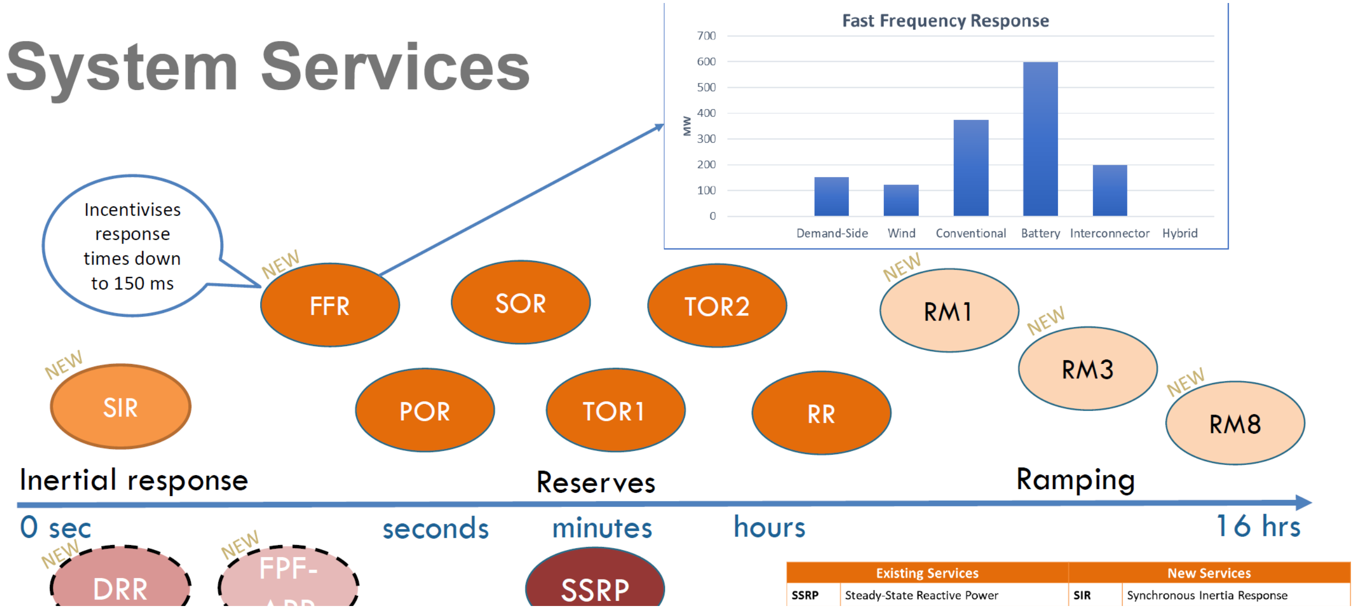
Frequency response in a 100% IBR small island grid

Source: F. Doerfler

System services



- SM provides many system services (inertia, fault currents, damping of oscillations etc) by means of physics so they are free
- IBRs have to be programmed to deliver those services and have to be paid for them – additional costs
- What are the grid needs and the services needed to satisfy them in IBR dominated system?
- Proliferation and fragmentation of services
- New codes, standards, tariff structures
- New market mechanisms needed
  - See the new stability market in GB



Long-term (Y-4) stability market

Further information will be provided on the development of the long-term (Y-4) market at a later date. Please continue to monitor our website and newsletters for future updates.

Mid-term (Y-1) stability market

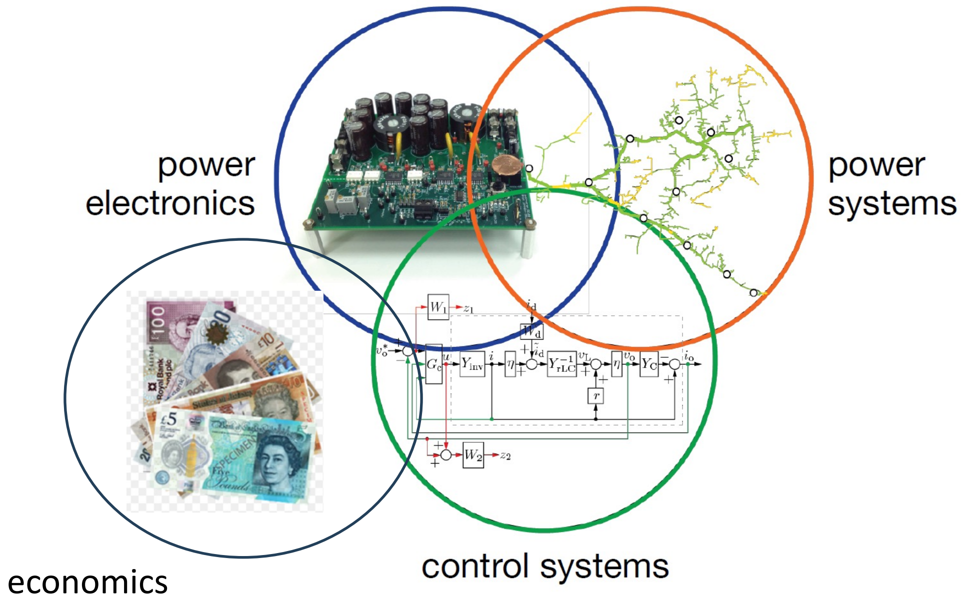
Launching the mid-term (Y-1) market is the first step in the implementation of the enduring Stability Market.

