Weak Grids to Condensers to Grid-Forming Inverters: The Right Progression?

ESIG Spring Workshop - Webinar

March 25, 2020

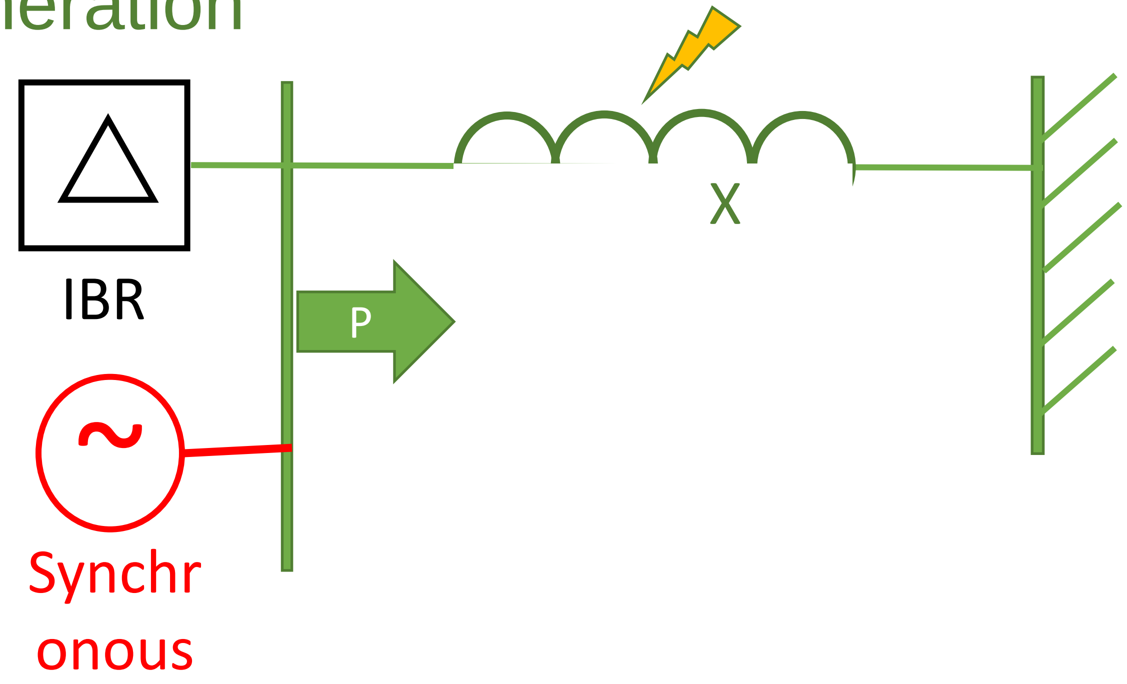
Nick Miller

Getting the Power Out (aka, The Great Displacement)

- High level narrative… you know this stuff!
- Wind (especially) and Solar PV (sometimes) are developed relatively remote from load centers.
- Exporting large amounts of power has always presented stability problems
- The problems look different with inverter-based resources compared to synchronous machines
- Are we on the right trajectory, towards making the best use of existing and new infrastructure?

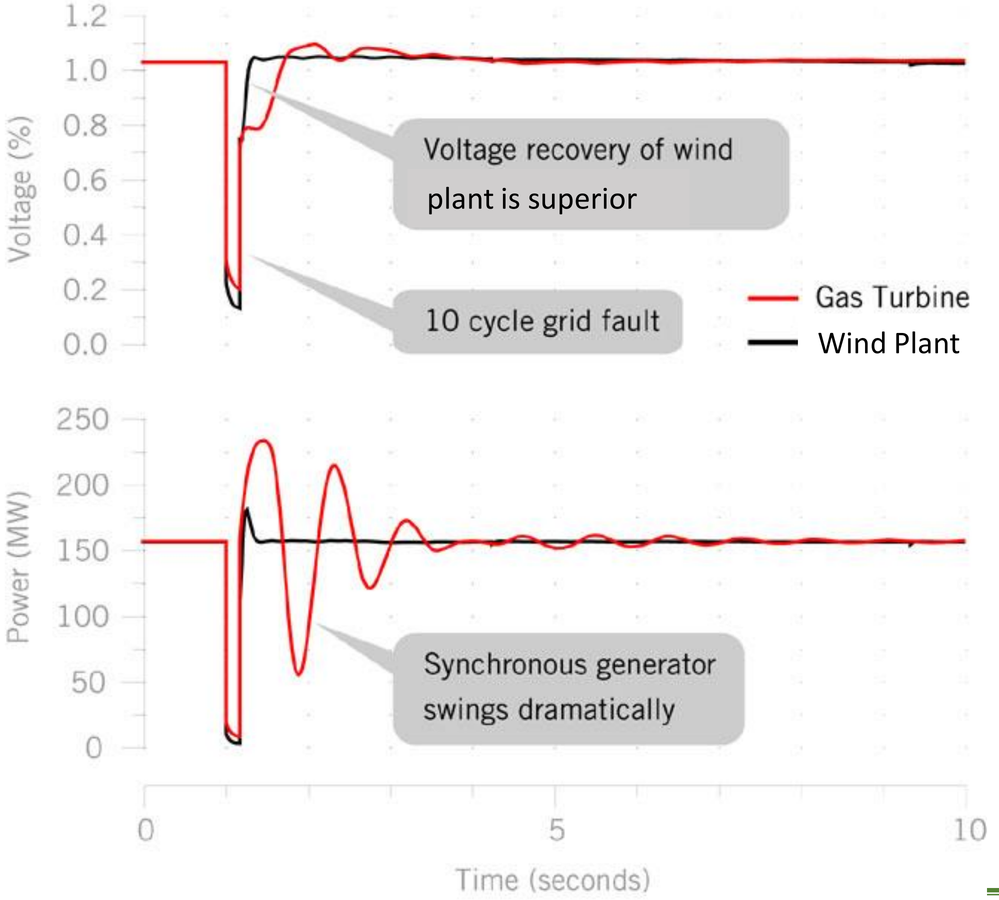
What's going on?

- Another look at some old basics….but maybe a little differently
- IBR displacing synchronous generation
- Three tools:
  - Angle Area Curves
  - Nose Curves
  - Phasors

