ESIG Webinar Series:

Operational Considerations for a 100% Instantaneous Converter Fed Power System

Wednesday, Feb. 12 – 2:00 p.m. (eastern US)

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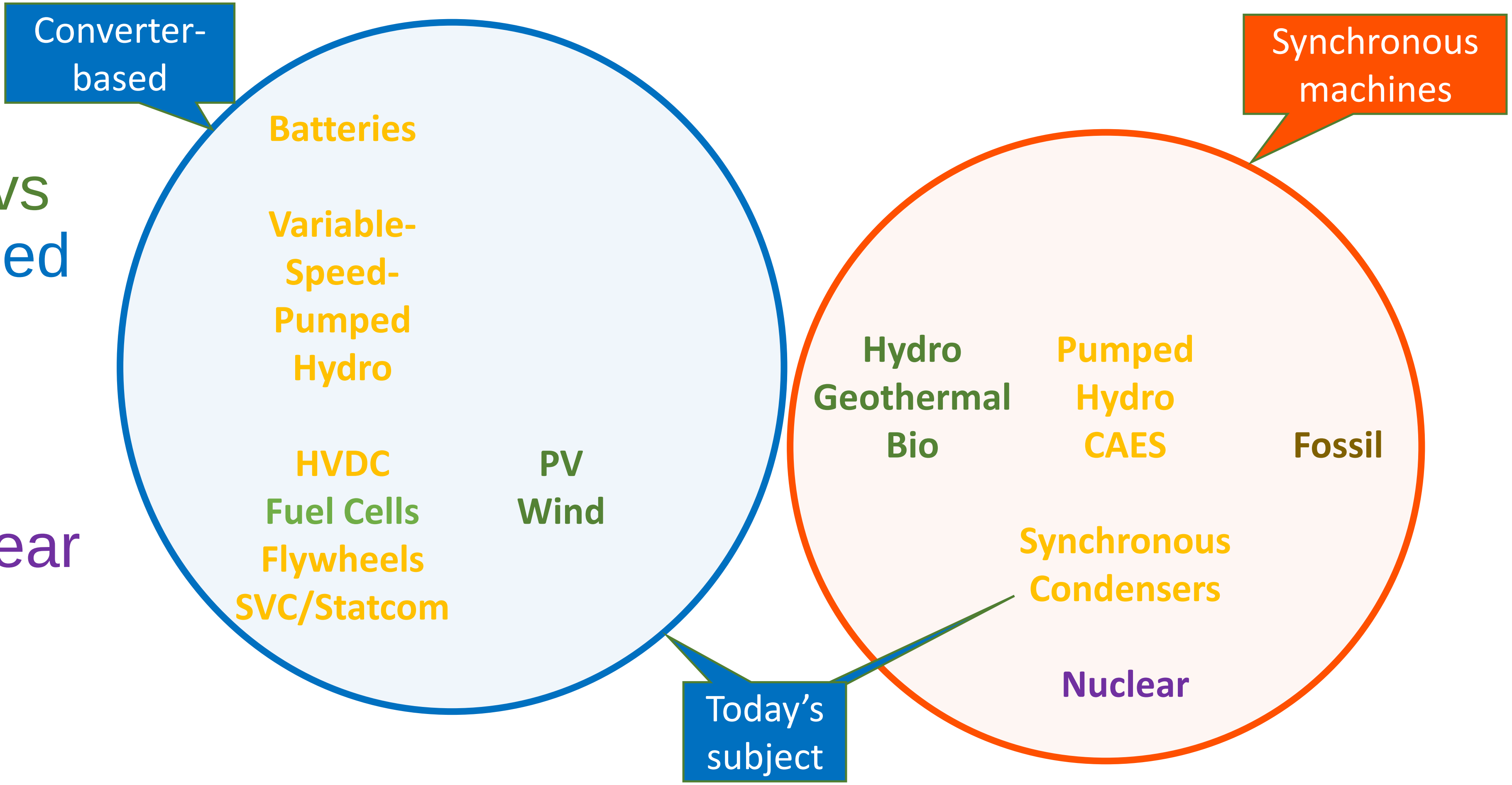
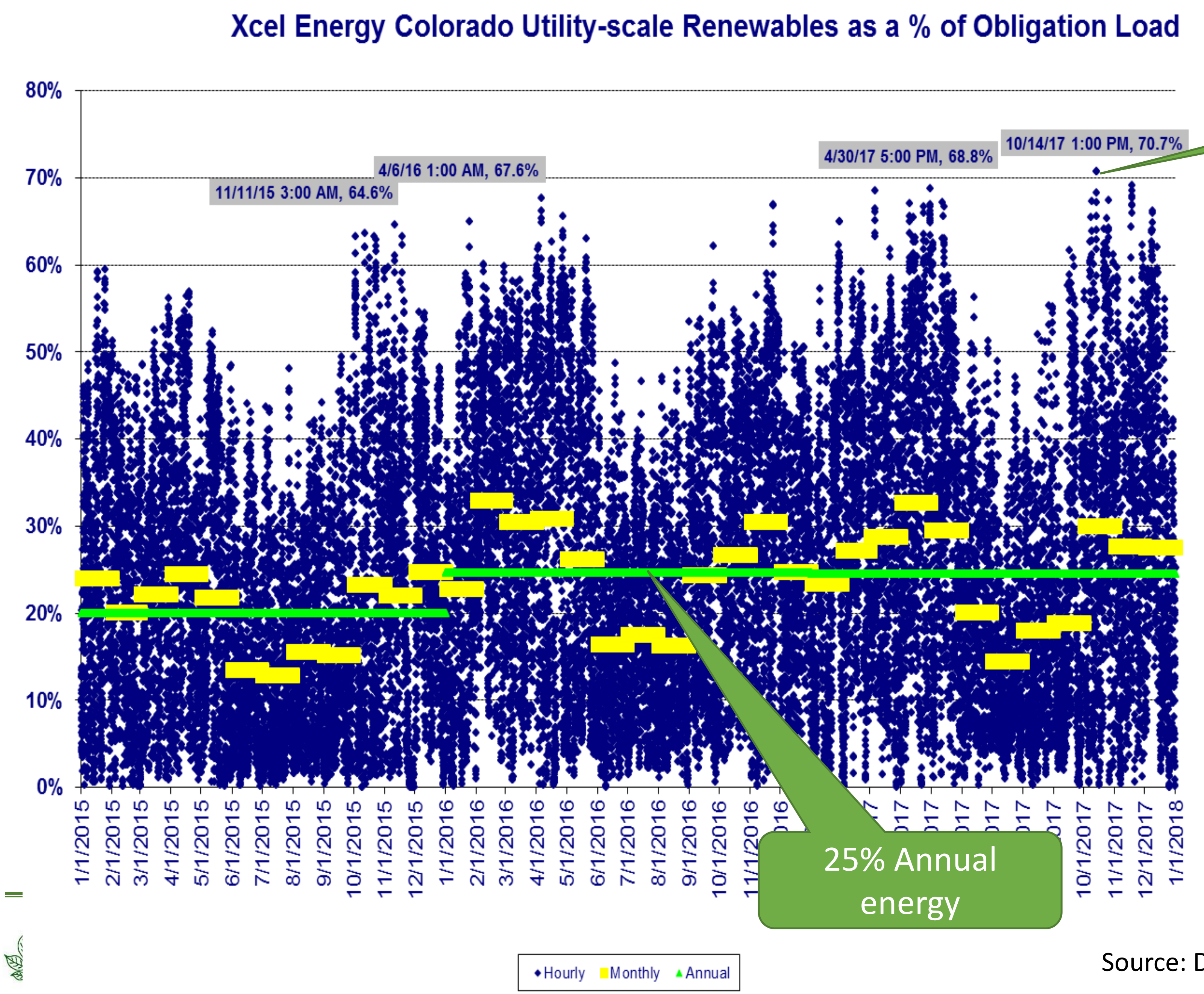
ESIG
ENERGY SYSTEMS INTEGRATION GROUP

100% Renewables vs. 100% Converters:
Closely related, but NOT interchangeable!

- *Some slices:*
- Synchronous vs Converter-based
- Renewable Generation vs "Enabler" vs Fossil vs Nuclear





71% instantaneous

Moderate annual averages translate to high instantaneous penetrations

The question isn't "100% Inverters ALL the time?"

It's "100% Inverters EVER?"

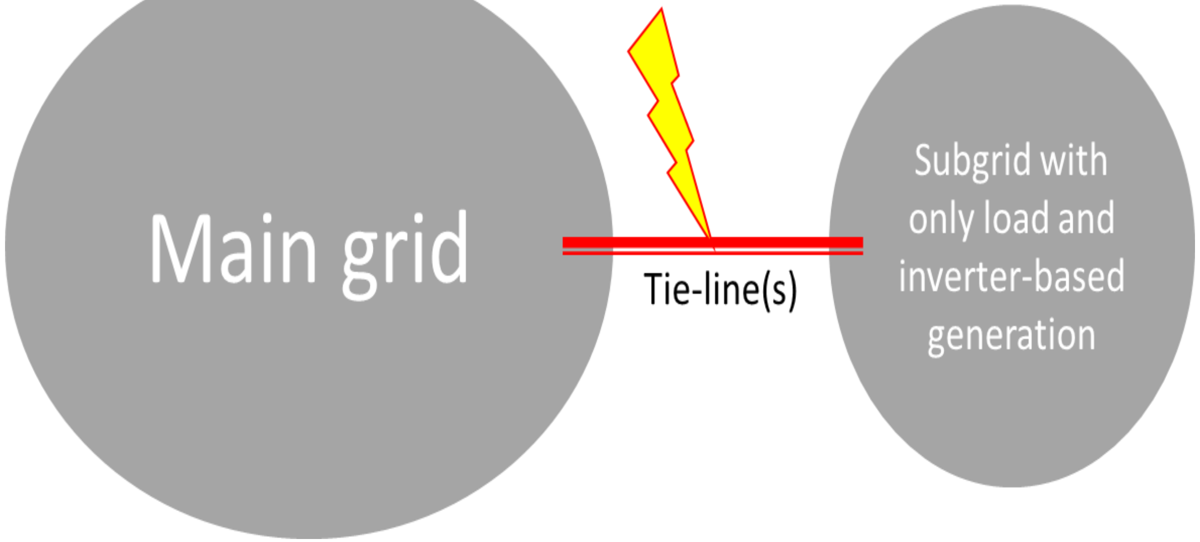
Whether the source is inverter-based only matters for the fast stuff:

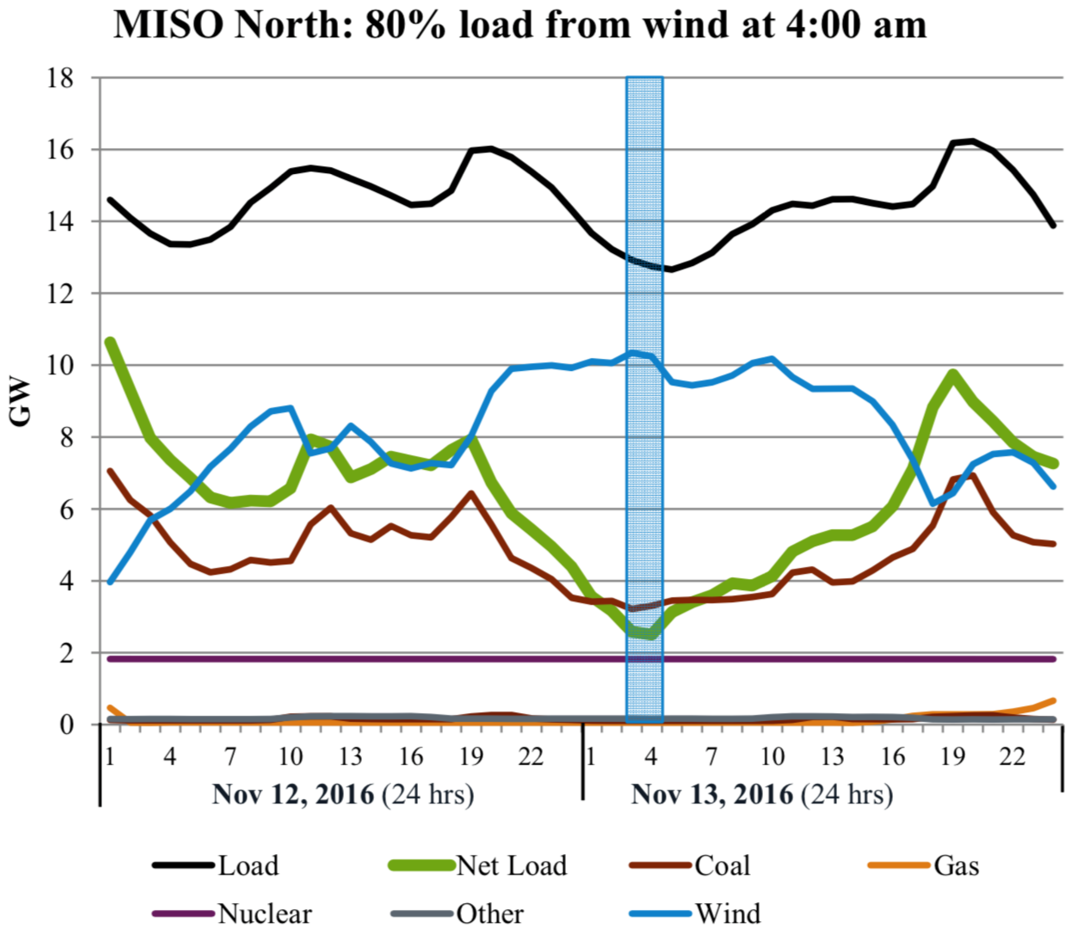
Only Instantaneous Penetration counts

Source: Drake Bartlett, PSCO, 2018; Debra Lew LLC

We live in an N-1 world

What happens when a (big) island forms?





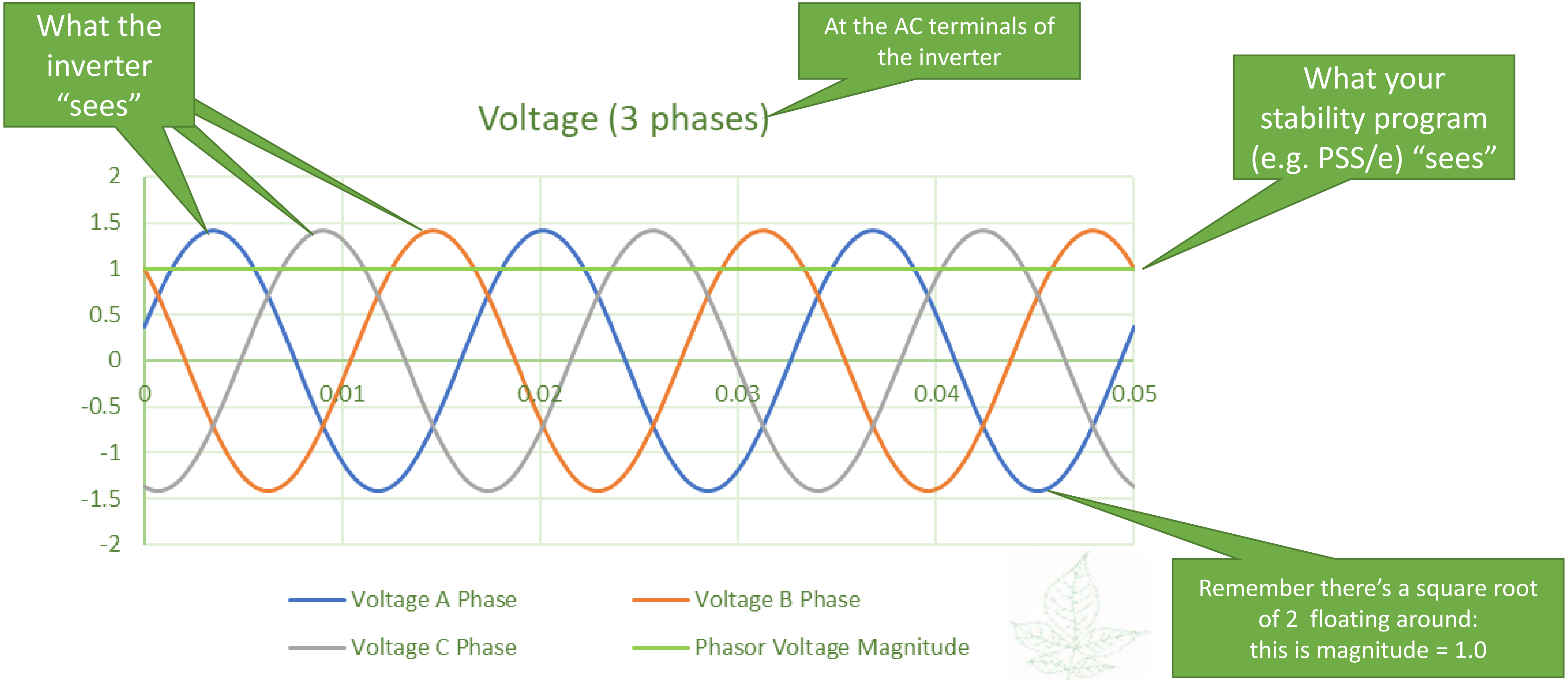
Source: IEEE Power and Energy Magazine, "A future without inertia is closer than you think", Thomas Ackermann, Thibault Prevost, Vijay Vittal, Andrew J. Roscoe, Julia Matevosyan, Nicholas Miller*

Source: D. Manjure, MISO, 2016

Some really basic stuff (sorry)

- All commercially available utility-scale wind and PV today, use grid-following inverters.
- Today, we will start there
- Grid forming inverters are expected to be part of the path forward.
- Today, we will discuss them as well