Short-term (D-1) stability market

Further information will be provided on the development of the short-term (D-1) market at a later date. Please continue to monitor our website and newsletters for future updates.

Summary

- Power system technical characteristics are changing rapidly due to replacement of SMs by IBRs
- SM: Physics-based, robust but slow
- IBRs: software-based, fast, agile but fragile
- Inverter challenge: operate the system efficiently and to the same reliability standard but using IBRs
- Significant challenges for frequency control and other services
- Need for interdisciplinary effort



Market design implications of high penetrations of inverter-based resources

ESIG
ENERGY SYSTEMS INTEGRATION GROUP

Julia Matevosyan
Chief Engineer
ESIG

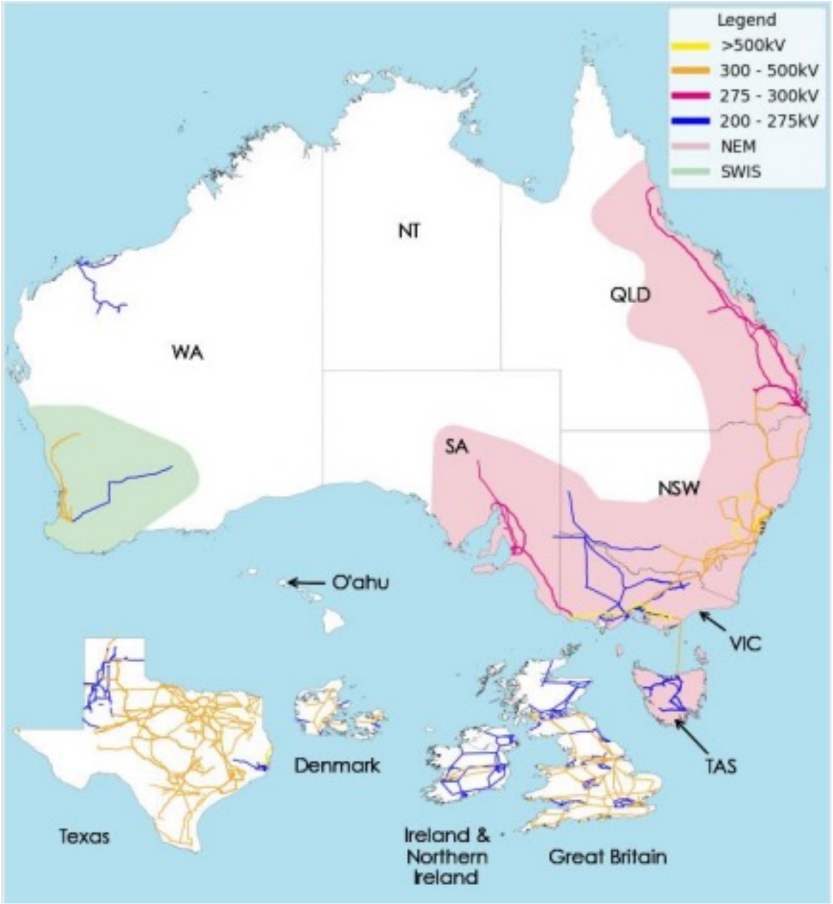
03/15/2024

What are the issues?

ESIG

- System services inherently provided by synchronous machines are becoming scarce and need to be provided by inverter-based resources (IBRs) such as wind, solar, battery storage
- **Frequency Stability**
  - Low inertia leading to fast rate of change of frequency after contingencies (e.g. generator trip)
  - Too fast frequency control may introduce oscillations in lower inertia systems
  - Common mode events resulting in loss of multiple IBRs
- **Voltage and Angular Stability**
  - Long distance high power transfer (wind and solar IBR often far from load)
  - Convergence of voltage stability limits on normal voltage range, brittleness of the system
  - Low system strength, voltage oscillations
- **Control Stability**
  - Control interactions

Will all power systems get see same issues at the same time?