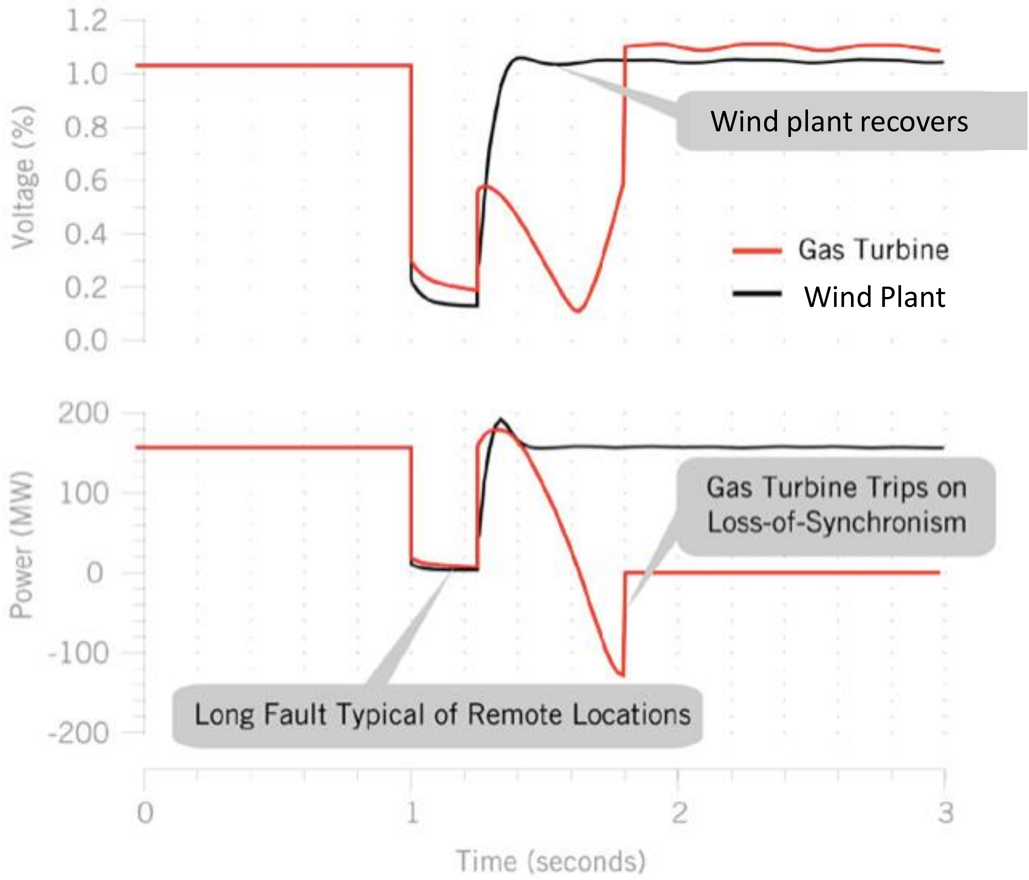


Wind and PV plants are more stable than conventional synchronous generators

Primary Cleared Fault



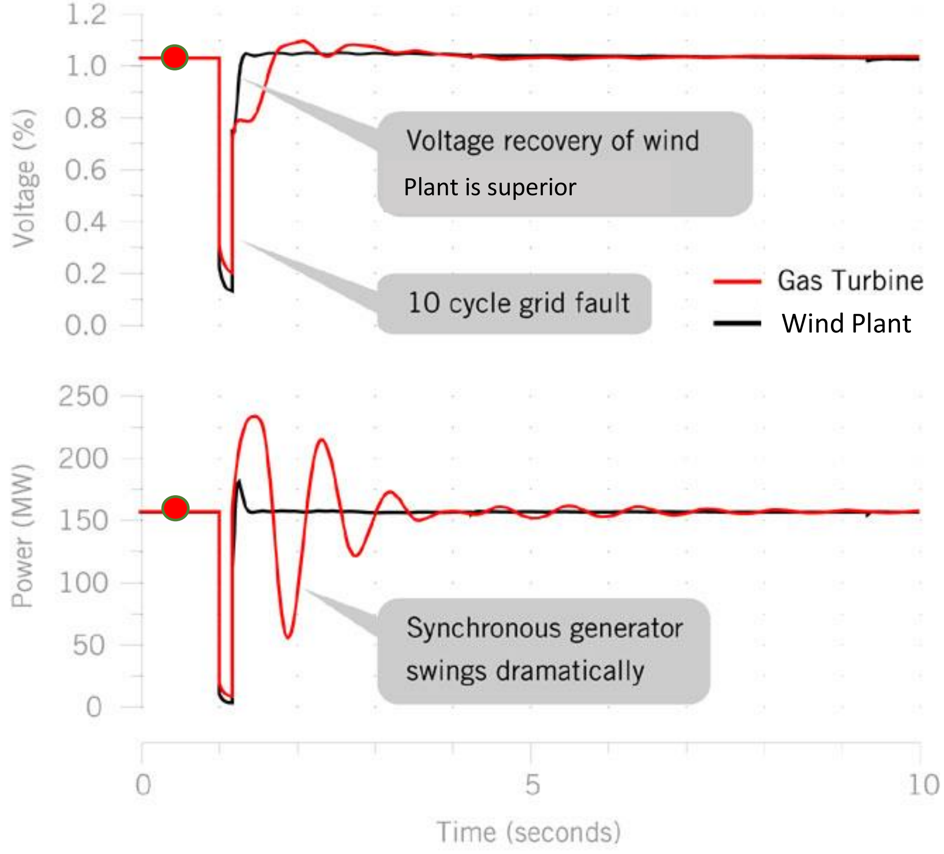
Delayed Clearing Fault

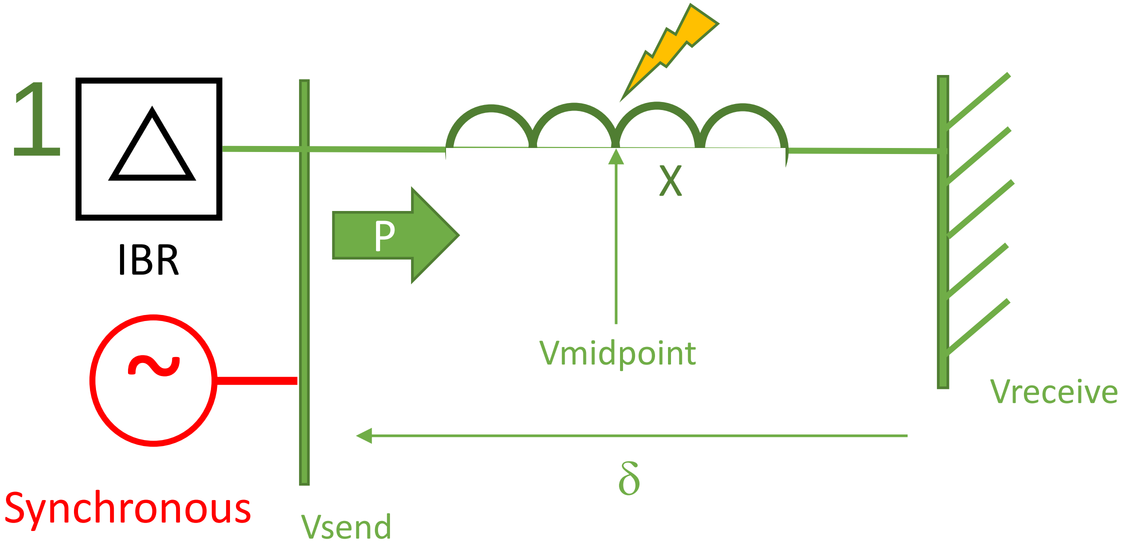


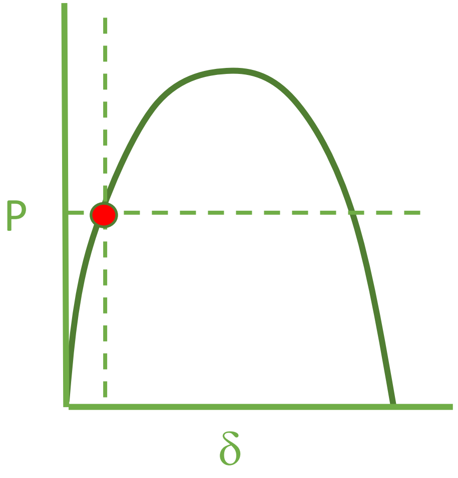
You've seen me use these curves for 15 years!

Source: GE Energy Consulting c.2005

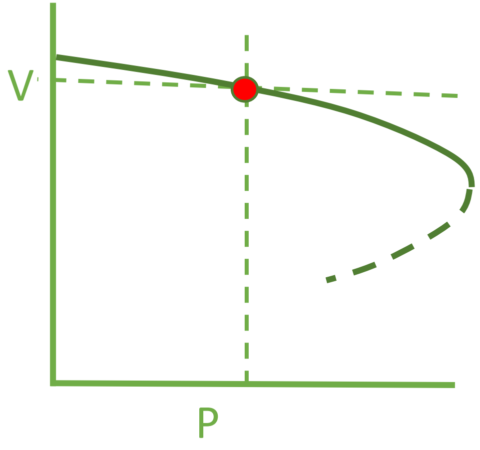
Transient Stability 101.1
(pre-fault condition)



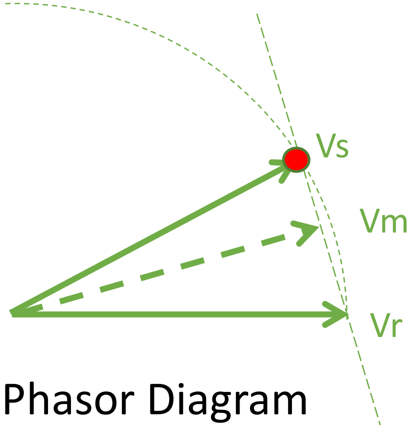




Equal Area Curve

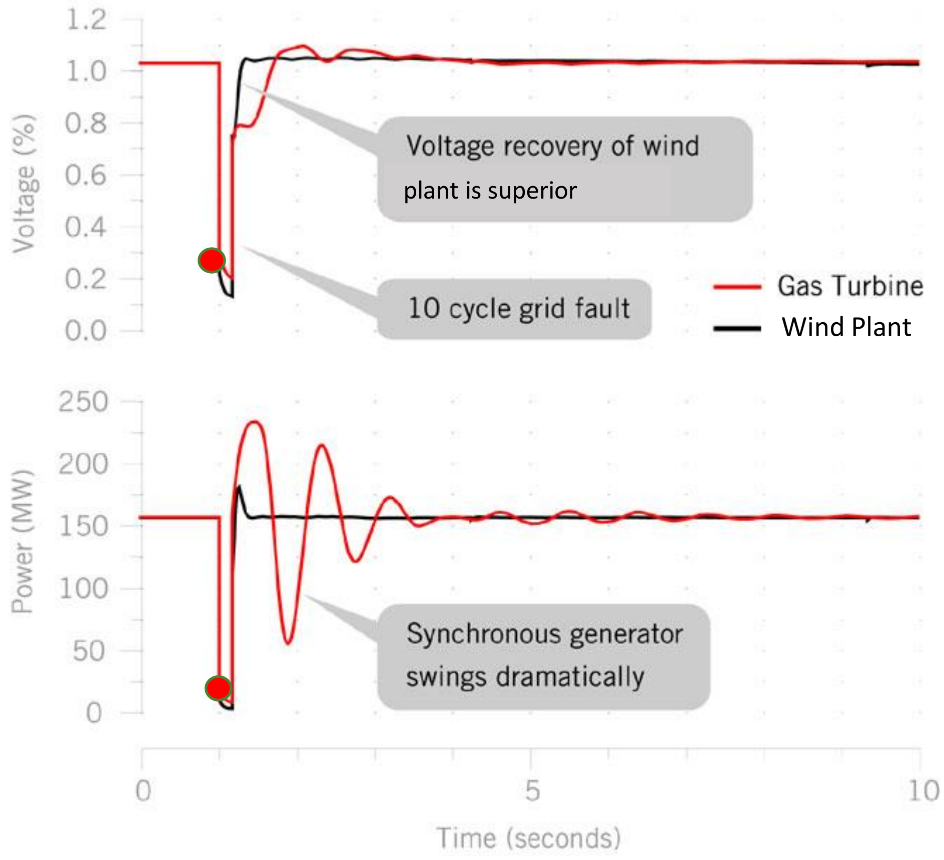


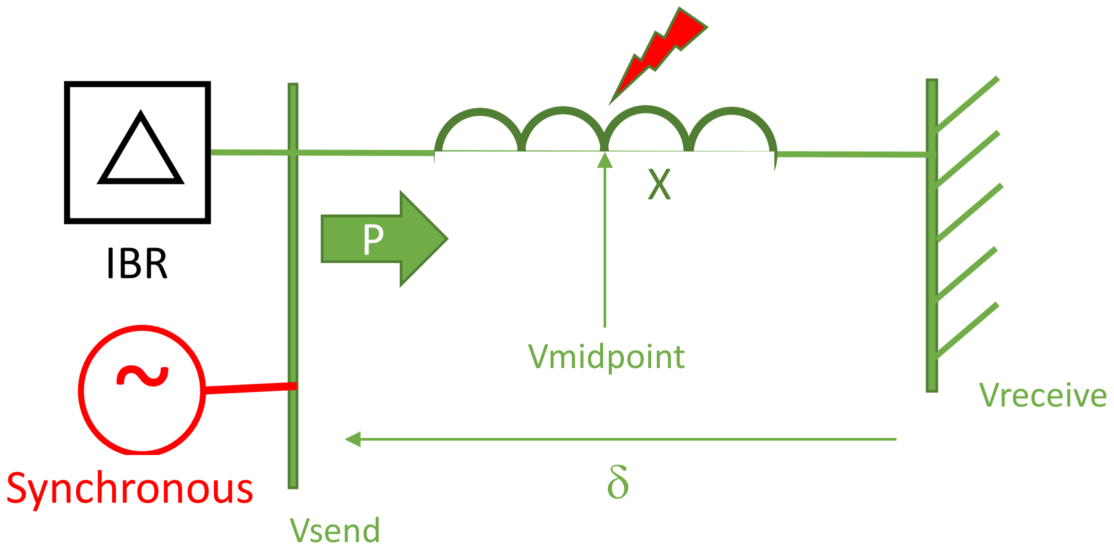
PV/Nose Curve

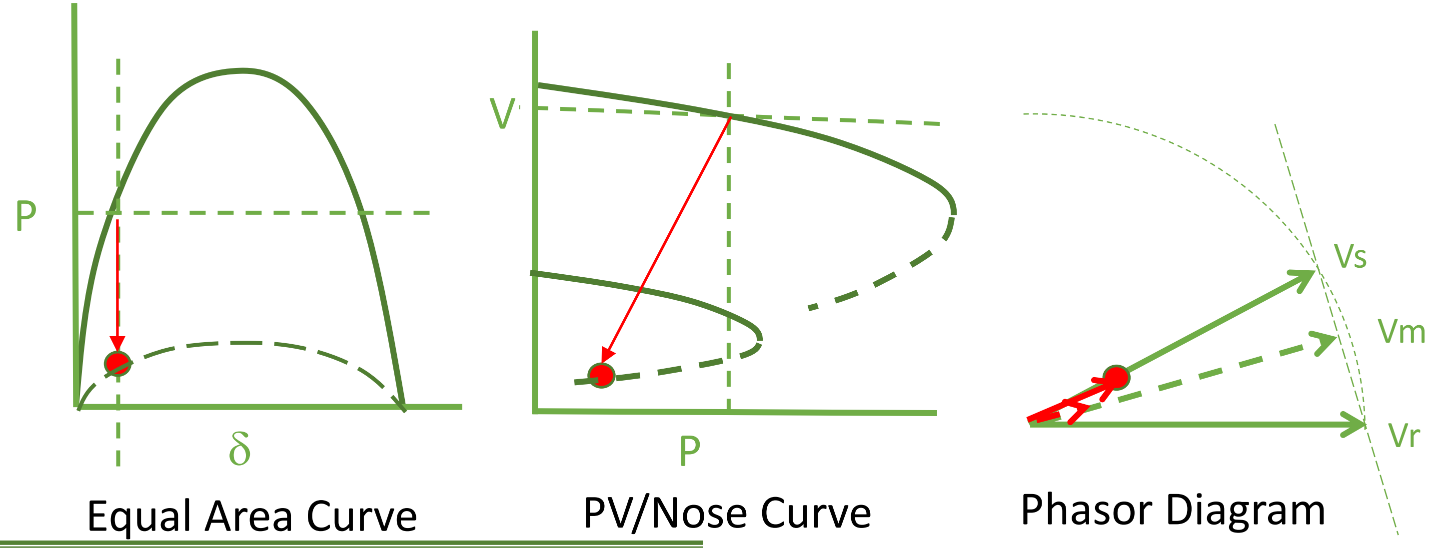


Phasor Diagram

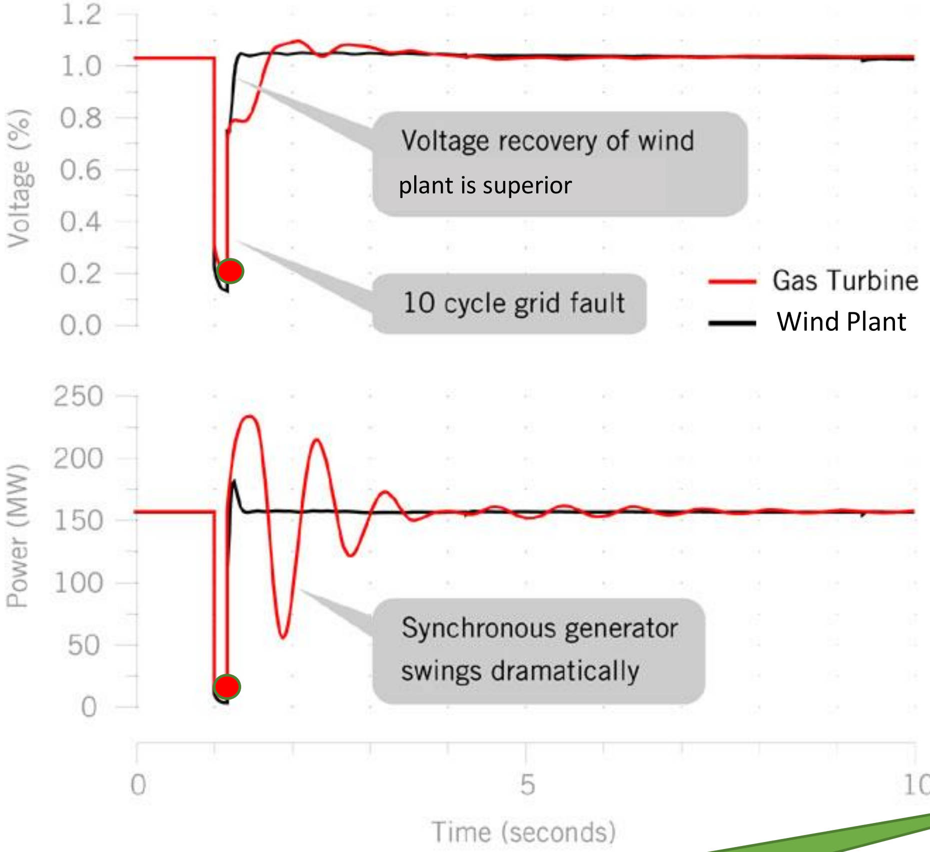
Stability 101.2
(fault inception)