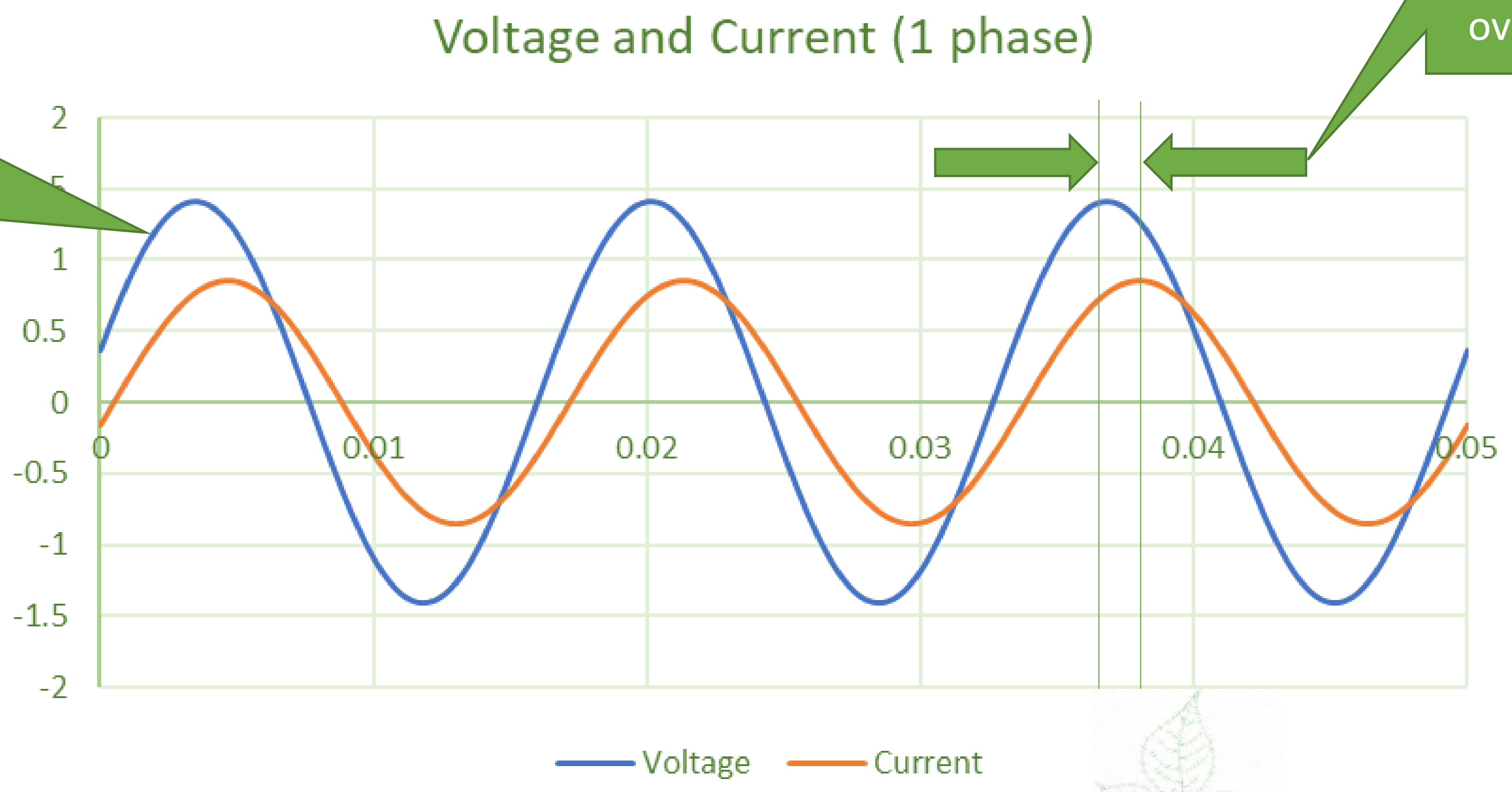
“Real” World and Phasors



A Tale of Two Sine Waves

The magnitude and angle of the sinewave defines the phasor

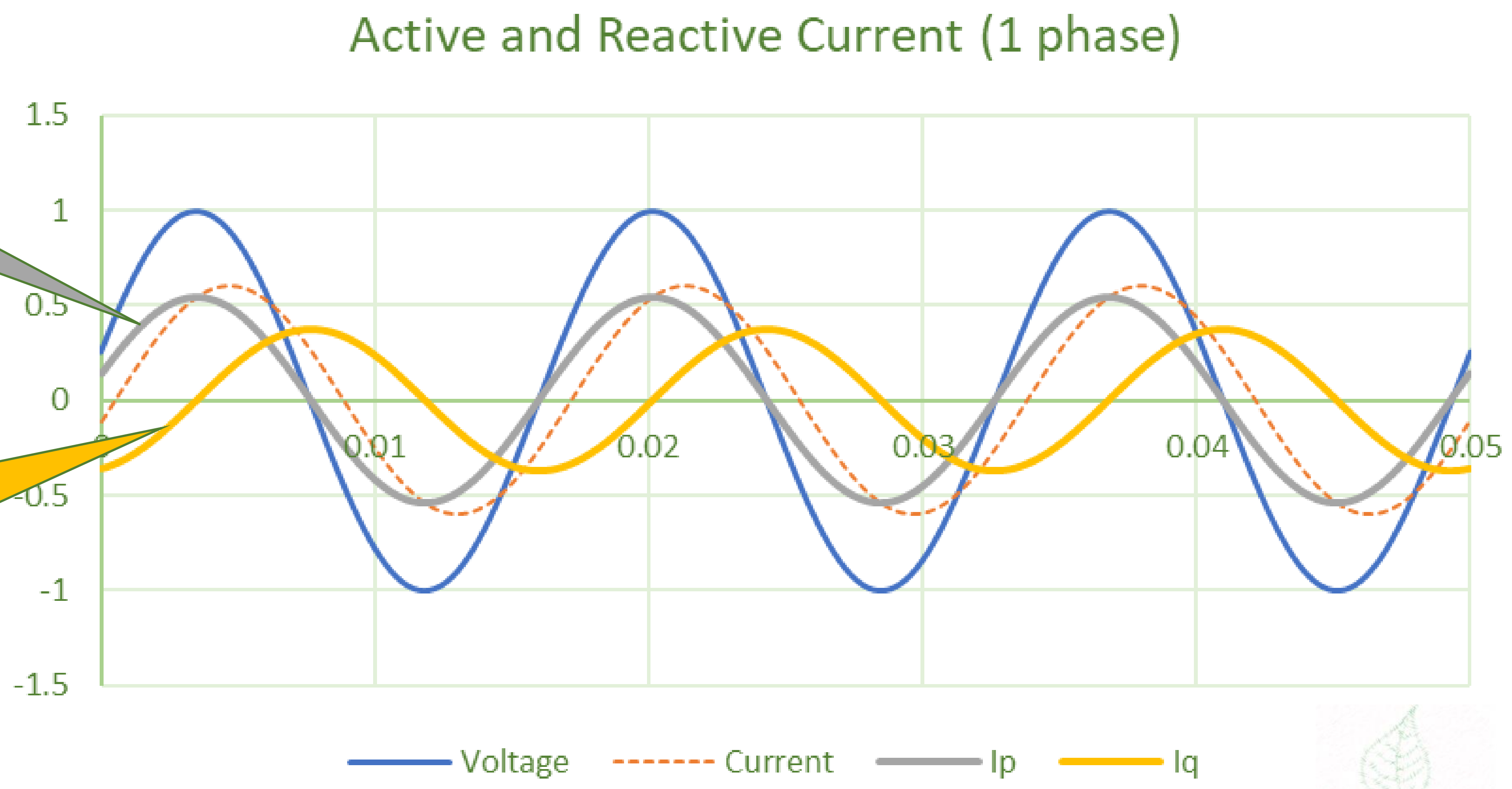
Power Factor Angle
(this is 0.9 pf over-excited)



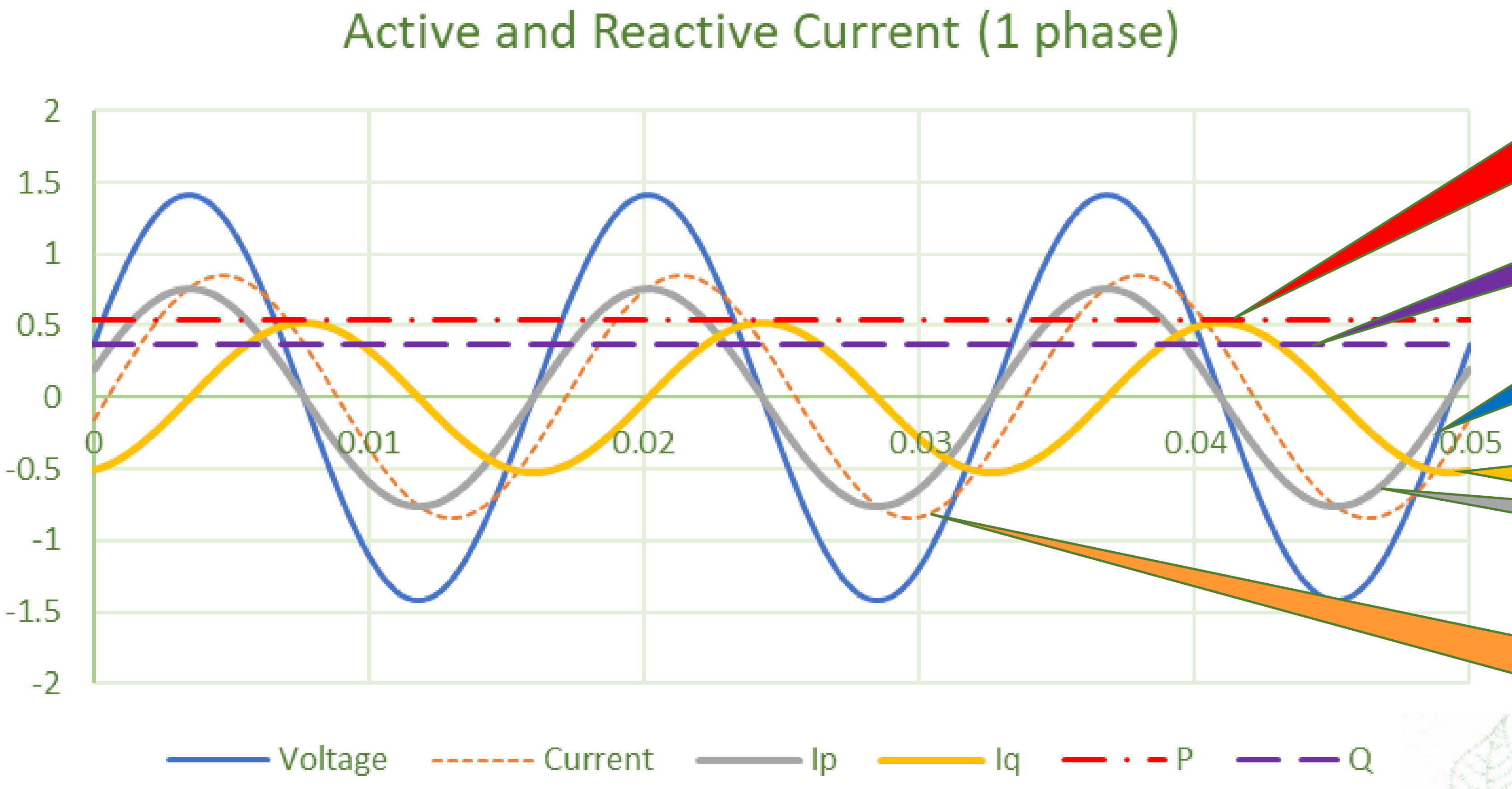
Separating P & Q from Current

This component of the current, Ip, makes WATTS – active power

This component of the current, Iq, makes VARs – reactive power



The anthropomorphic inverter



1. Power regulator, including frequency control: “give me this much power”

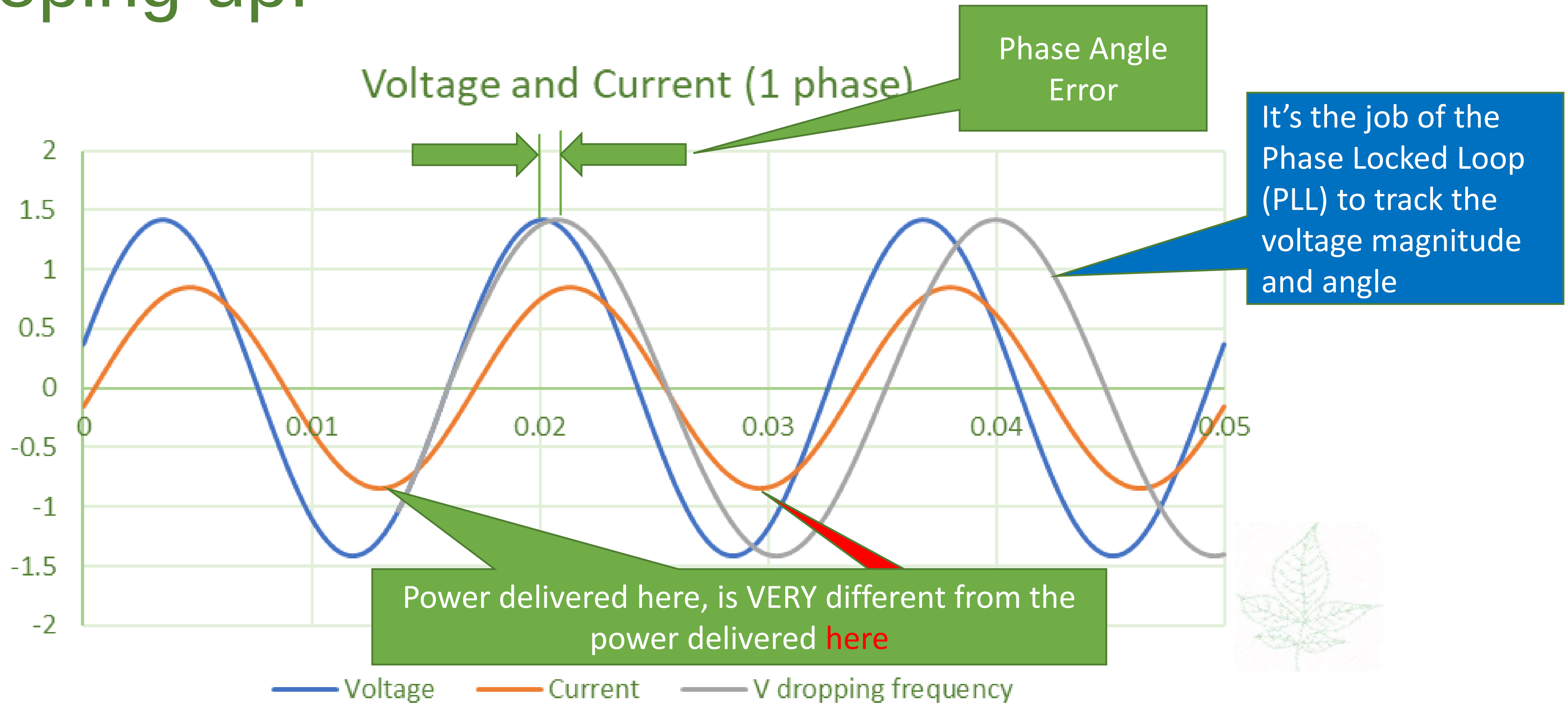
2. Voltage regulator: “give me this much reactive power”

3. Phase Locked Loop (PLL): “the voltage magnitude and angle is HERE”

4. Current regulator: “inject this much power current (Ip) and reactive current (Iq)”

5. Firing control: “inject this current at this phase angle”

Keeping up!