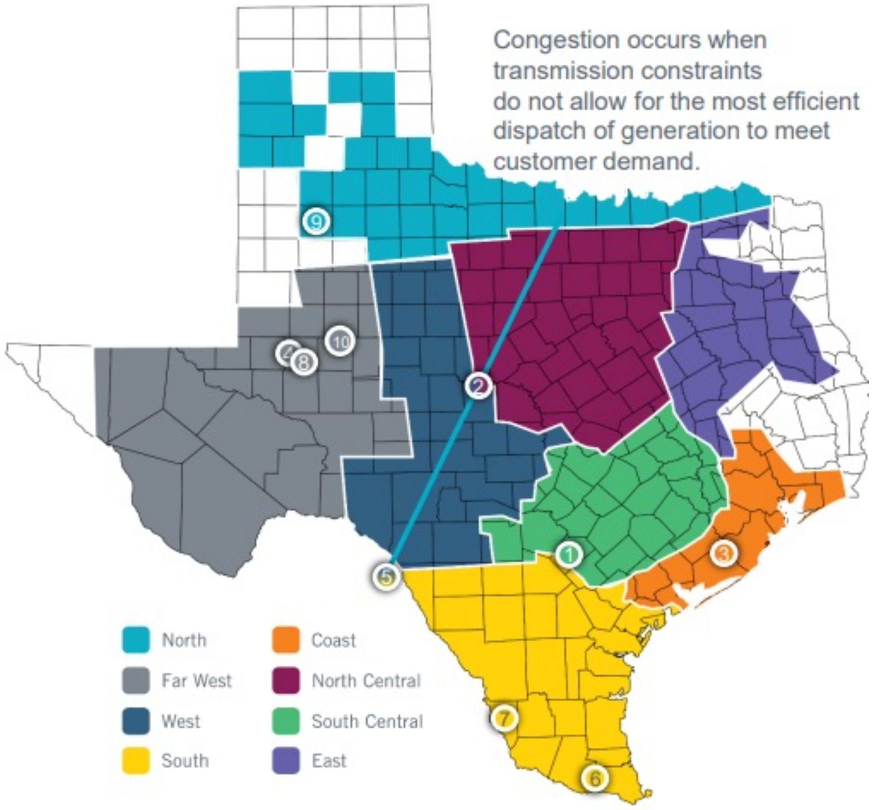
- Small electrical islands, e.g. Hawaii, are the first to experience a number of issues at once, but are more meshed, coordination is easier, solutions are not necessarily scalable for larger systems;
- Medium electrical islands, e.g. Ireland, more meshed, frequency is an issue before other challenges;
- Large electrical islands, e.g. Great Britain, ERCOT and mainland Australia, further challenges due to IBRs being far from load centers, in weak grid locations.
- Geographically Large Interconnected Systems, e.g. Central Europe, Eastern Interconnection and Western Interconnection in the U.S., no issues with IBRs for intact system, but high concerns during system splits.

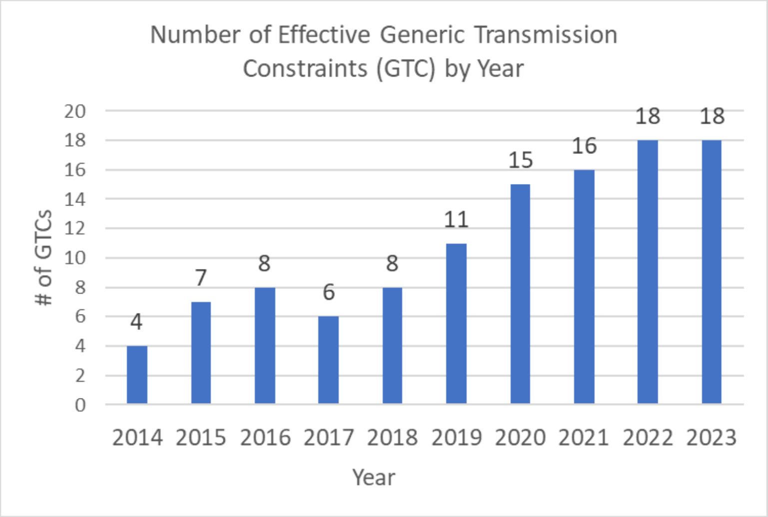
Source: https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Future-Energy-Systems/2019/AEMO-RIS-International-Review-Oct-19.pdf

Stability-Related Constraints & Renewable Curtailments, with Example of ERCOT

ESIG

Top 10 Constraints on ERCOT System
(based on real time data)





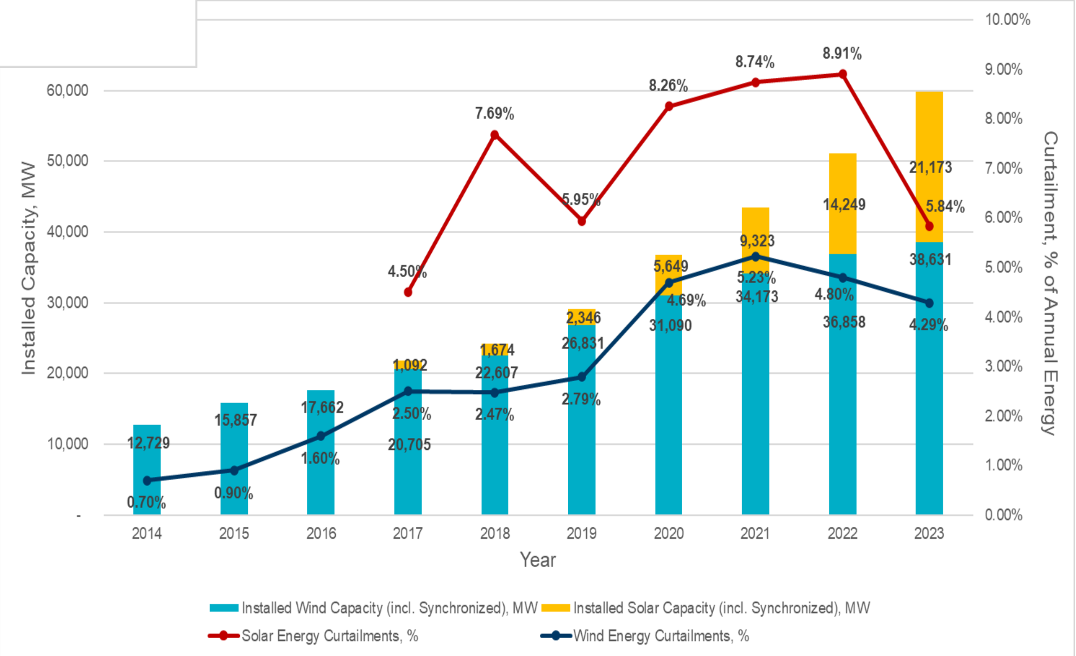
Wind - 38.8 GW
Solar – 22 GW
Battery – 5 GW (1-2 h duration)