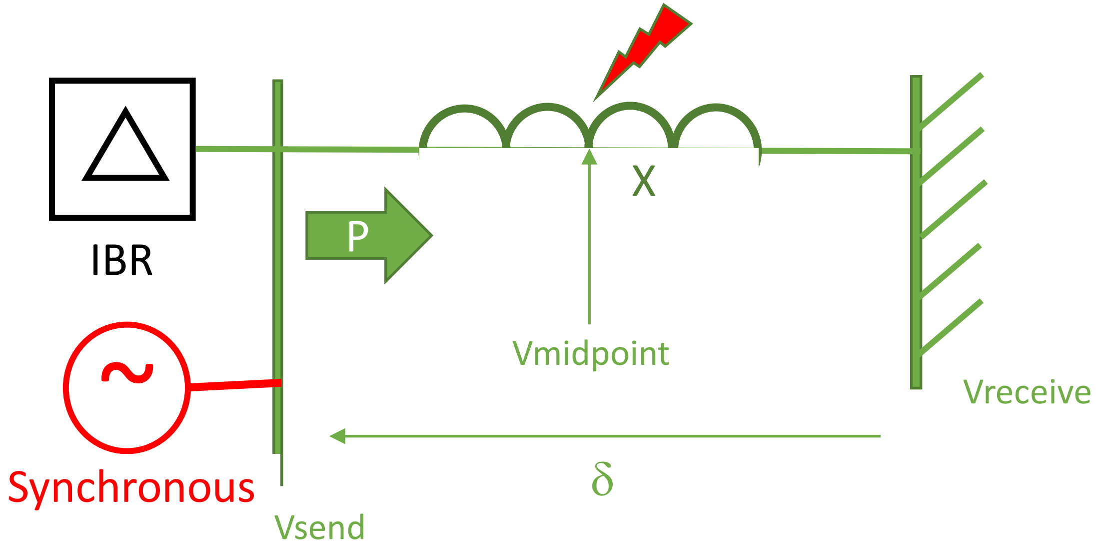




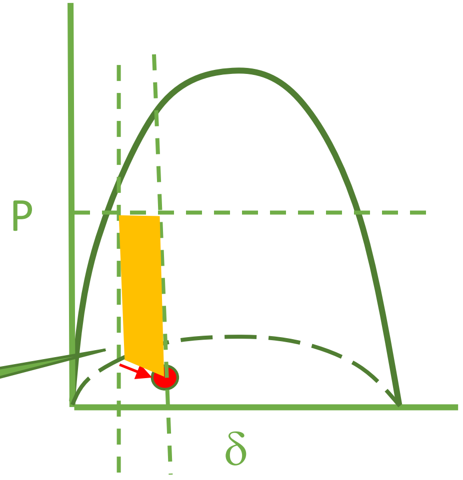


Stability 101.3
(end of fault, before clearing)

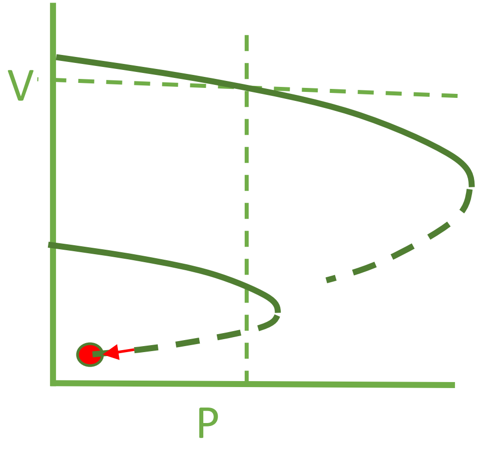




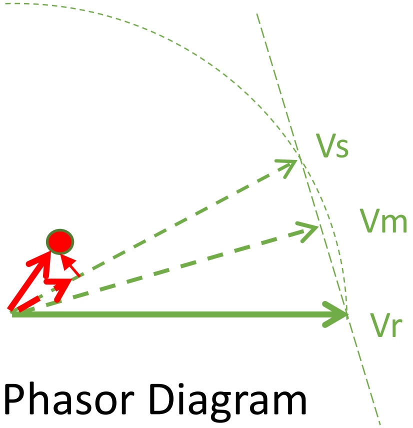
Accelerating Energy acquired by the inertia during the fault



Equal Area Curve

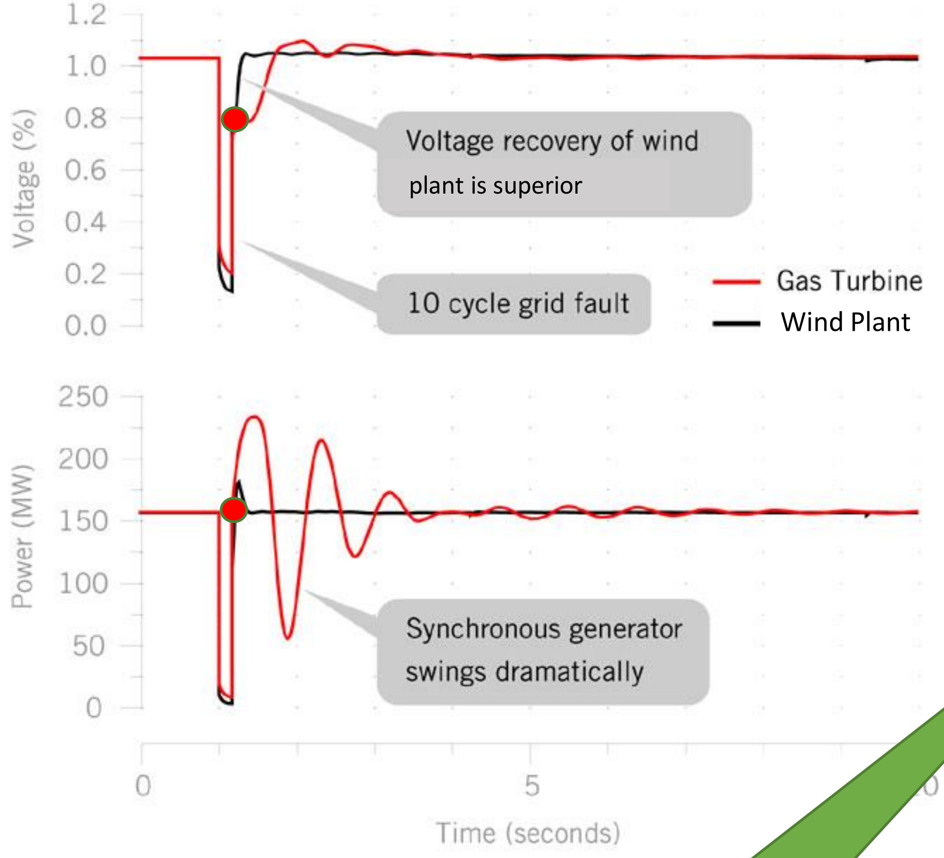


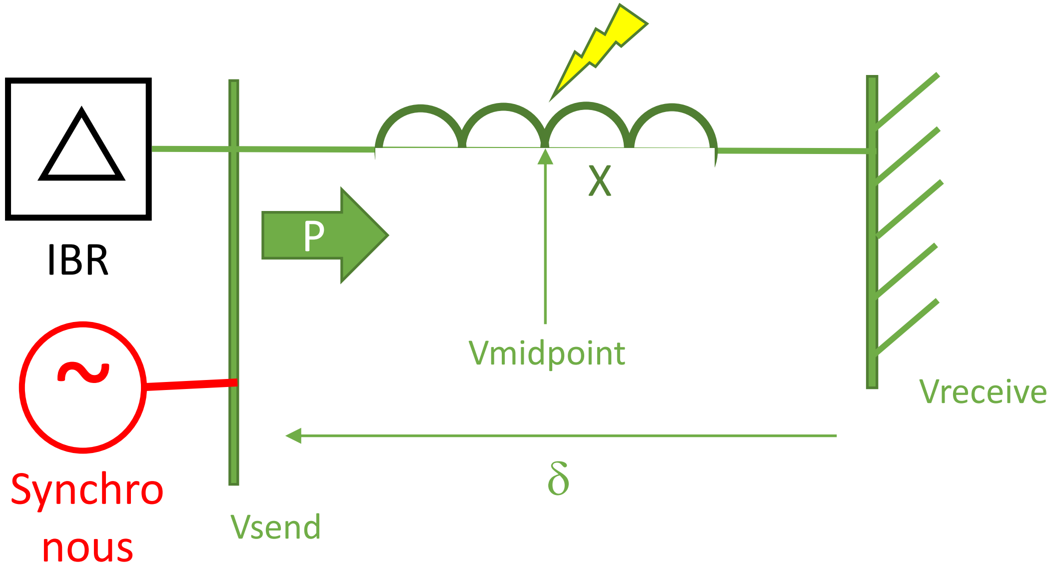
PV/Nose Curve

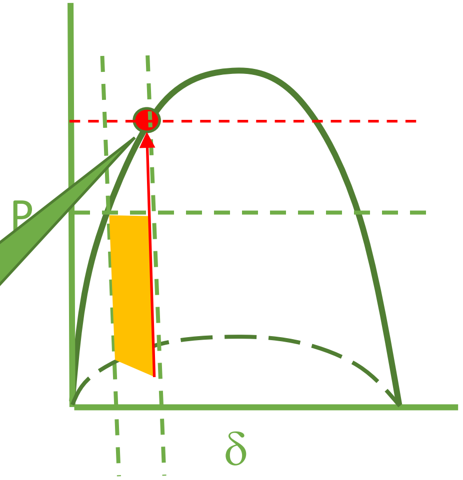


Phasor Diagram

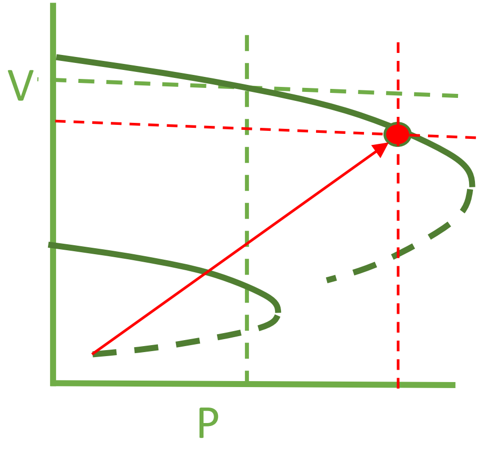
Stability 101.4
(immediately after fault clearing)