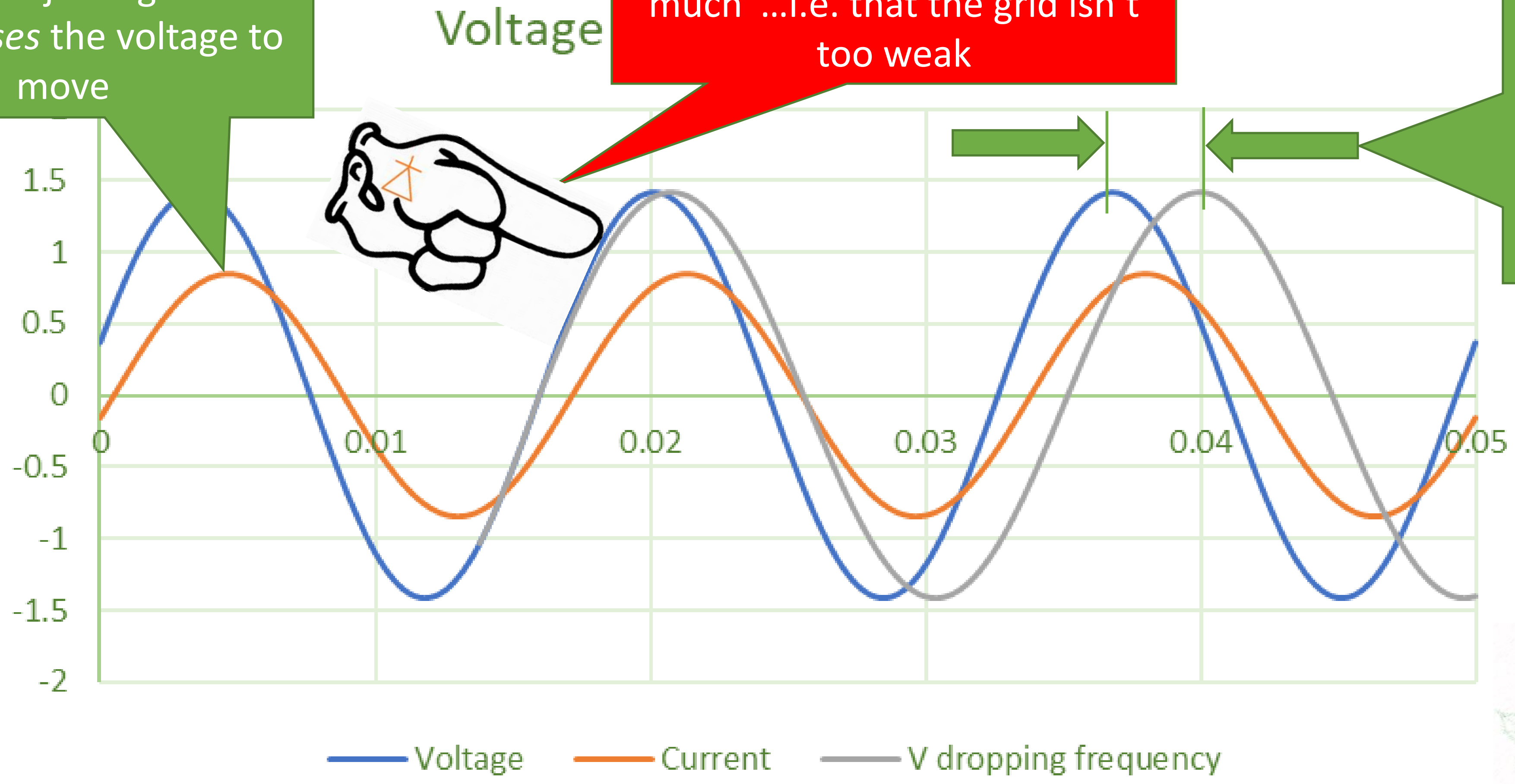
Voltage and Current (1 phase)
Phase Angle Error
It's the job of the Phase Locked Loop (PLL) to track the voltage magnitude and angle
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
0.01
0.02
0.03
0.04
0.05
Power delivered here, is VERY different from the power delivered here
Voltage
Current
V dropping frequency

Self-inflicted pain

The act of injecting current here *causes* the voltage to move

Control design and stability is based on the assumption that the voltage won't move "too much"…i.e. that the grid isn't too weak

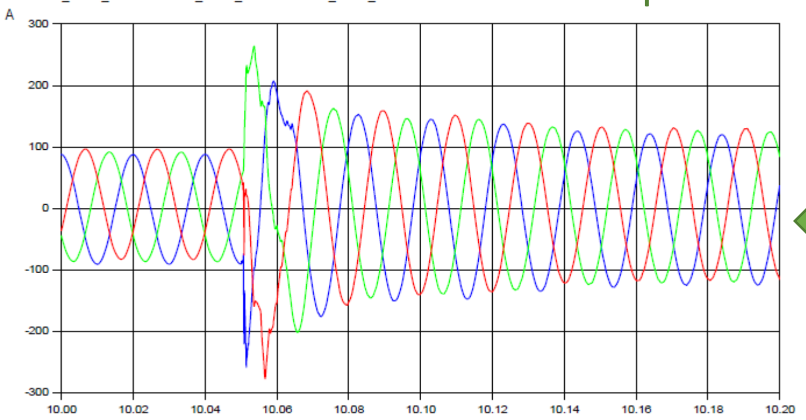
When the voltage moves too much, the current control either can't keep up or it gets confused: i.e. it becomes unstable



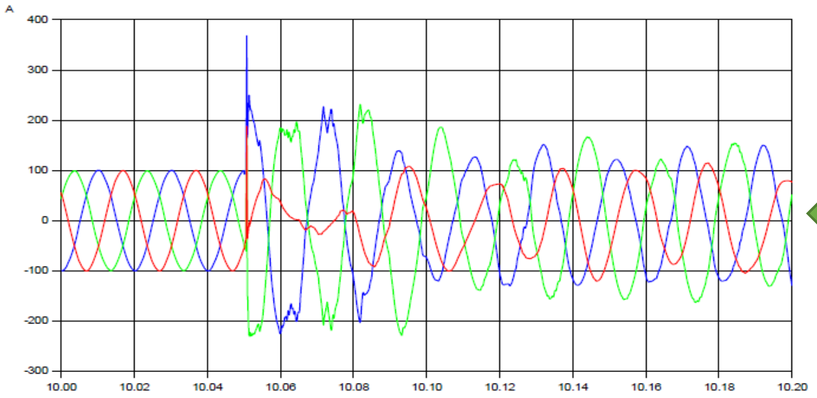
It’s not that simple

- Real life intrudes
- Waveforms can be difficult
- Even in normal systems, it can take a few cycles to figure out what’s going on
- So, there’s a limit to how fast you can make things act with confidence

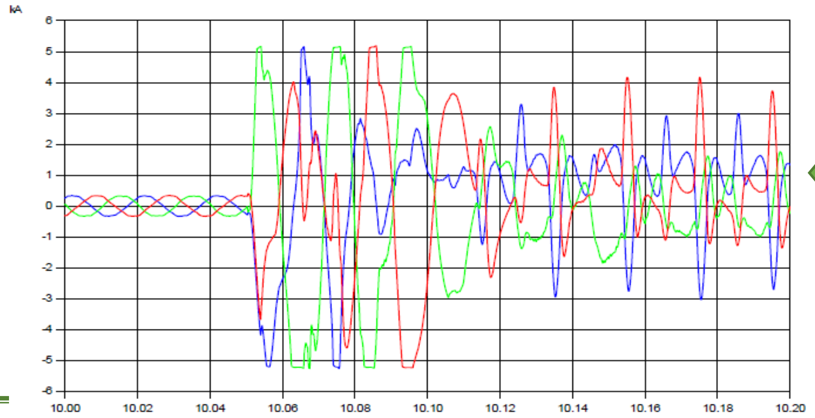
Some fault current examples



Balanced 3 phase fault



2 phase fault

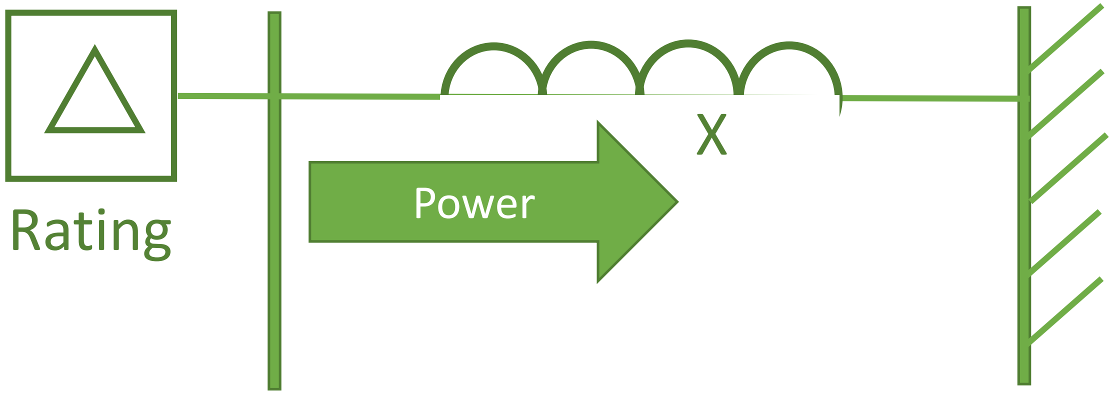


2 phase fault, at v low initial current

eSCR (effective short circuit ratio) and beyond: basics

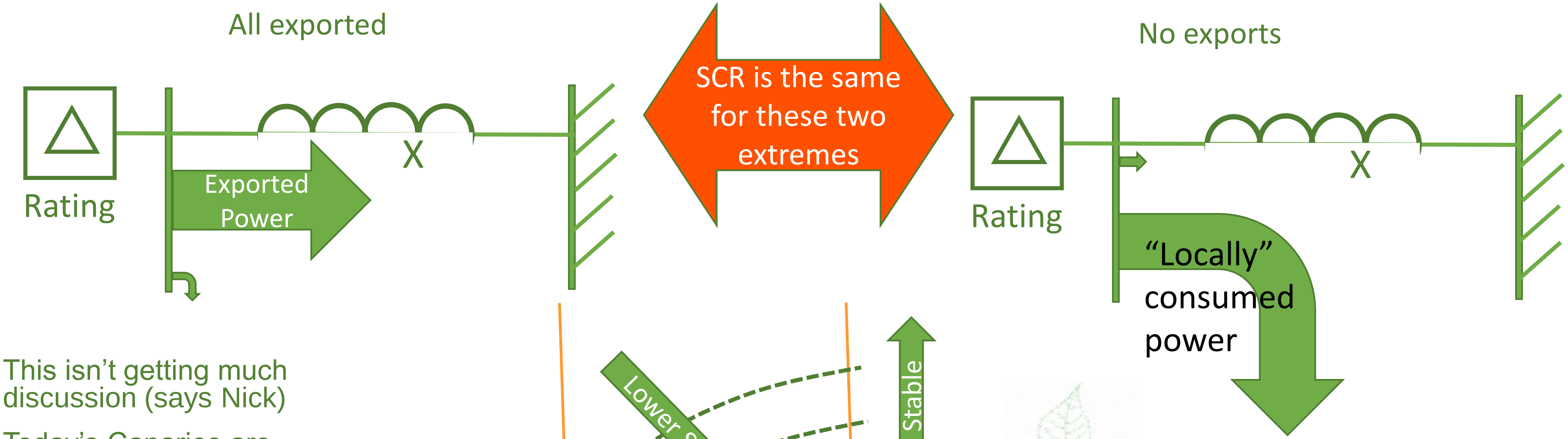
Short Circuit Ratio is a convenient way to talk about the strength of the grid, it's not about faults

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.