Peak Load – 85.5 GW

69.15% instantaneous wind penetration record (04/22)

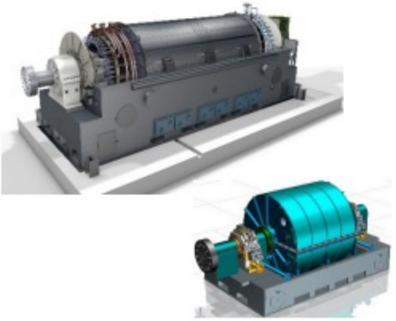
IBRs already providing some system services

Growth of Wind and Solar Curtailments as More Capacity is Added to the ERCOT Grid, 2014-2023



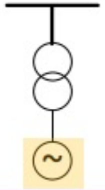
Source: ERCOT, Report on Existing and Potential Electric System Constraints and Needs, December 2023

Current Strategies for Relief the Stability Constraints – Adding Transmission Assets



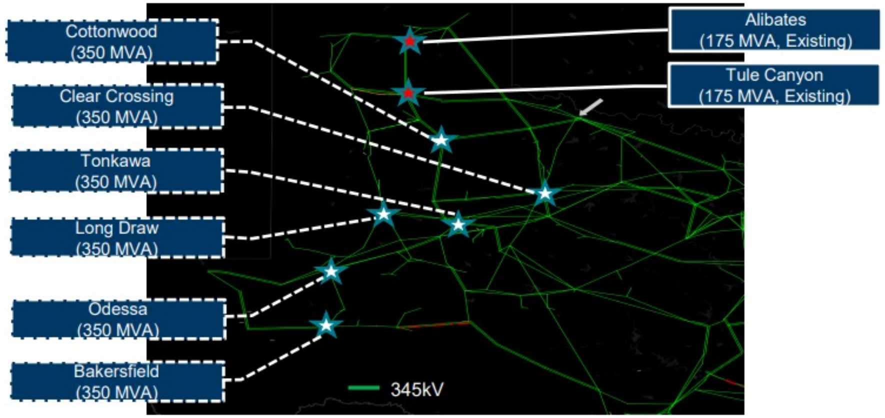
Synchronous Condenser – (w/wo Flywheel)

- Short circuit power and inertia support
- Rotating equipment



Source: Siemens Energy, Ian Ramsay, EIPC Workshop, June 2022

Additional six synchronous condensers with total of 2,100 MVA were identified that will provide effective improvement to WTX.



Source: ERCOT, *Strengthening the West Texas Grid to Mitigate Widespread Inverter-Based Events – Operation Assessment Results*, Regional Planning Group meeting, Feb 2023

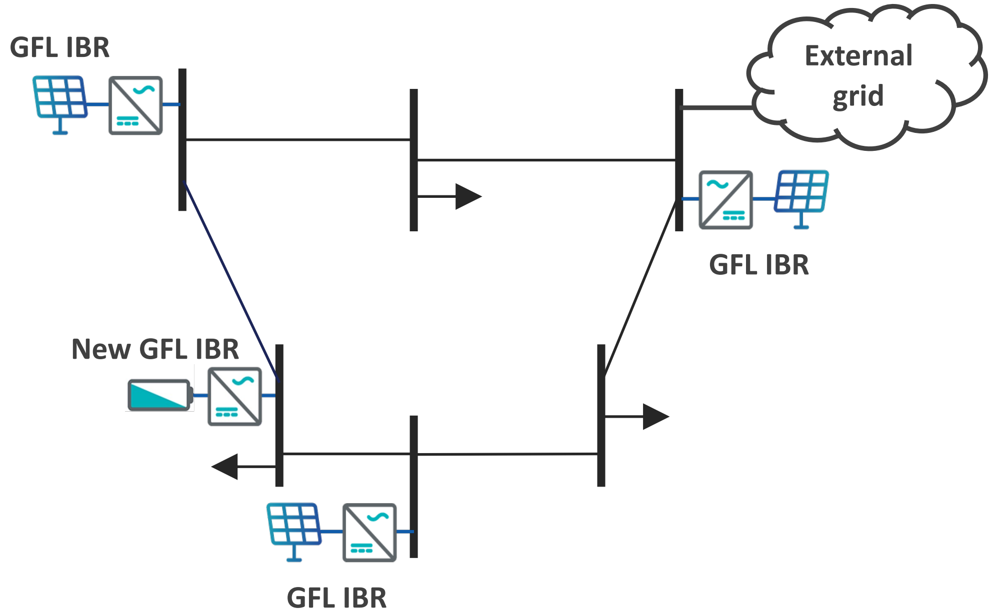
New transmission lines to reduce electric distance between high IBR areas with low system strength and strong grid areas

Source: iStockphoto/Yelantsevv

Grid Forming Controls as an Alternative for Grid Strength Support

- Grid Forming (GFM) IBRs can be designed to provide, within equipment limits, most of the services that are currently inherently provided by synchronous generators
- GFM IBRs have a stabilizing effect in weak grid areas and improve stability for IBRs with conventional grid-following (GFL) controls
- If GFM controls are implemented on planned IBRs, they may provide more cost-effective alternative to improve stability.