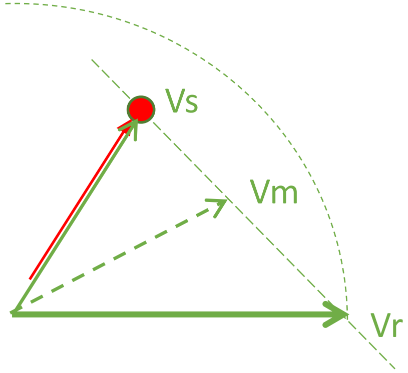




Equal Area Curve



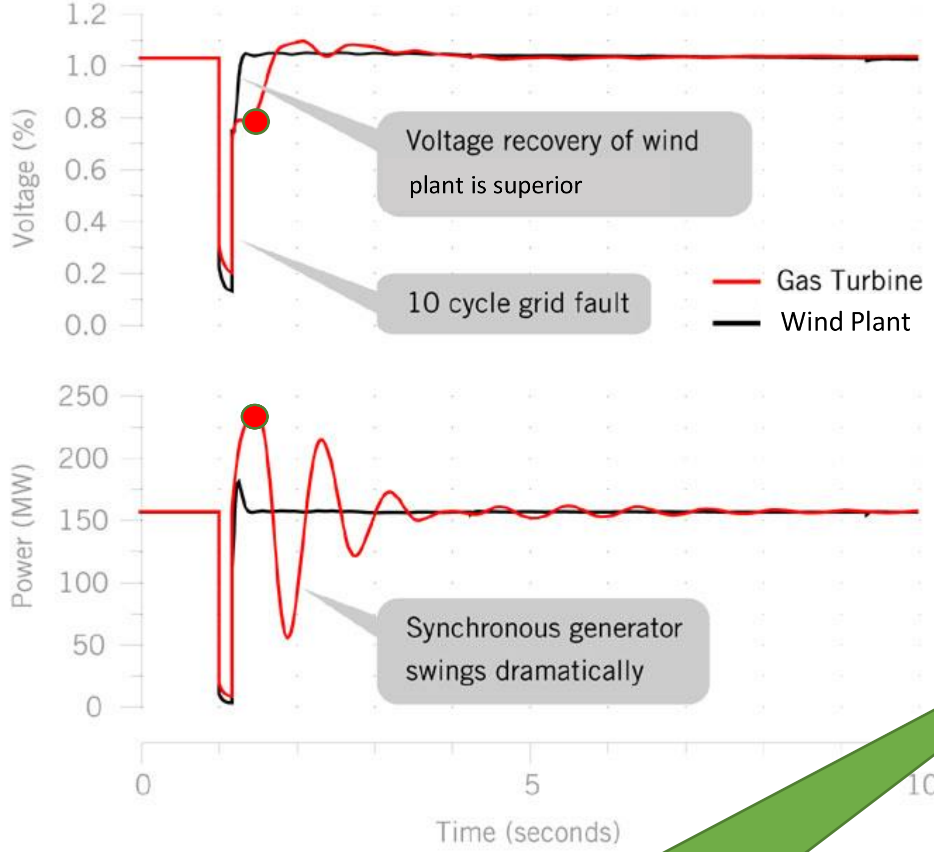
PV/Nose Curve

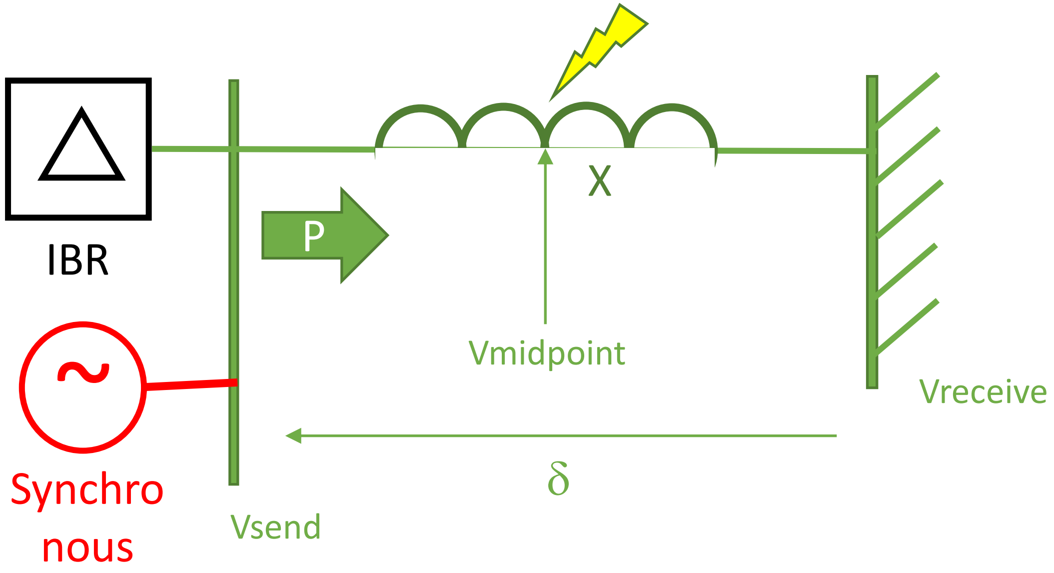


Phasor Diagram

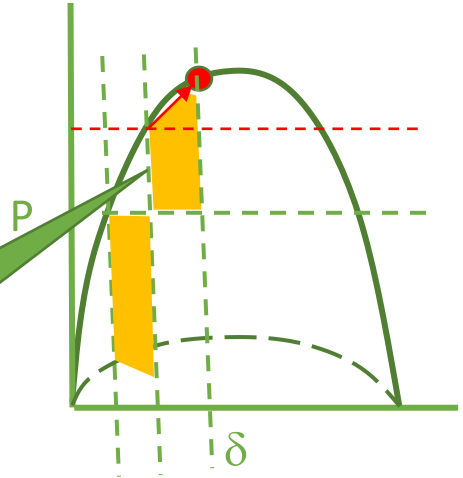
Post-clearing power MUST exceed pre-disturbance power

Stability 101.5
(peak of post fault swing)

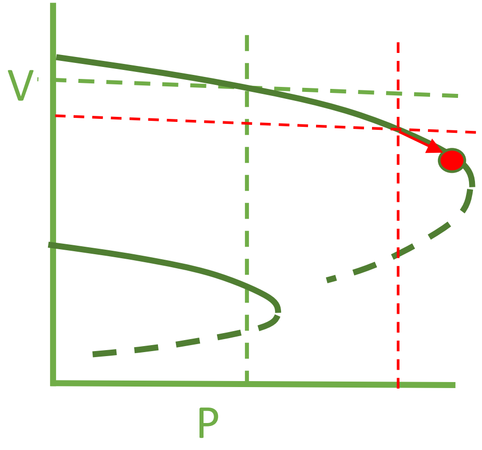




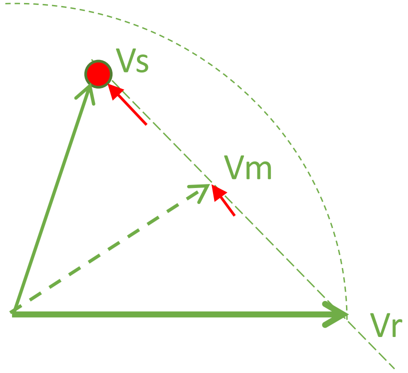
Accelerating Energy dissipated by swing = energy acquired during fault



Equal Area Curve



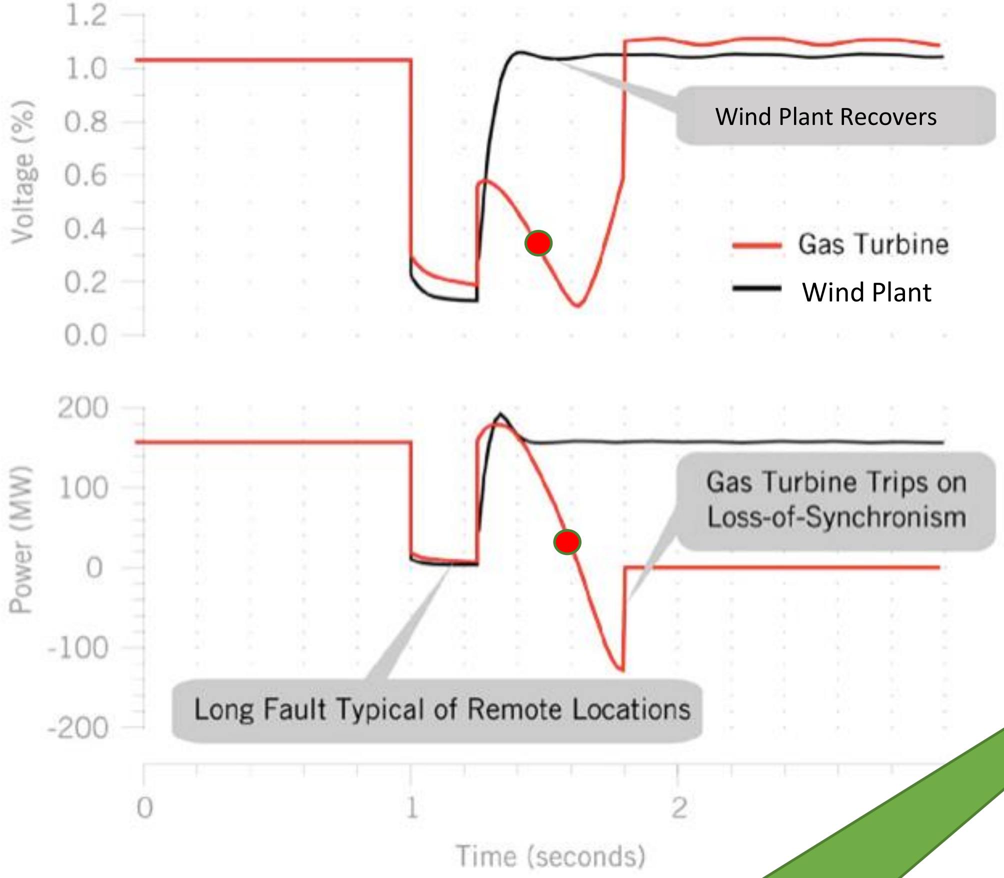
PV/Nose Curve

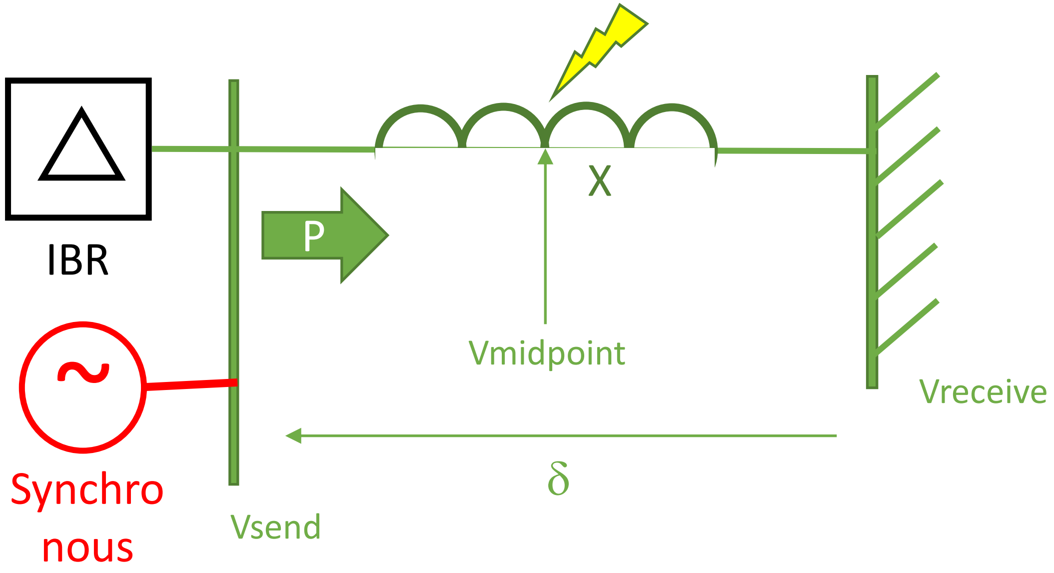


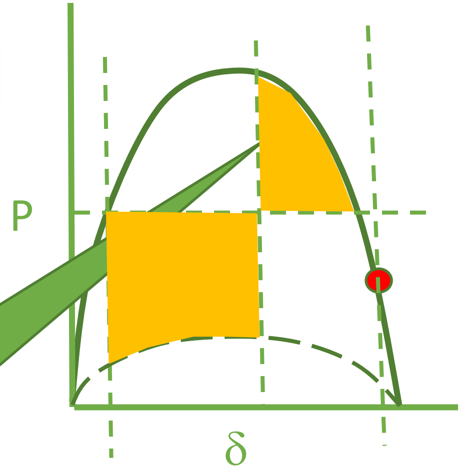
Phasor Diagram

Stability 101.6

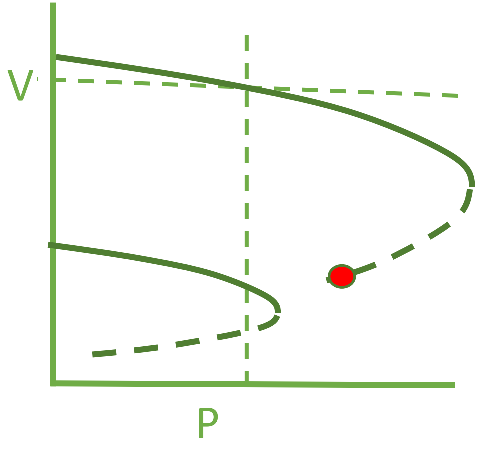
(you are toast – when the fault's too long)