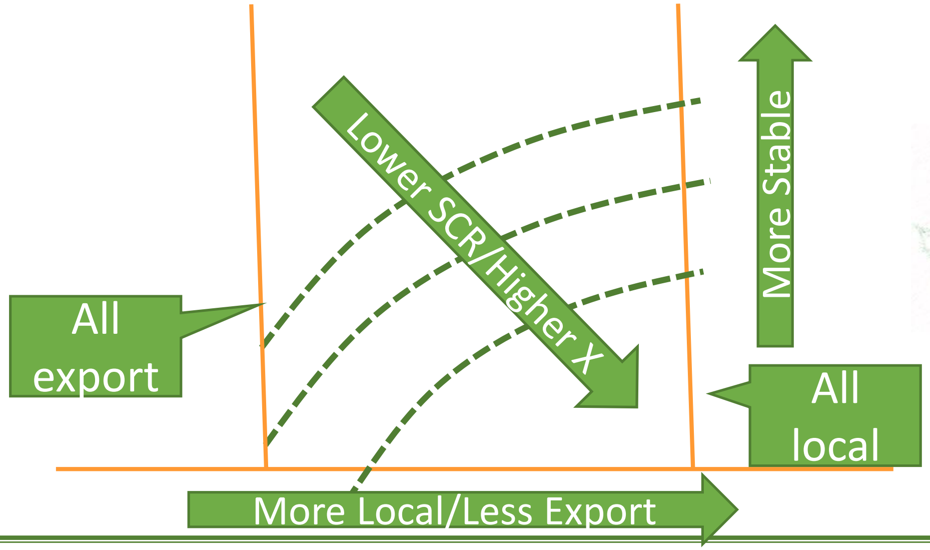


- All things being equal, the lower the short circuit ratio, the harder it is to stay stable.
- All things are never equal.

eSCR and beyond: Where is the power going?

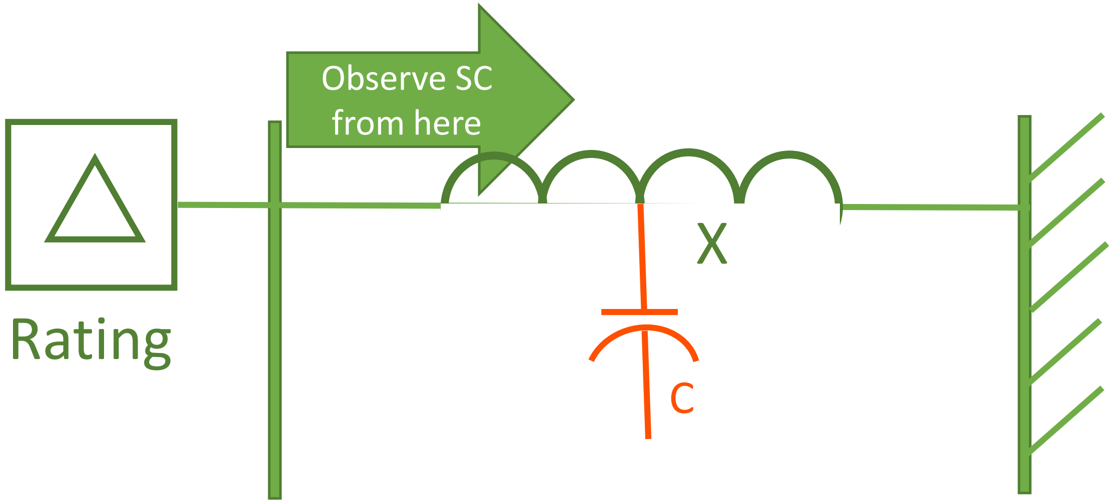


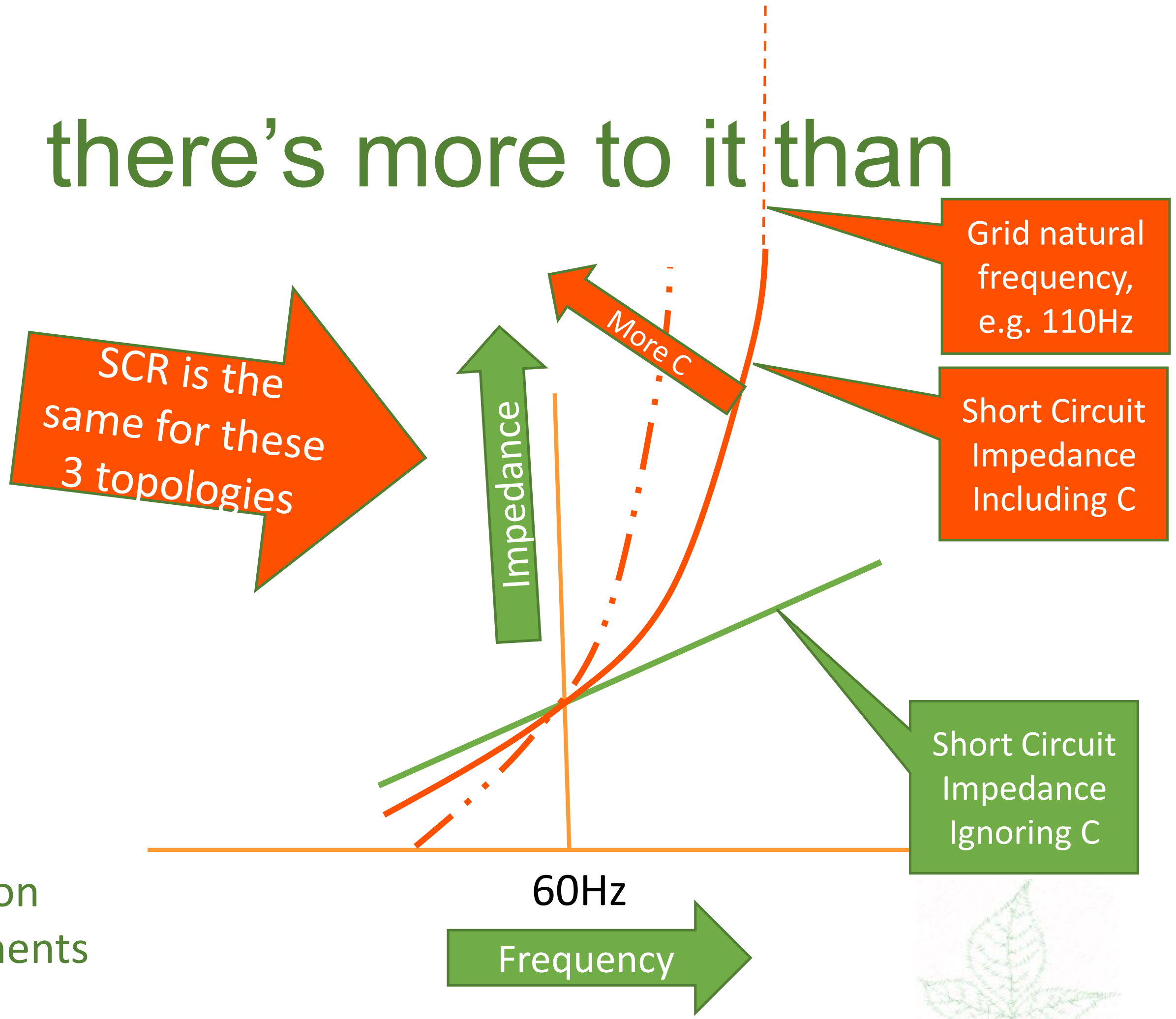
- This isn’t getting much discussion (says Nick)
- Today’s Canaries are mostly exporting
- In future, some systems will have much more “local” consumption.



Note the absence of numbers: we (the industry) have not adequately explored this relationship.

eSCR and beyond, part 2: there's more to it than 60Hz





Crib sheet:

1. X, the reactive impedance of the grid, is a useful simplification
2. Real systems are more complex, and include capacitive elements (C) in the lines and for compensation.
3. Long distances normally involve more C
4. Grid natural frequency drops with more C
5. Synchronous condensers add strength by reducing X, not adding C
6. This frequency effect is ignored in short circuit ratio calculations

As natural frequency drops (towards 60Hz), high speed controllers become less stable.

Limitations of Stability Models
(a.k.a. what could go wrong?)

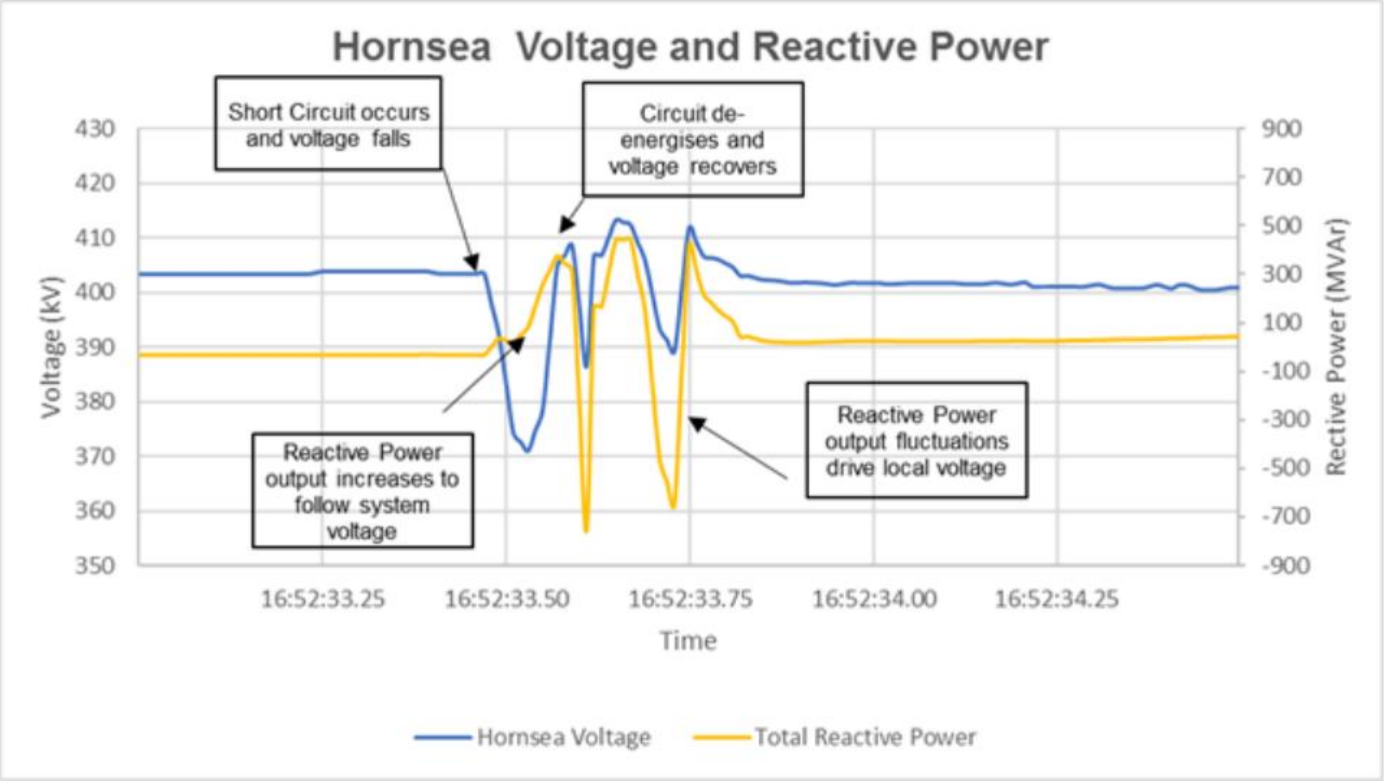
- Simulations crash.
  - These models are numerically challenging for the equation solvers.
  - Crashes are a measure of stress. But a crude one.
  - A simulation crash is a yellow flag, but NOT firm evidence of instability
- High frequency oscillations.
  - Fast oscillations, i.e. anything above about 3-5Hz, isn't very meaningful for stability (phasor) analysis.
  - Again, a yellow flag, but NOT firm evidence of instability
- False assurance.
  - Stability models may make the results optimistic. Ouch
  - Assumption of "perfect" PLL performance is one culprit

Sometimes, detailed, point-on-wave, EMT analysis is needed. (e.g. PSCAD…)

- It's not simple.
- Opportunities for garbage results abound.