  This is because the improvement is provided by the new IBRs themselves as they are added to the system and addition of supplemental transmission assets may not be needed.



Source: [ESIG Report Grid-Forming Technology in Energy Systems Integration]

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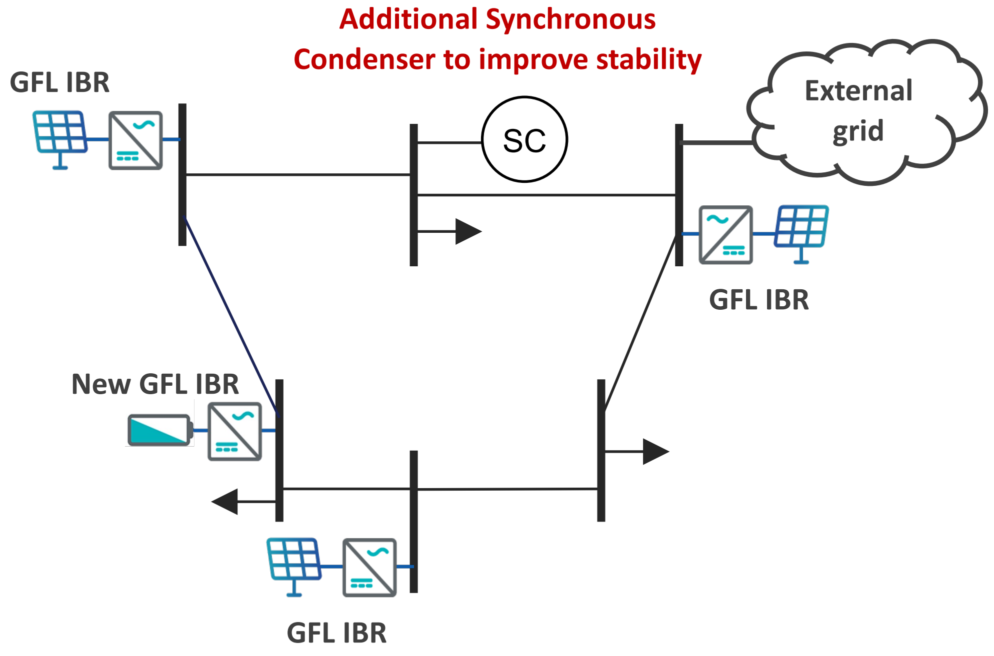

Source: ESIG Report Grid-Forming Technology in Energy Systems Integration

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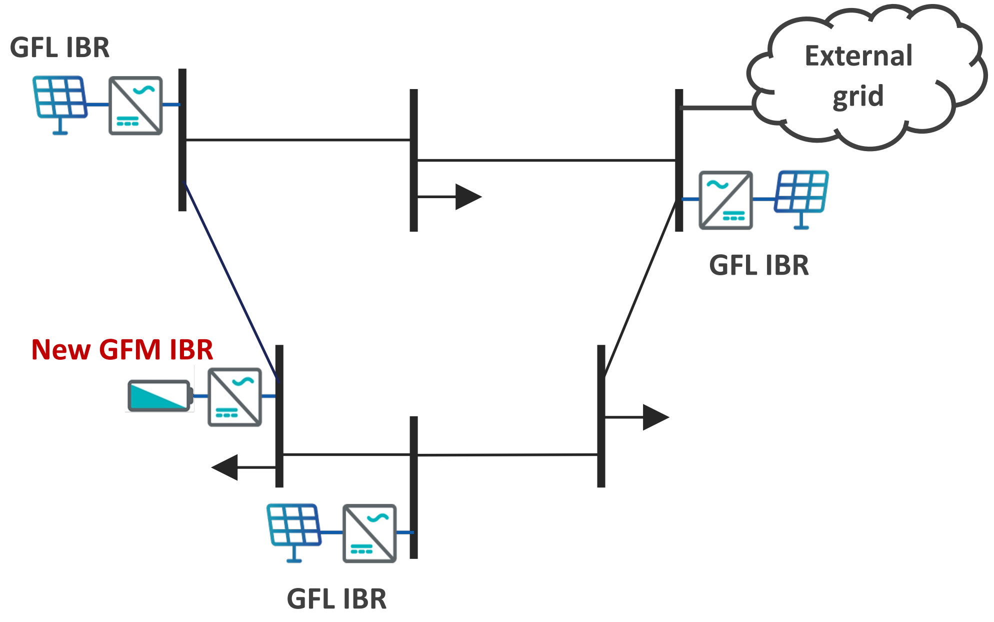
- If GFM controls are implemented on planned IBRs, they may provide more cost-effective alternative to improve stability.

  This is because the improvement is provided by the new IBRs themselves as they are added to the system and addition of supplemental transmission assets may not be needed.