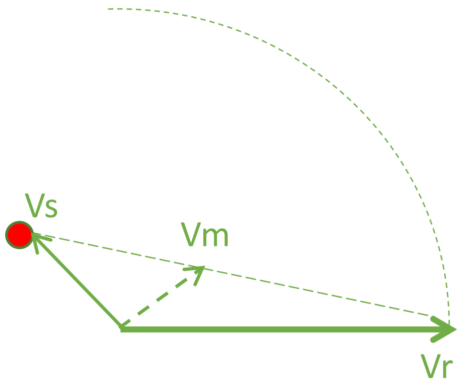




Equal Area Curve



PV/Nose Curve



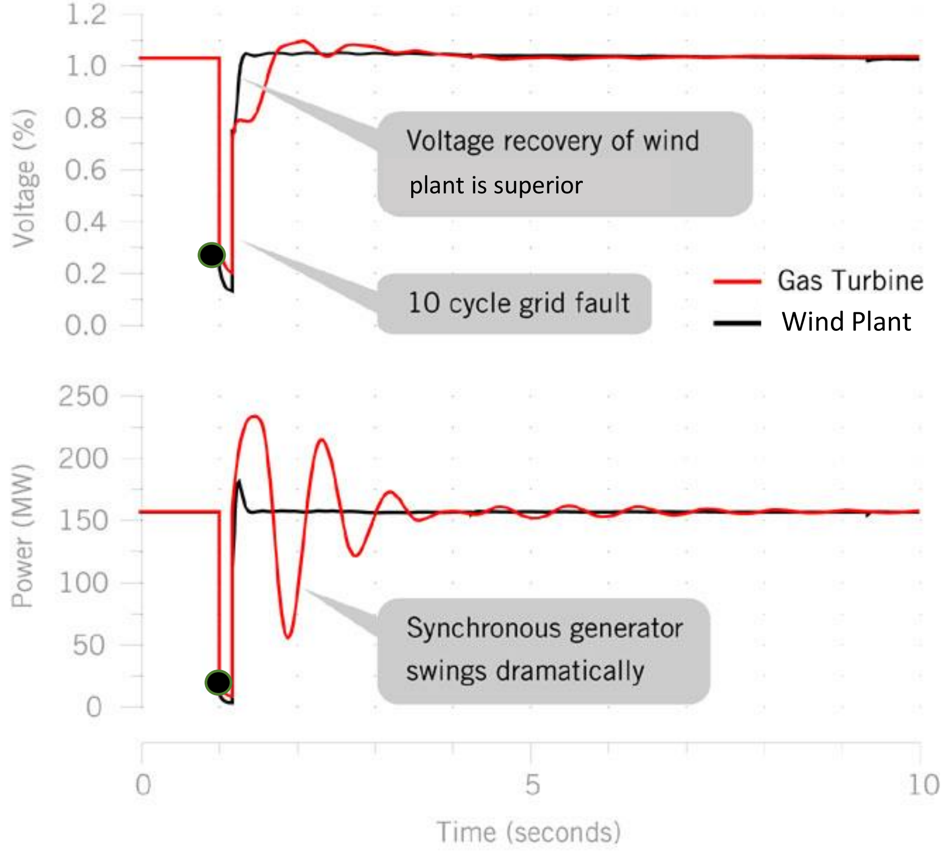
Phasor Diagram

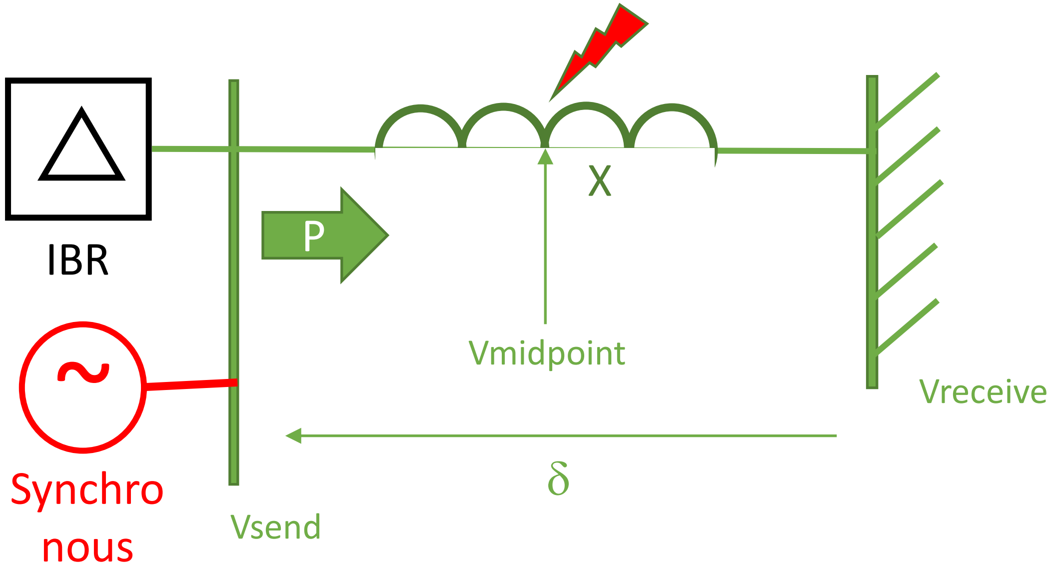
Insufficient deceleration = loss of synchronism

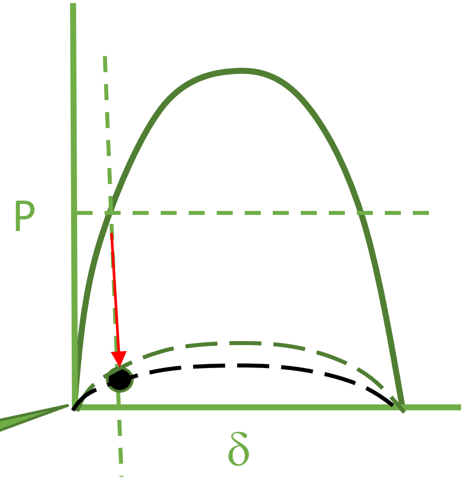
Thanks Nick…we knew all that!

Stability 102.2 - IBR

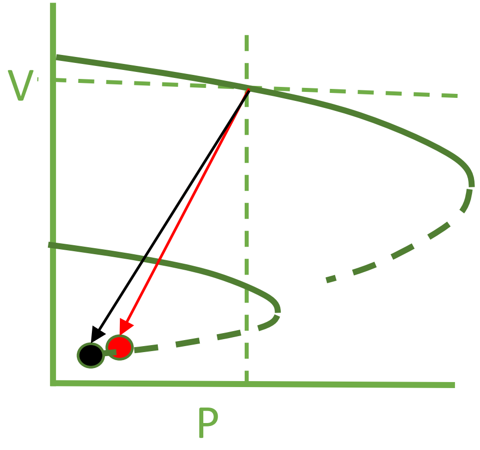
(fault inception)



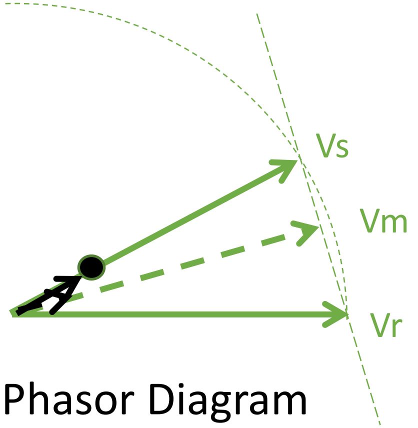




Equal Area Curve



PV/Nose Curve

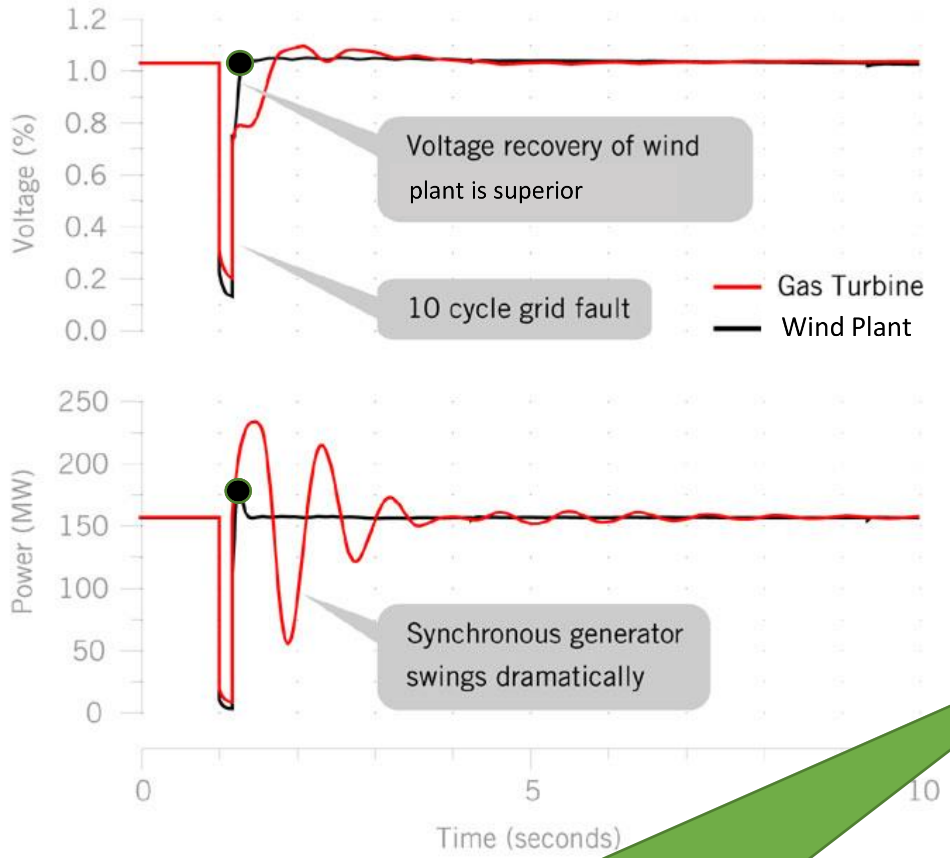


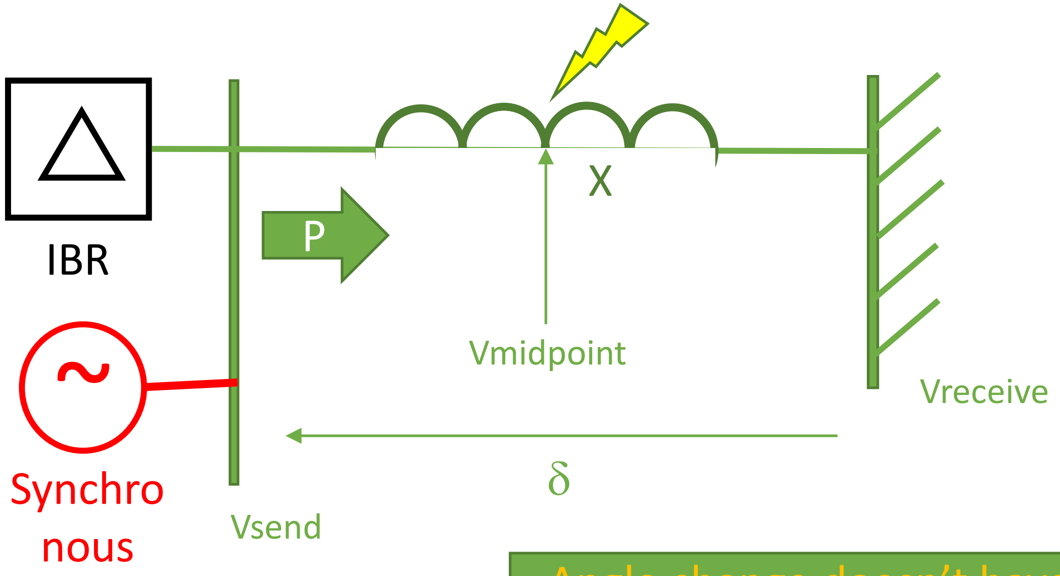
Phasor Diagram

Less fault current from IBR = lower during fault voltage

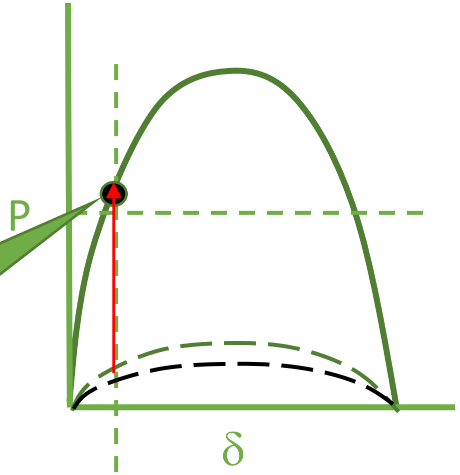
Stability 102.4 - IBR

(immediately after fault clearing)