Example: UK Blackout August 9, 2019

- Huge 800 MW offshore, AC connected wind plant
- Small event: Shouldn't have tripped
- UFLS activated; ~1M customers affected.
- Ugly: Some rail customers stranded for 6+ hours
- V/Q regulator not tuned for weak grid
- OEM quickly retrofit with more appropriate weak grid controls
- ~10Hz instability; outside of PSS/e, etc. simulation bandwidth



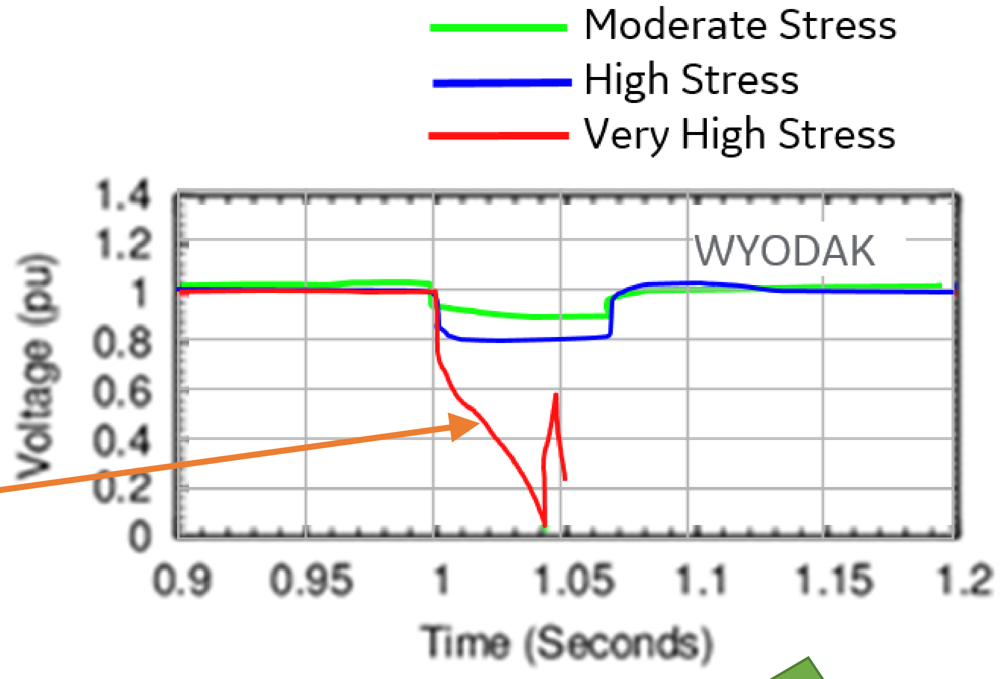
Nick Miller

Source: National Grid ESO LFDD 09/08/2019 Incident Report
https://www.ofgem.gov.uk/system/files/docs/2019/09/eso_technical_report_-_appendices_-_final.pdf

Paradoxically: Grids are both stronger and more brittle.

With SOA grid-following inverters, stability limits tend to be **higher – that is good for reliability and economy.**

But, when the grid fails, it **fails faster and with less warning**



We need better :

- Understanding
- WTG (and inverter) controls
- Simulation tools
- Predictive tools and metrics

- Condenser conversion "fixed" this; be careful of transient stability
- Weak grid WTG controls fixed this particular problem

Source: Miller; NREL/GE WWSIS 3a

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

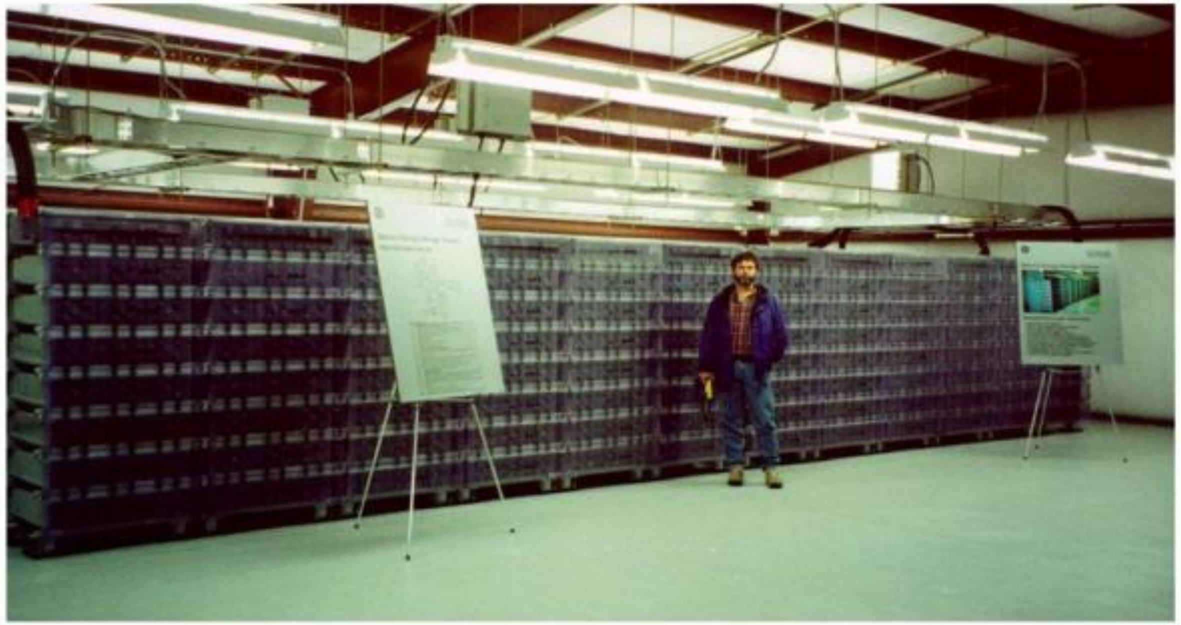
Grid-following vs Grid-forming Inverters

- Grid following (Inverter follows): Inverters measure the grid voltage and frequency, and then try to inject the correct real and reactive power.
- Grid forming (Inverter leads): Inverters create a local voltage and frequency, and then try to move that voltage to cause the correct real and reactive power to flow into the system

A bit oversimplified, but close enough - the point is this behavior is fundamentally different.

Grid-forming inverters are not new

But we don't know how we'd want them to perform or how to operate a large system with them or how we'd manage them with the rest of the system



Metlakatla 1MW/1.4MWhr BESS. c. 1996

Imperial Irrigation District (IID) 30MW, 20MWh BESS project

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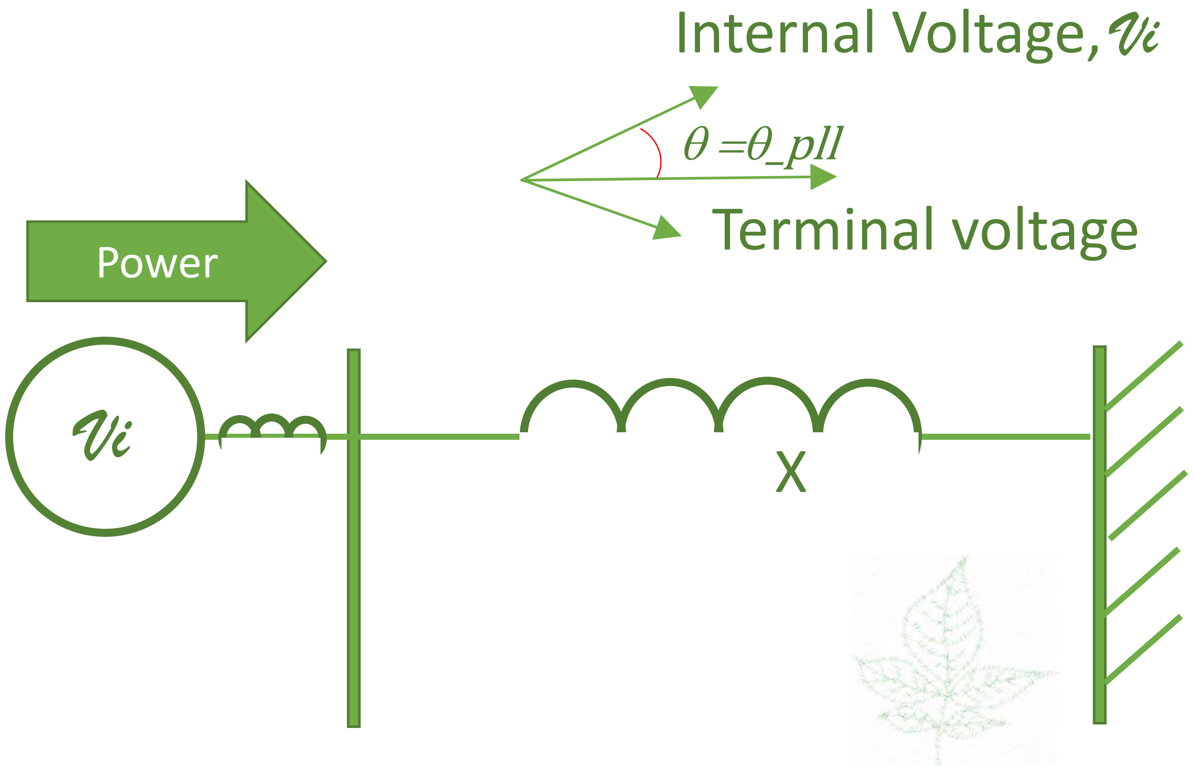
Source: GE