Source: [ESIG Report Grid-Forming Technology in Energy Systems Integration]

ERCOT and MISO’s GFM IBR Deployment Initiatives

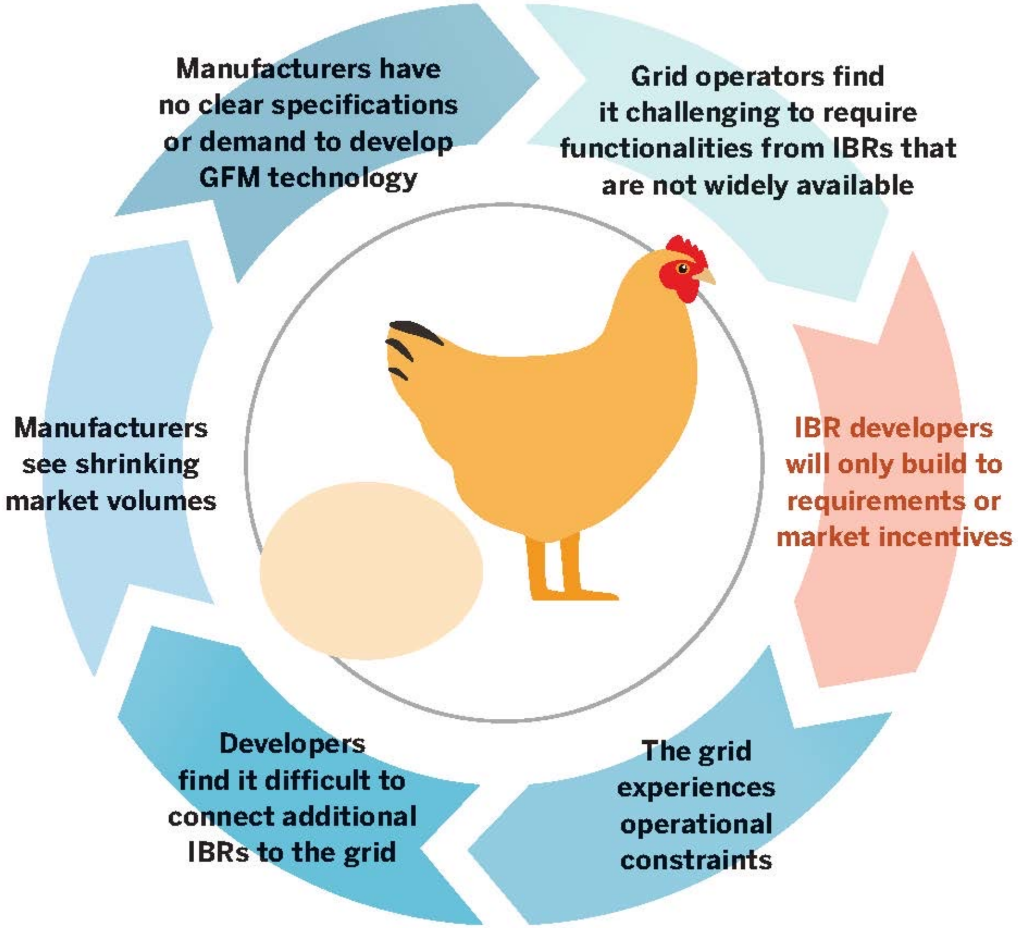
ERCOT:

- In summer 2023, ERCOT ran a study evaluating benefits of GFM IBRs for ERCOT grid
- Results indicate the GFM IBR could be a viable option to improve system stability
- Currently, working on the GFM IBR requirements including but not limited to performance, models, studies, and verification (expected by summer 2024).

MISO

- Gathering background information on GFM IBR capabilities and specification practices
- Working with stakeholders to develop GFM IBR performance requirements, which will include aspects of modeling and conformance (expected by the end of 2024)

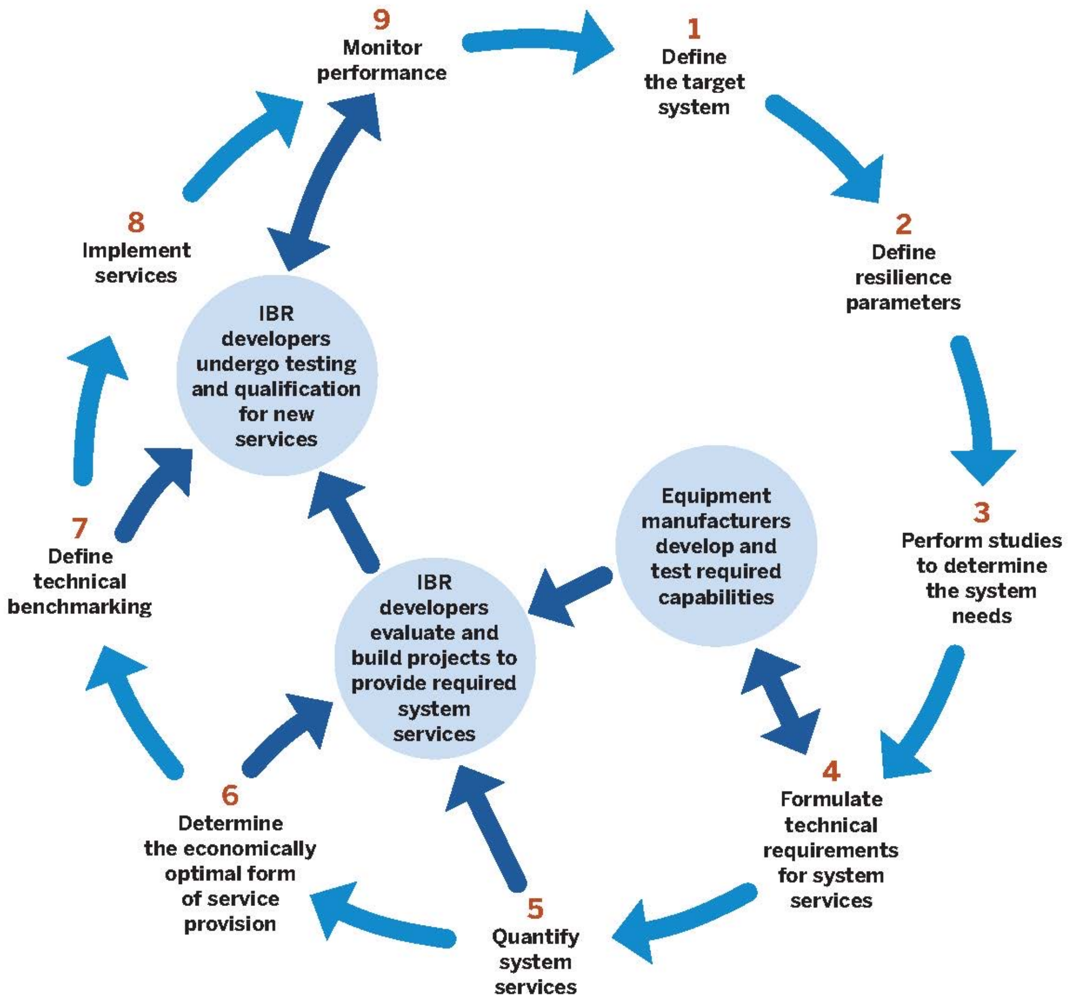
The Circular Problem of Incentivizing and Deploying Advanced IBR Controls