Angle change doesn't have to be substantial. It's all control



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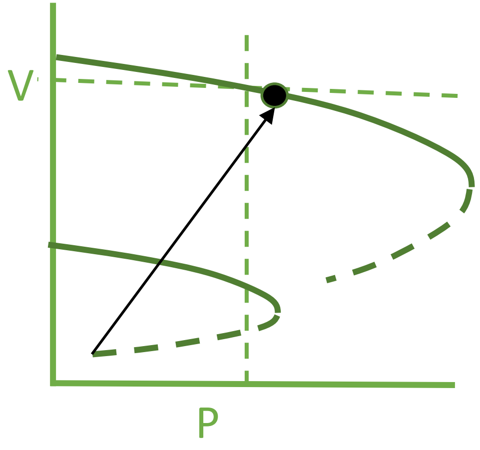
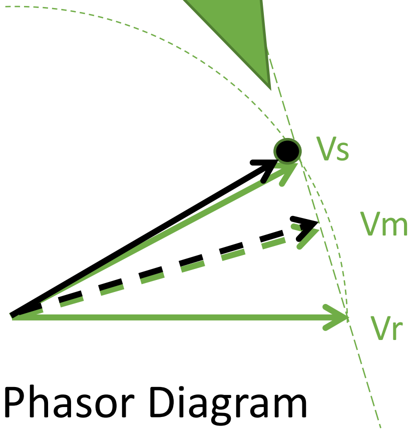


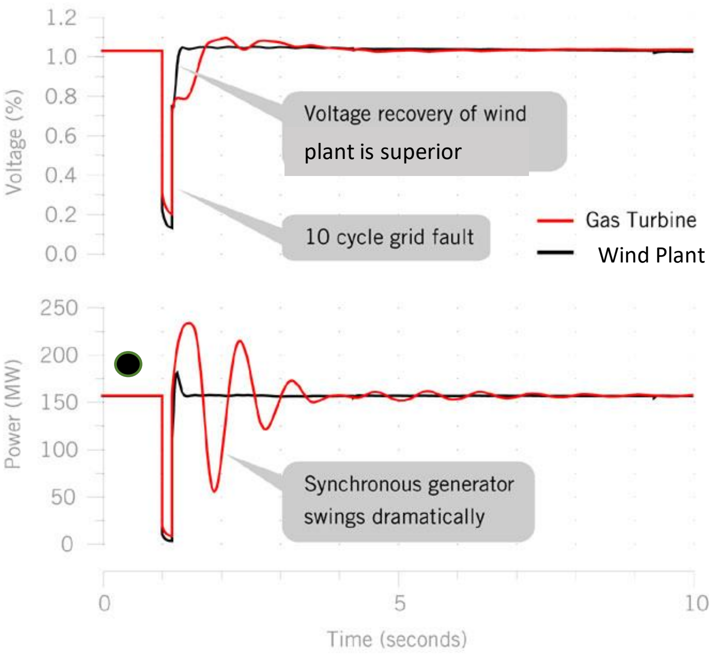
PV/Nose Curve

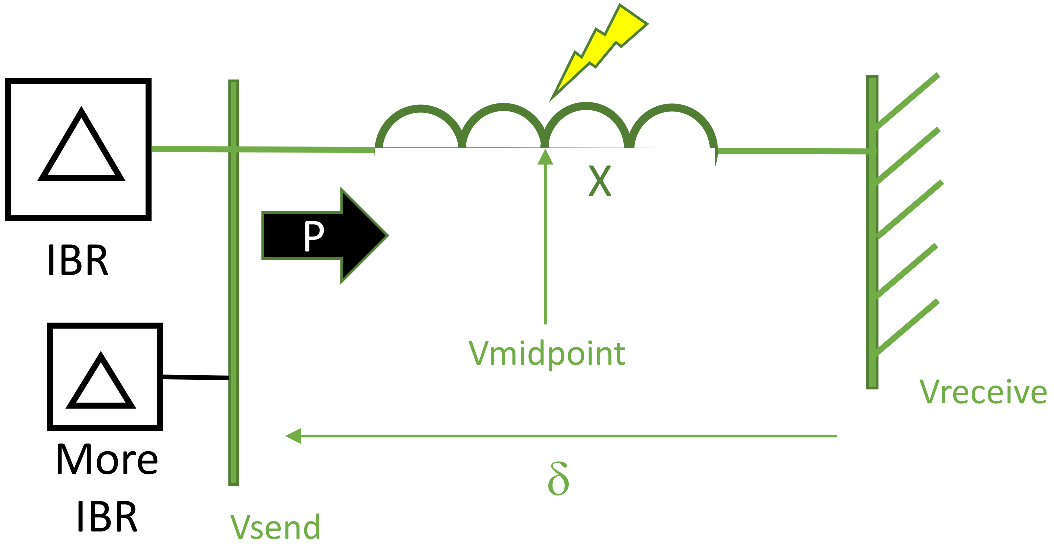


Phasor Diagram

Some change in power, as inverter rebalances. Behavior is different between wind and solar

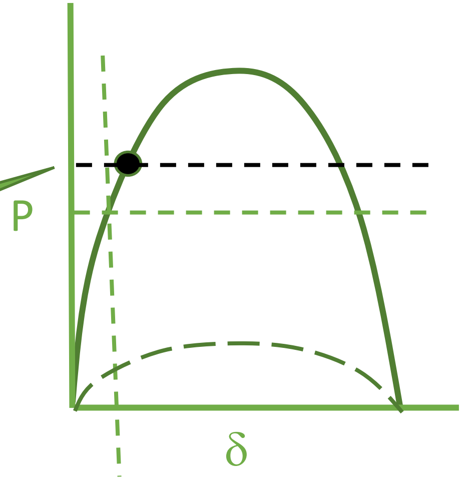
Stability –
Loading up with IBRs



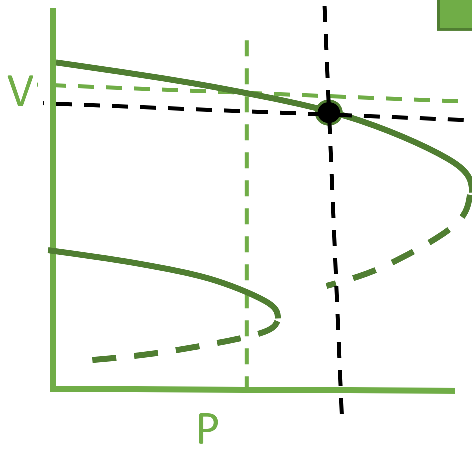


Midpoint more stressed

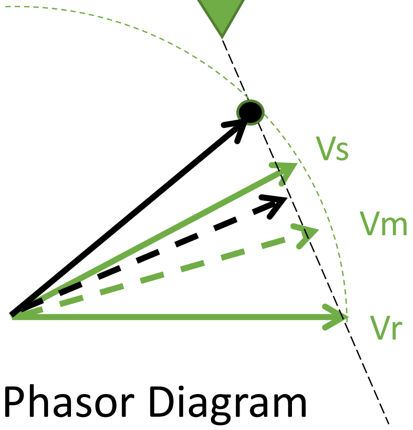
"It's more stable…let's export more"



Equal Area Curve

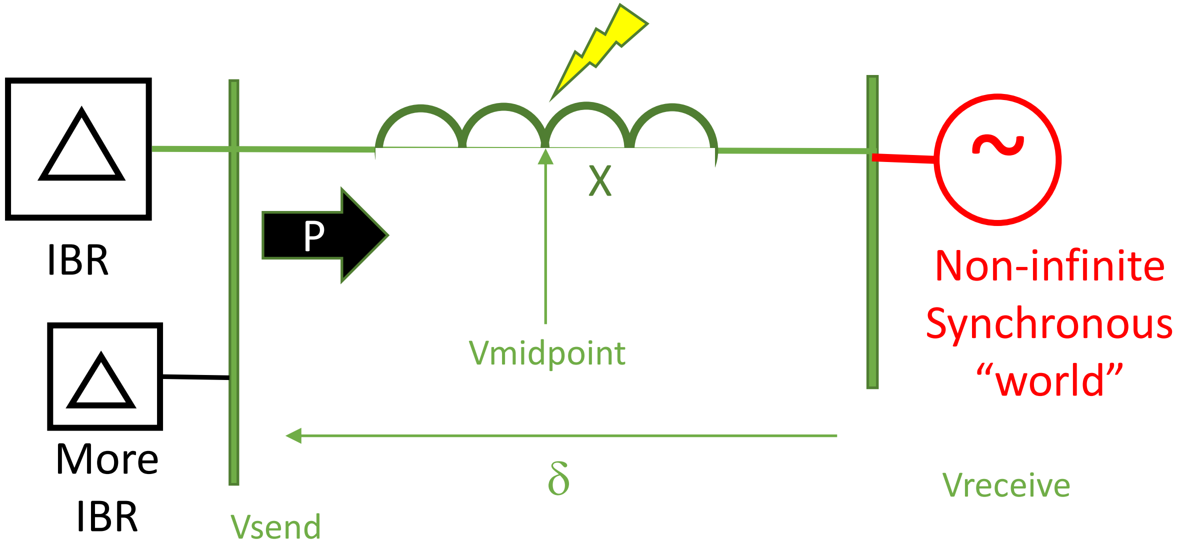


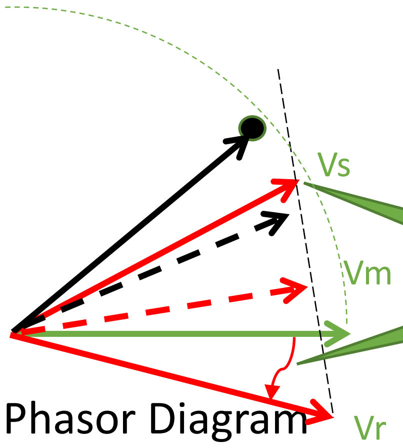
PV/Nose Curve



Phasor Diagram

Stability – when the rest of the world moves





Phasor Diagram

The "world" is starved for power, so it slows down. The angle drops

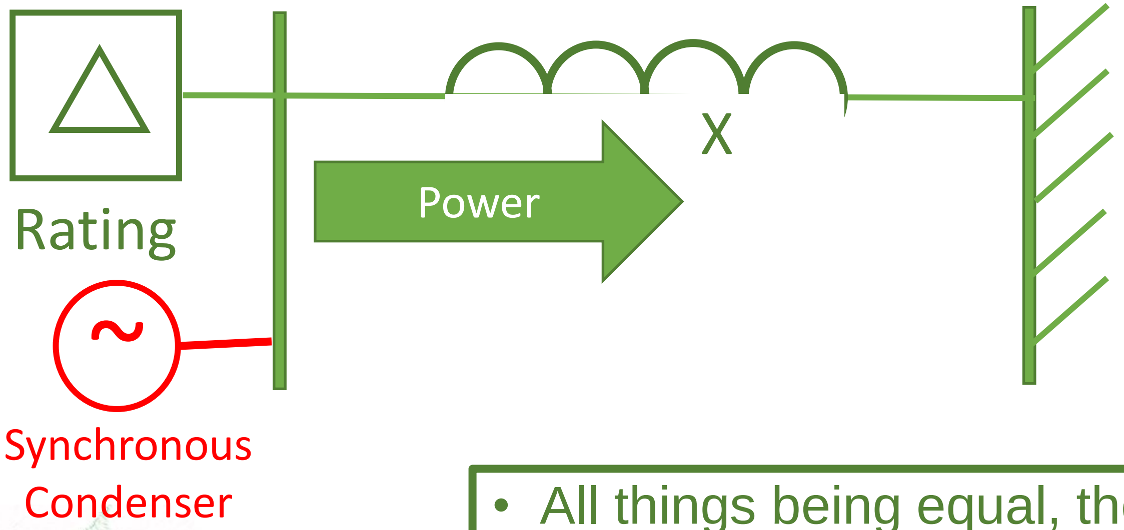
PLL of IBR follows, controlling its angle if it can, keeping P relatively steady