Grid-forming basics

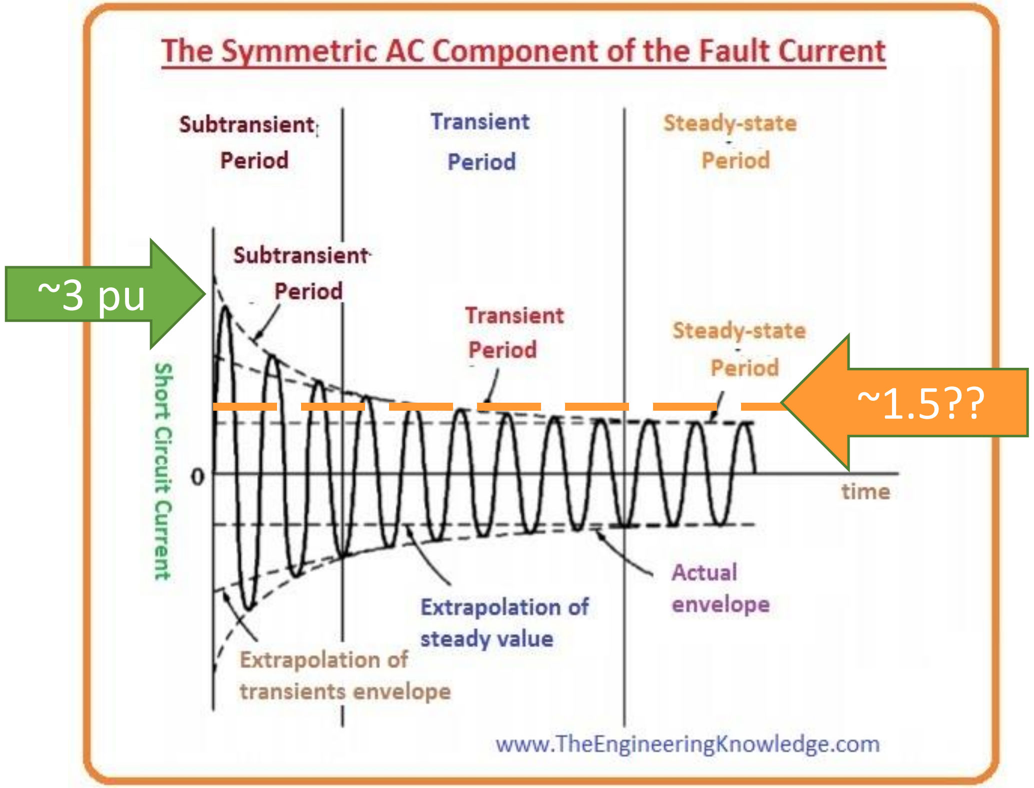
1. The GFI *creates* a voltage phasor, $\mathcal{V}_i$. That has a magnitude and angle
2. The current that flows is a result of the relationship between that "created" voltage and the grid.
3. The GFI moves the internal voltage, but not instantly, to meet the current instruction.
4. The current instruction 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

Current Limits: a different beast

- Synchronous machines have maximum current (and voltage) capabilities, but they don't have <u>limiters.</u>
- Inverters also have current (and voltage) capabilities. They are harder ones: i.e. they must be respected much faster.
- They don't care a lot whether the control is grid following or grid forming.
- There are difference strategies to manage or limit over-current and over-voltage.
- Whatever grid forming you thought you were doing is compromised when the inverter hits limits.
- Higher current limits = higher inverter costs
- Future systems will probably have lower fault current levels. The fault currents will be more complicated
- We will probably have to rethink at least some aspects of protective relaying

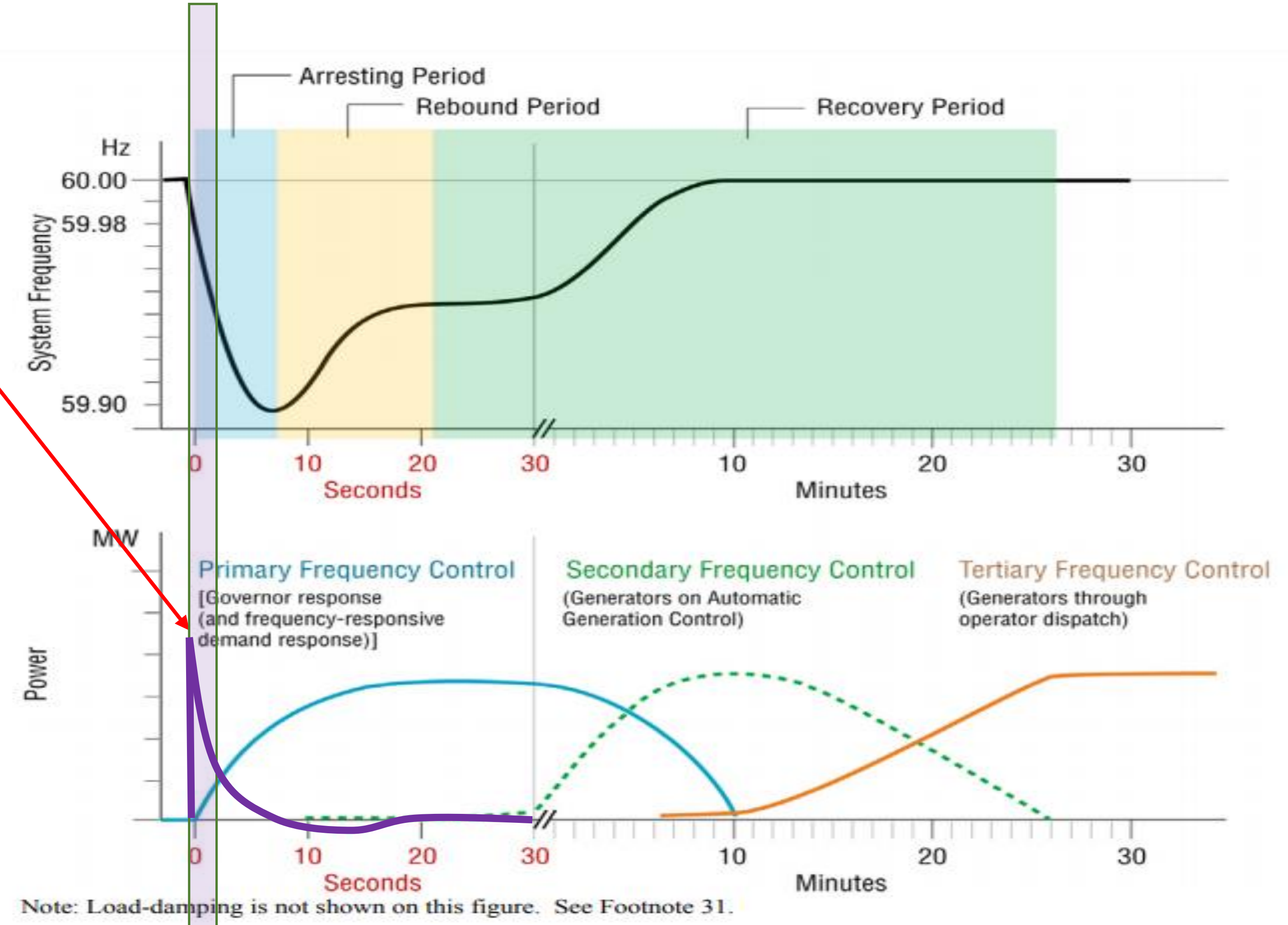


Power Limits

Uncontrolled Synchronous Inertial Response: the available power is dictated by the inertia and current

Power for inertia response from Inverter-based resources is determined by the generation/resource.

- For batteries, power is from the cells.
- For wind, power initially is from the inertia (or storage on the DC link) – NOT curtailment
- For PV, power is from curtailment (or storage).



It's not enough that the inverter asks for power, the resource needs to be able to supply it then

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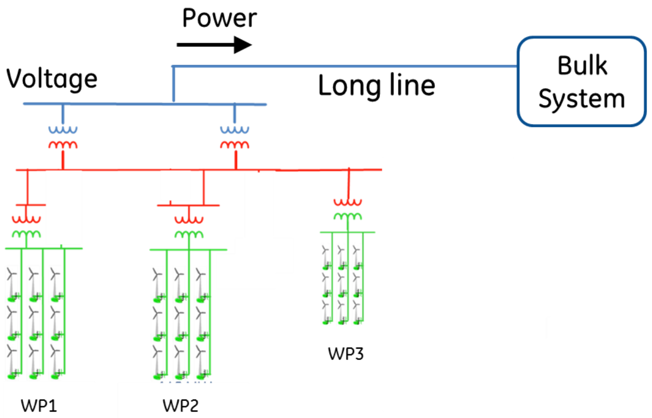
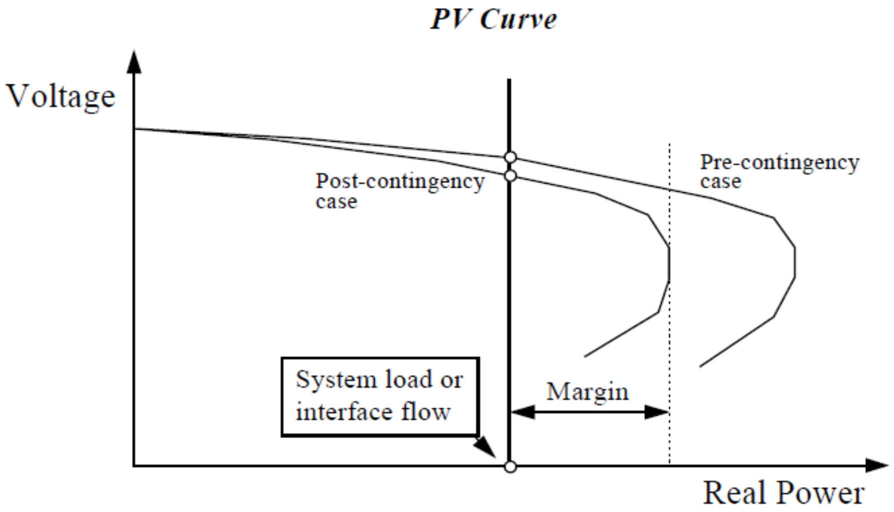
Courtesy J. Eto, J. Undrill, M. O'Malley et al, "Use of Frequency Response Metrics to Assess the Planning and Operating Requirements for Reliable Integration of Variable Renewable Generation", 2010

Grid Forming Inverters- End of Stability concerns?

- Power transfer limits are not necessarily improved with grid forming inverters for long and weak corridors





Transfer capability limits still exist with grid-forming inverters

Source: S. Achilles, GE. ESIG Reliability Working Group, March 2019

Why drive your Ferrari like a dump truck?

- We’ve been here before:
  - Stability problems surfaced as we pushed performance of synchronous machines. We found solutions.
  - In the past 15 years, grid-following inverters have gotten spectacularly better.
- *We’ve learned to live with synchronous machines, but it doesn’t mean their behavior is always desirable or optimal.*
- With inverters, we aren’t stuck with the characteristics of synchronous machines
  - We have a broader spectrum of options
  - One size doesn’t fit all
  - We won’t get grid-forming inverters perfect over-night.