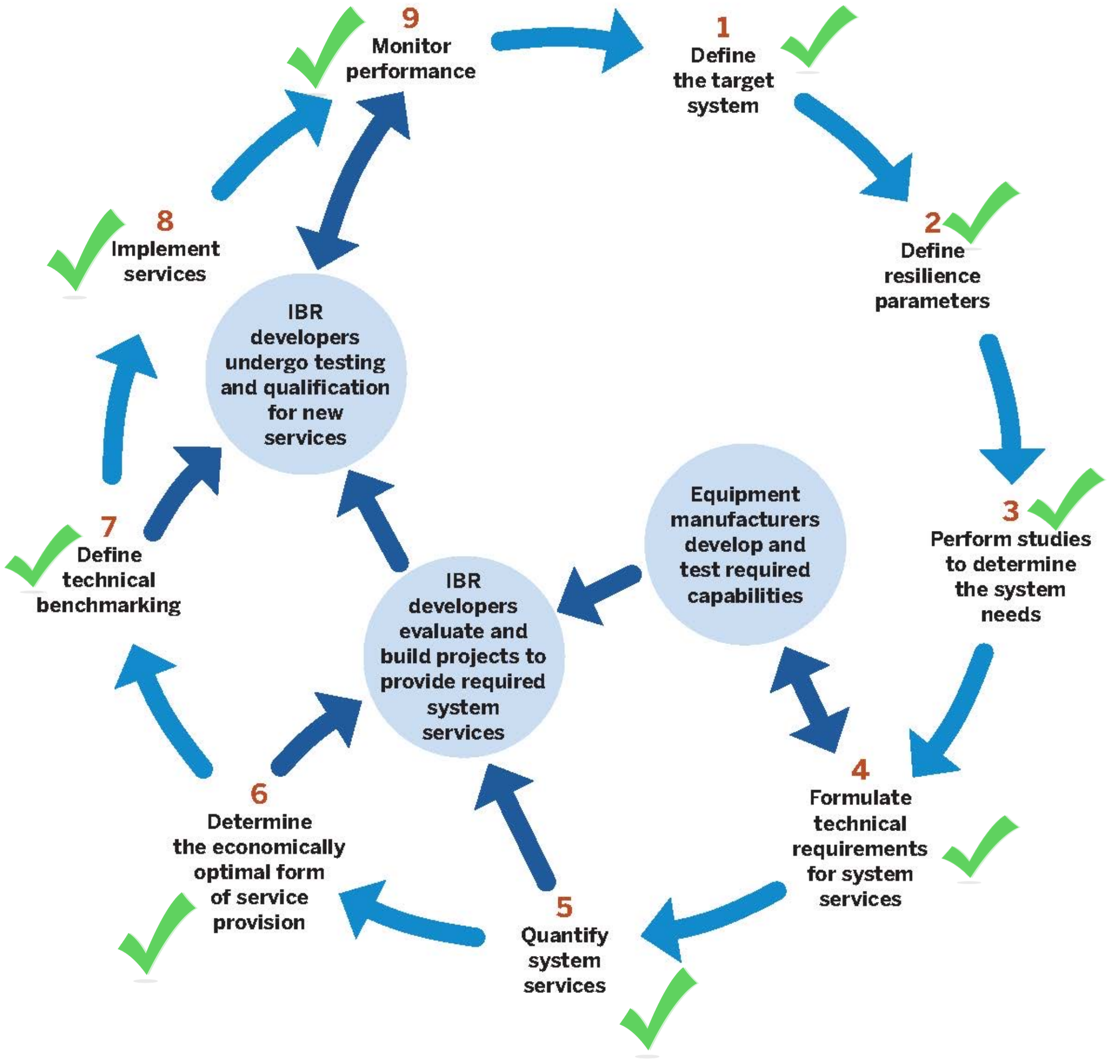
- Which comes first, the requirement for a capability or the capability itself?
- How do grid operators know what performance or capability is possible from new equipment, and therefore what they could conceivably require?
- How can they go about evaluating the costs and benefits of having such equipment on the grid?
- What drives manufacturers to invest in new technology without it being mandated or otherwise incentivized by the market?