If grid is too weak, control can get confused or unstable

SCR & The Simple Export Problem

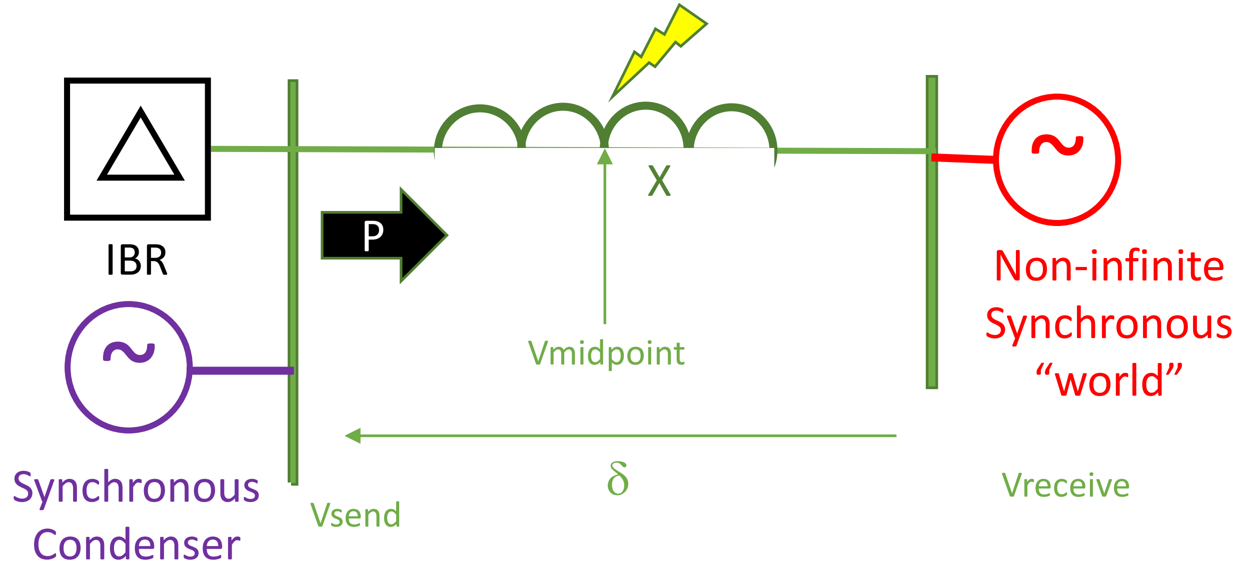
Short Circuit Ratio is a convenient way to talk about the strength of the grid, it's not about faults

1. SCR Bigger X (more impedance) = weaker grid
2. Short circuit strength is the inverse of X
3. X gets bigger with distance
4. X gets smaller with more transmission; higher voltage ratings
5. "weak" is relative:
6. If the devices are big, i.e. "rating" is large, relative to the short circuit strength, the **short circuit ratio** is low, and grid is weak
7. There are several clever analytical techniques to calculate weighted/equivalent/composite/effective short circuit ratio.
8. Adding synchronous condensers in the electrical vicinity of the IBRs improves the SCR

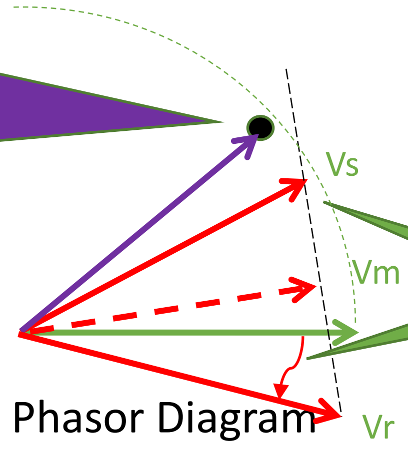


- All things being equal, the lower the short circuit ratio, the harder it is to stay stable.
- All things are never equal.

Stability – when we add a condenser for SCR



But the angle of a condenser is anchored to its inertia. It gets left behind!

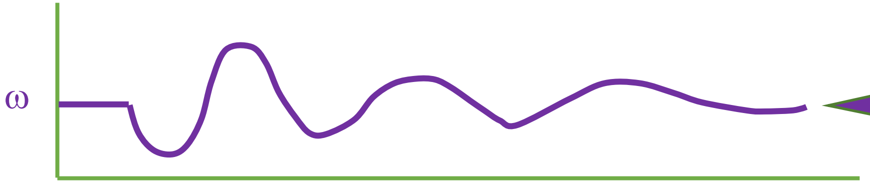


Phasor Diagram

The "world" is starved for power, so it slows down.

PLL of IBR follows, if it can, keeping P relatively steady

And swings, trying to realign with Vs

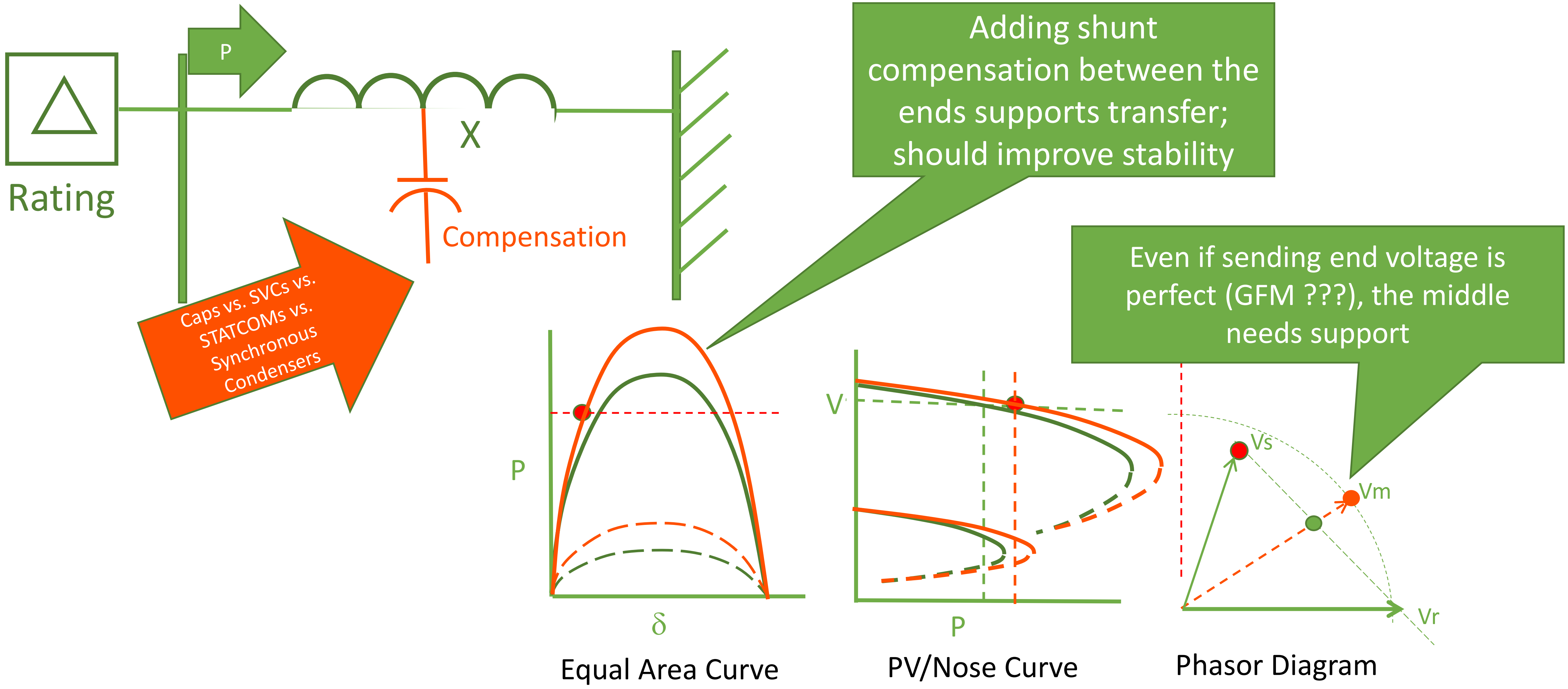


A new, rather different stability worry

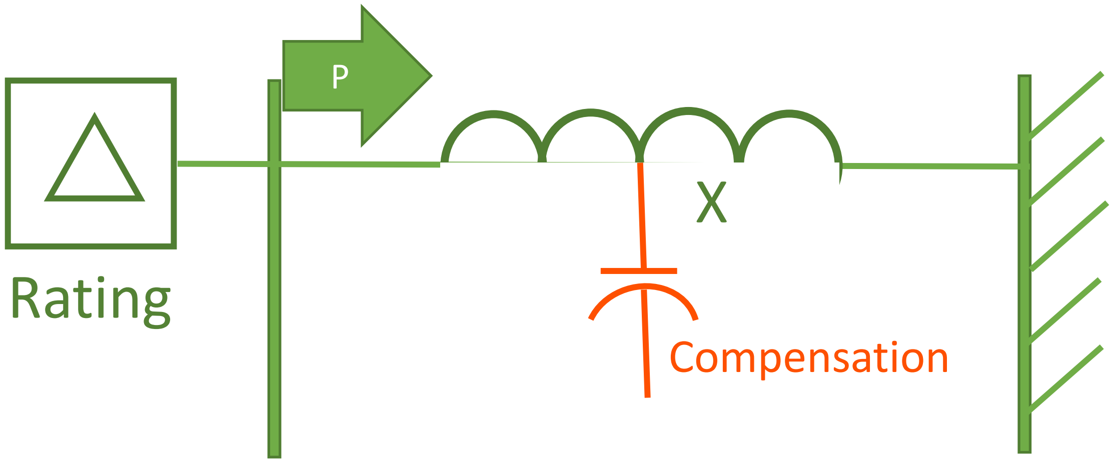
What might Grid-forming (GFM) do for us?

- By "creating" its own Vs phasor, GFM *should* remove (or reduce) the need for the synchronous condenser *at the exporting end*. This reduces the exposure to the condenser stability risk just outlined.
- The angle of the GFM, *should* (probably) not move instantly, but *could* move quickly…producing most of the stability benefit we already get with grid-following IBR.
- If the control does not mimic the synchronous machines, the post-fault clearing power swing *could be designed* to be less severe.
- The synchronism problem is not eliminated, but might be eased, by control of the post-fault power.
- GFM is not required to realize this benefit. Best in class grid-following inverters are already doing this.