Source: ESIG Report Grid-Forming Technology in Energy Systems Integration

Solving the Chicken-and-Egg Problem Through Adoption of a System Needs Perspective



Solving the Chicken-and-Egg Problem Through Adoption of a System Needs Perspective



Example of National Grid Electricity System Operator:

- Carried out a number of studies of system performance with a large share of IBRs (incl.100 % IBR), steps 1-3.
- Developed performance requirements for GFM capability (to be procured as service), consistent with steps 4 and 7.
- At the same time, launched a series of competitive tenders, called Stability Pathfinder, to procure new system services needed with the changing generation mix—specifically, system strength support and rate of change of frequency mitigation. This is consistent with steps 5, 6, and 8 above.
- Building on lessons learned from Stability Pathfinder designed market-based stability service product as well as performance evaluation requirements for provision of this service, consistent with steps 8 and 9.

Conclusions and Recommendations

- Provision of services from IBRs is one of the necessary enablers for higher renewable penetration.
- Not all IBRs need to have all possible characteristics to provide all services. Services need to be approached from system needs perspective not a specific technology capability perspective.
- Step by step approach of defining and implementing new services is recommended.
- Early adopters such as, e.g. Great Britain, are breaking the circular problem through defining grid services based on system needs. This provides clarity for advanced IBR design and incentives for deployment.
- **GFM capability in batteries is a low hanging fruit. Not incentivizing it today will result in higher costs of supplemental stabilizing equipment in the future.**
- Further reinforcements of transmission system will be necessary to enable long-distance high-power transfer from remote areas rich with renewable resources .

THANK YOU

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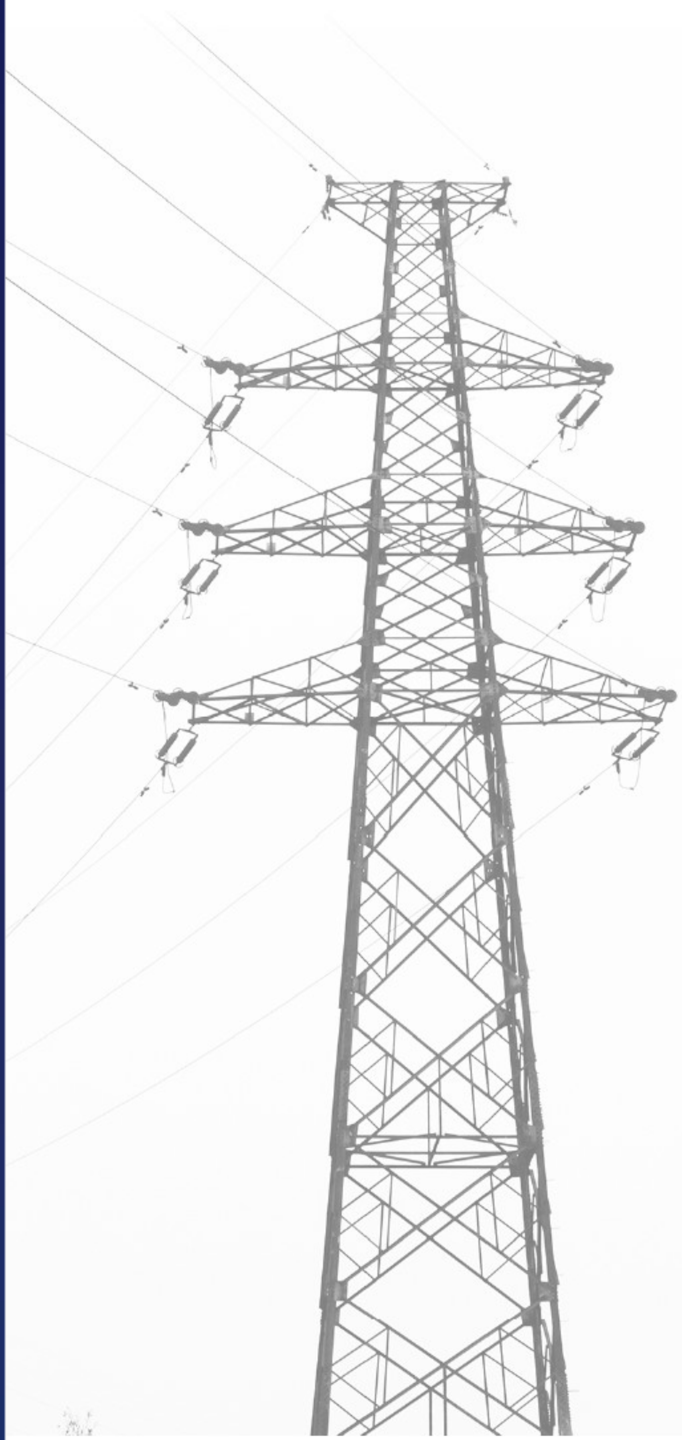

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