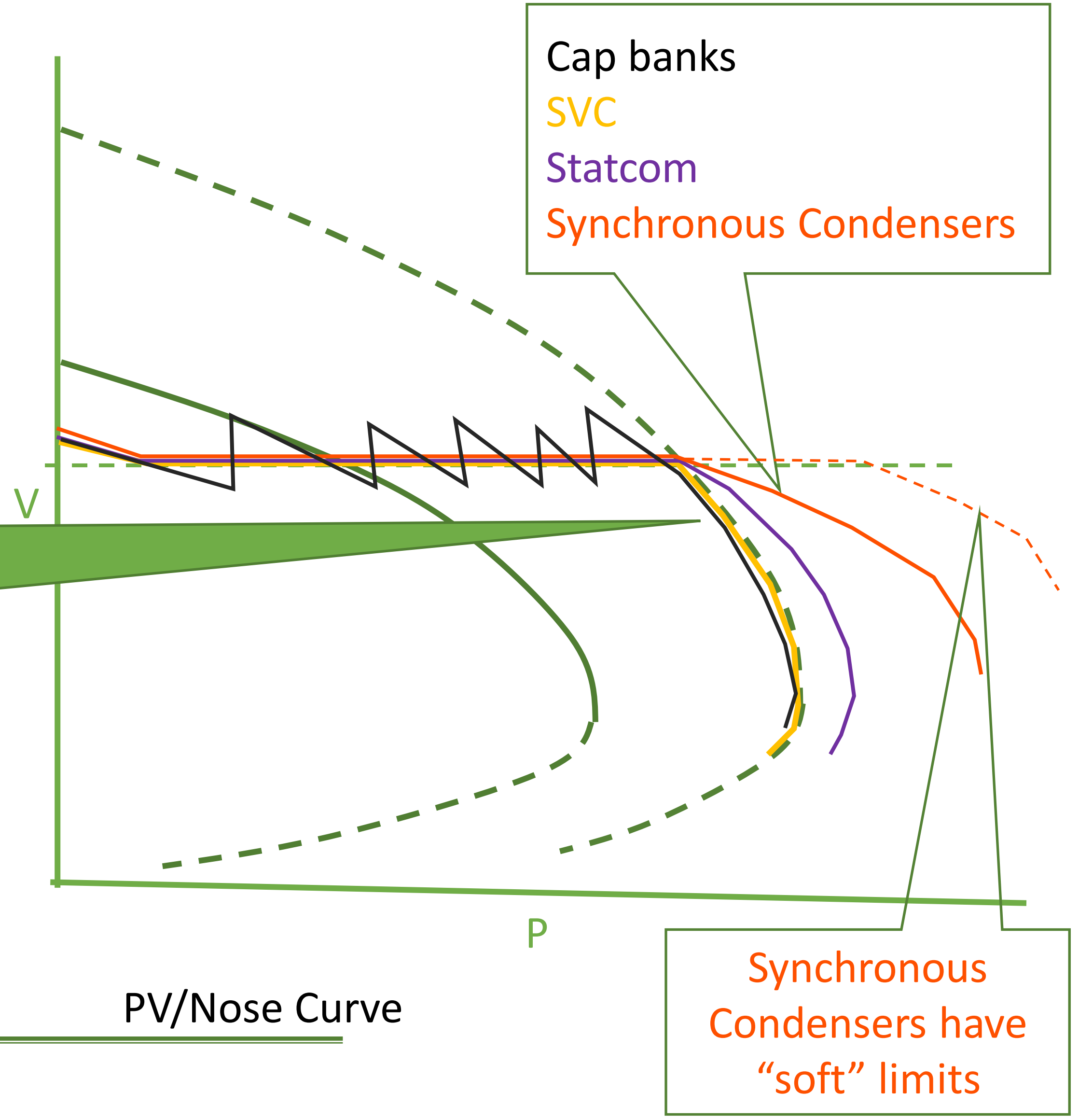
Simple Export Problem: what about the soft middle?



Export Problem: the type of support makes a difference

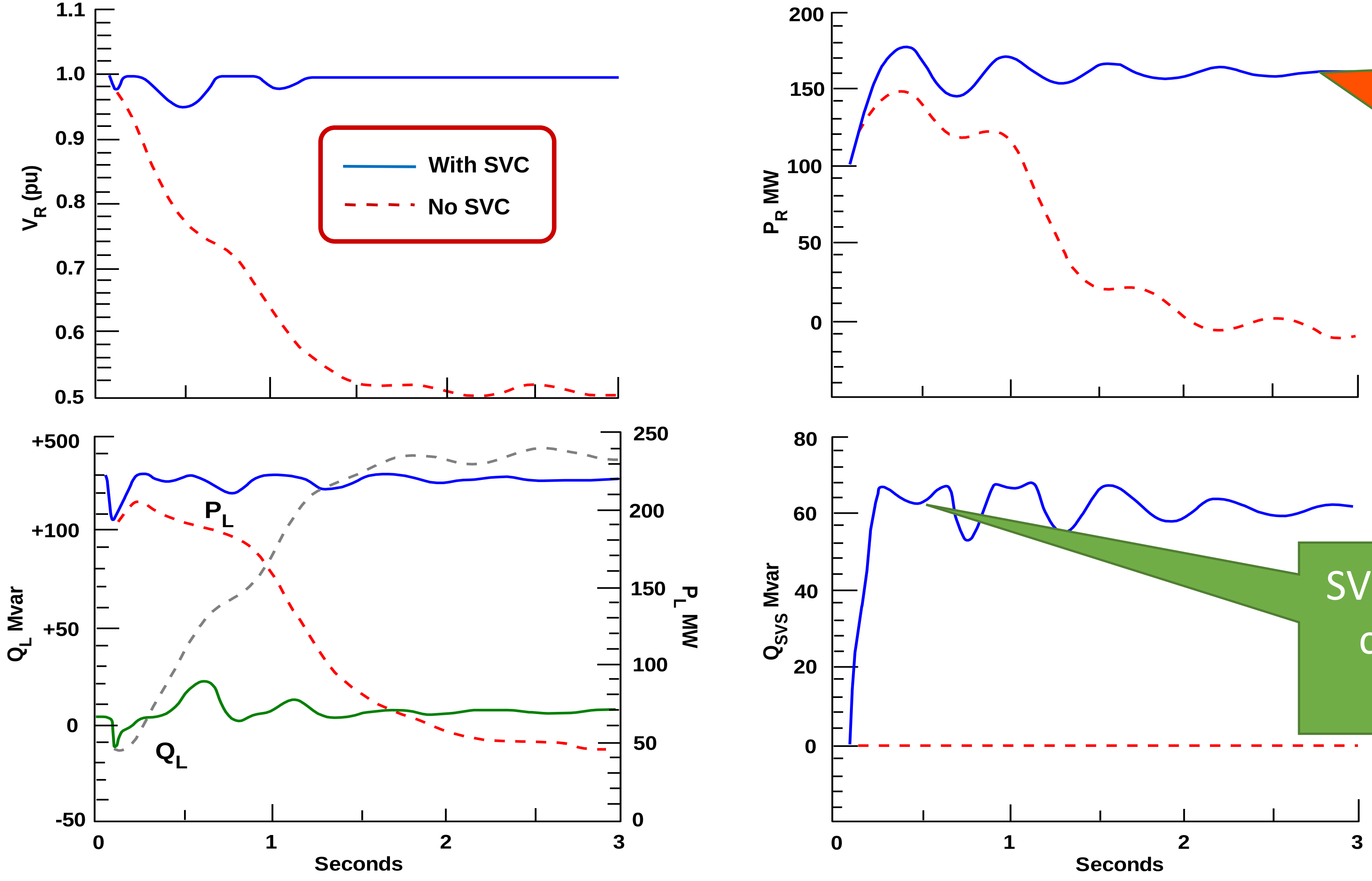


Behavior of the shunt compensation can be especially important at limits



Response of System to Local Generator Trip

With and Without SVC



Mechanical swings of Synchronous Condenser during this behavior may be an issue

SVC becomes a cap bank at limits

Source: GE Energy Consulting. c 2000

Condensers vs. SVC/STATCOM for the soft middle

Condensers

+ Help SCR problem
+ Raise natural frequency of ckts
+ Soft limits on Q support
+ Add inertia (especially with flywheels)

- Slower than SVC/STATCOM
- Inertia related stability issues created
- More physical constraints on control options

SVC/STATCOM

- Fast, agile
- Customizable, asymmetric Q range
- Lower losses (possibly)
- No inertia related stability problems introduced

- Hard Q limits
- Exacerbate SCR problem; lower natural frequency
- Don't contribute to inertia

Observations/Summary

Two related but distinct stability concerns

(a) Low SCR/weak grid in vicinity of IBRs that are exporting power

(b) Low synchronizing strength/poor voltage support between export region and receiving region

Condensers

1. Help with (a), but should be less necessary with GFM resources
2. Help with (b), but may have fewer advantages over SVC/STATCOM as GFM resources are deployed

As always: we’ve got more homework to do!

Thanks

nicholas.miller@hickoryledge.com

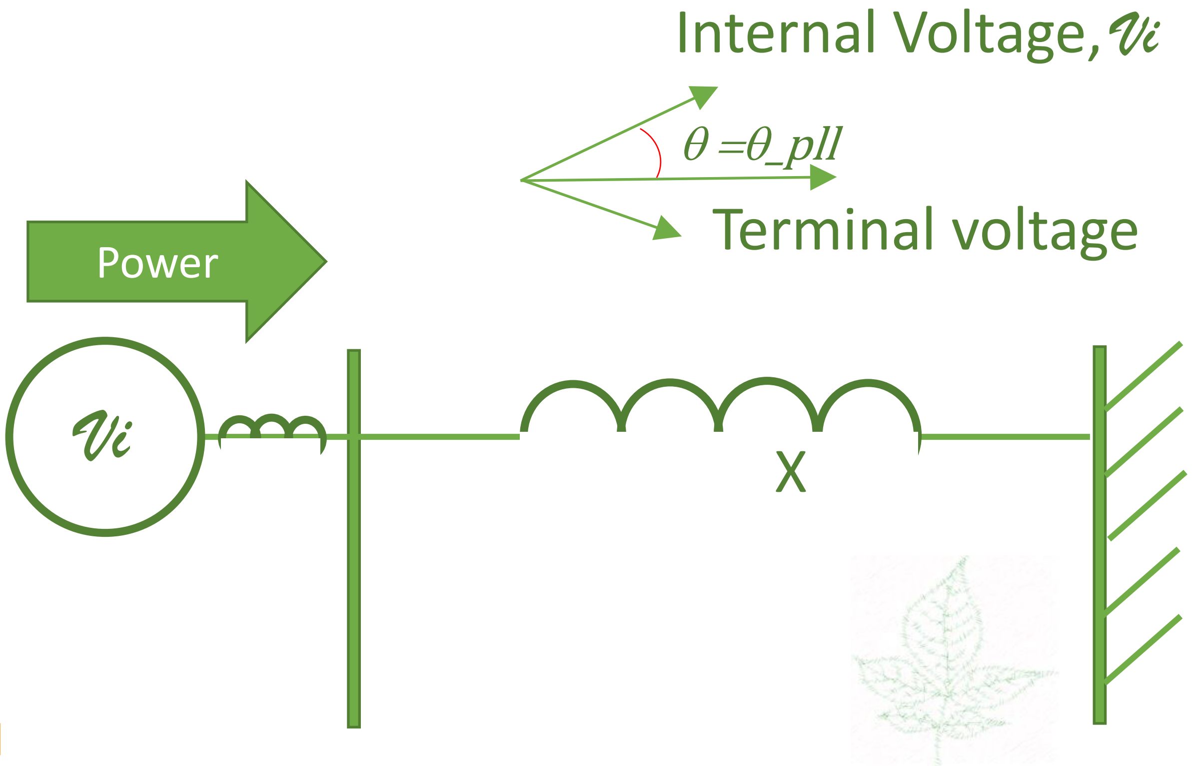
Parking Lot

Pushing the limits out with Grid Following Inverters: today's toolbox

- Better inverter controls. ("more robust controls")
  - Grid following inverters have gotten spectacularly better for high penetration and weak grids in recent years. Tolerate lower eSCR
  - This trend of improvement will continue, though a degree of diminishing return is expected.
- Additional transmission ("more wires").
  - New AC or DC lines
  - More power, additional circuits on existing right-of-way
- Synchronous condensers. ("stiffer grid")
  - Improve all aspects of eSCR. Watch for new stability problems.
- Grid Enhancing Technologies ("use the wires better")
  - power flow control, dynamic line ratings, and topology optimization
  - Series and advanced compensation

Grid-forming basics

1. The GFI *creates* a voltage phasor, $\mathcal{V}i$. That has a magnitude and angle
2. The current that flows is a result of the relationship between that "created" voltage and the grid.
3. The GFI moves the internal voltage, but not instantly, to meet the current instruction.
4. The current instruction is based on the active and reactive power orders AND the device current and voltage limits.
5. The fact that the current flows as a result of the created voltage, means that the terminal voltage need not be created by an outside agency: the grid is FORMED by the internal voltage.
6. If $\mathcal{V}i$ follows the same behavior as a synchronous machine, we have a "virtual synchronous machine".
7. There is no *requirement* that it do so.



A grid forming inverter can tolerate X = ∞,
a.k.a. Zero SCR,
a.k.a. Black Start