We need the next generation of converters to capture the best attributes of today’s best grid-following inverters AND the desirable attributes of synchronous machines

Grid Forming Inverters Reality Check:

- The elephant in the room relative to 100% inverters is "ever", not "always"
  - And yes, there are places that are getting close today.
  - They are limited, for now, but very real.
  - We need to learn from them.
- The reality that this is NOT close to being cooked.
  - The BESS experience isn't that big yet. And BESS isn't PV or wind.
  - It's not that simple. OEMs and others are actively chipping away for wind and PV
- There isn't a (single) "GFI" available.
  - Yes, we need to get moving, faster, better
  - No, we don't have all the technical issues resolved.
  - Yes, GFI can reasonably be expected to produce substantial benefits in some regards.
  - Yes, GFI performance can be worse than grid-following, especially if you're not careful.
  - No, we can't expect GFI to make all the grid problems go away
- Many unintended consequences there are.
  - Shouldn't and can't just replicate synchronous machines.
  - We can and must do better, and we don't know enough yet.
- There is every reason to expect good outcomes:
  - Don't panic and carry on
  - More studies, more demonstrations, more lab work, more investment!

Thanks

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HickoryLedge

GridLAB

A quick note on notation*

Converter. \ kən-ˈvər-tər \.

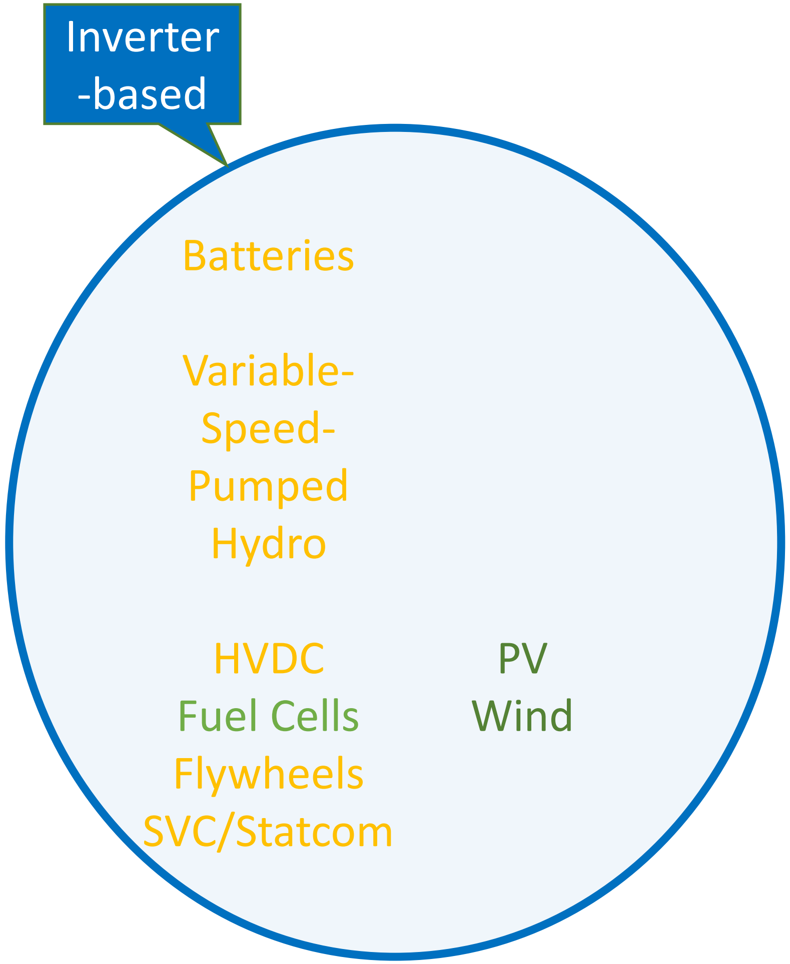
a. A device which uses power electronics, such as thyristors, diode, transistors, etc. to exchange energy between DC (direct current; not sinusoidally varying) voltage elements and AC (alternating current; sinusoidally varying – nominally 60Hz elements)

Inverter. \ in-ˈvər-tər \.

a. A device for converting DC to AC. Normally understood to specifically mean the direction of energy transfer is from DC to AC.

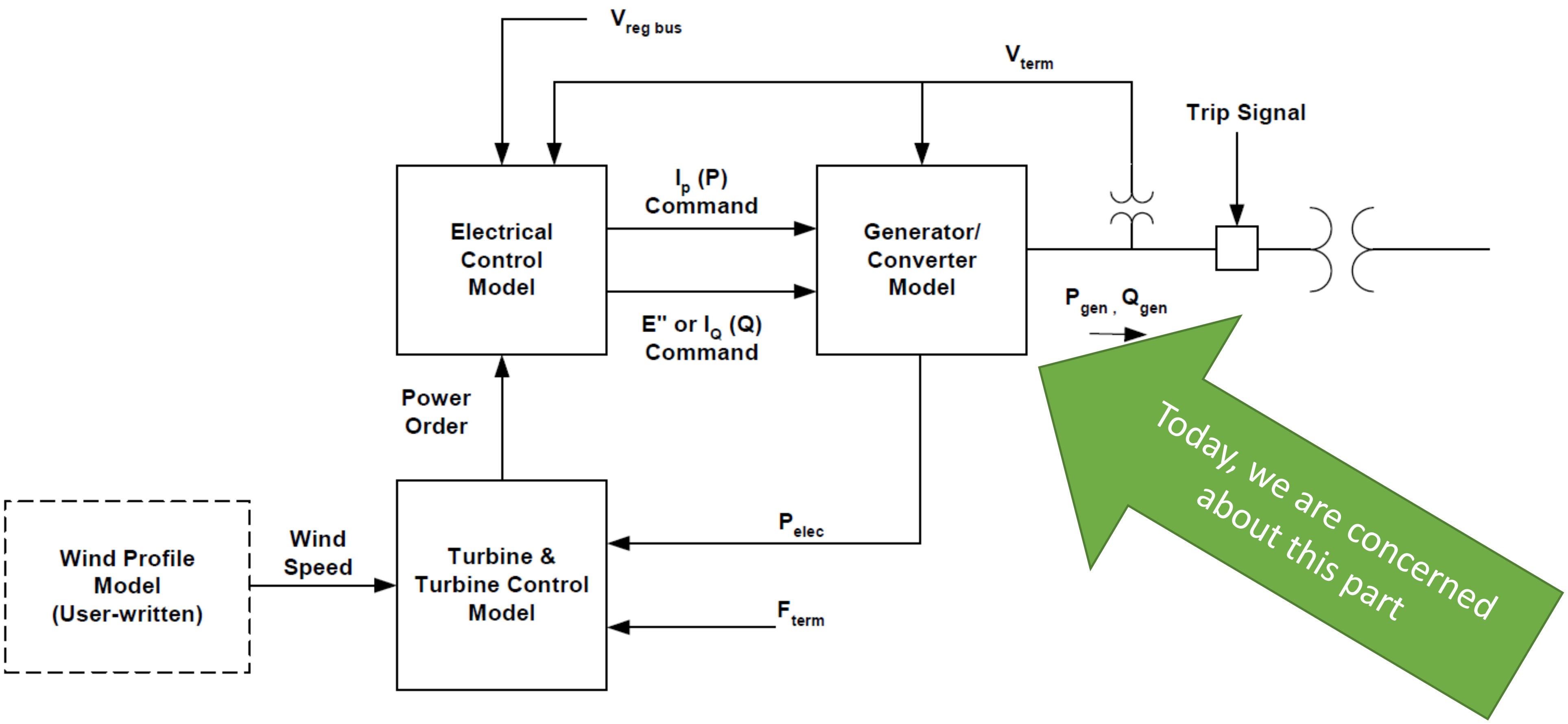
Rectifier. \ ˈrek-tə-ˌfī(-ə)r \.

a. A device for converting AC to DC. Normally understood to specifically mean the direction of energy transfer is from AC to DC.

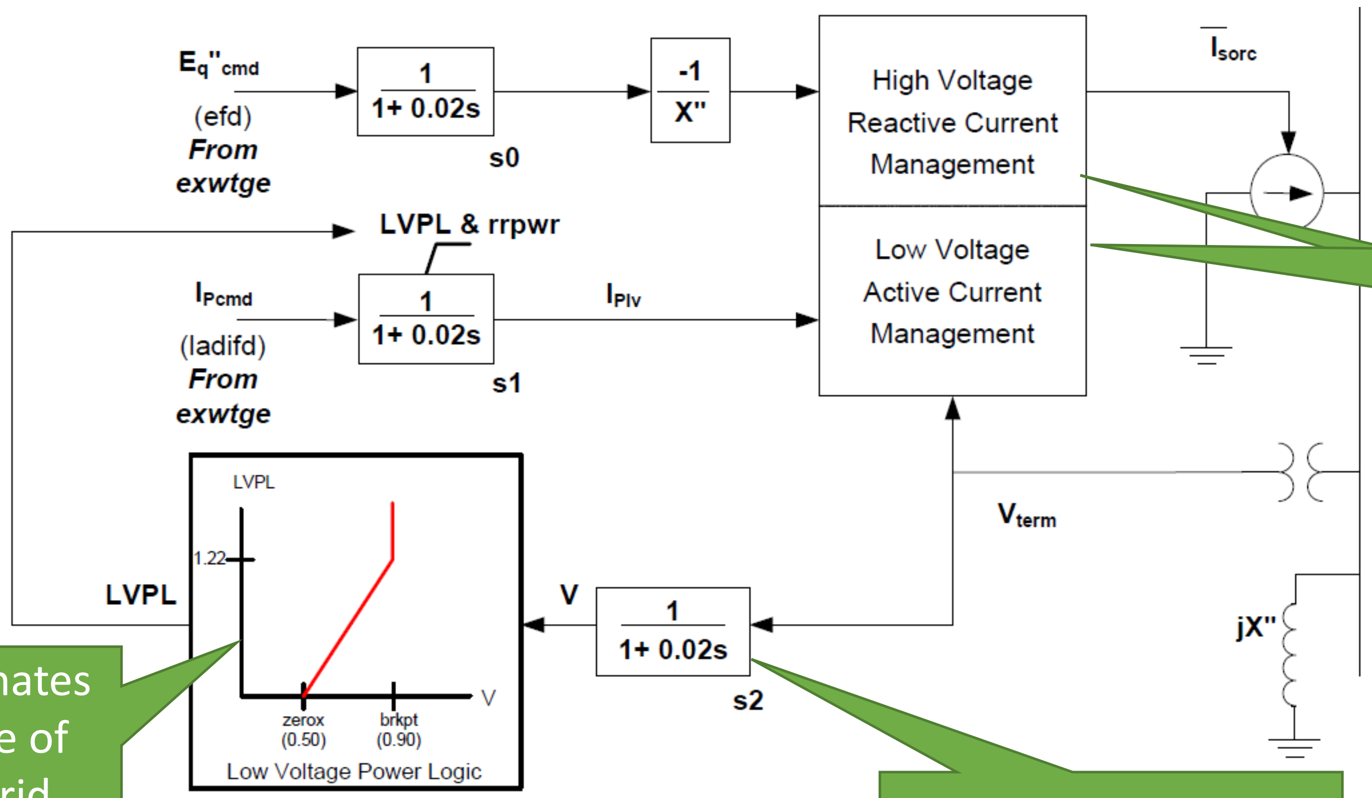


* Dictionary of Nick

Structure of Stability Models



The fast stuff is full of approximations because there are no sinewaves in phasor analysis



Approximates really fast responses, by making them instantaneous

When the grid is too weak, these approximations can result in low fidelity simulation results.

Approximates one type of weak grid adaptation

Approximates PLL

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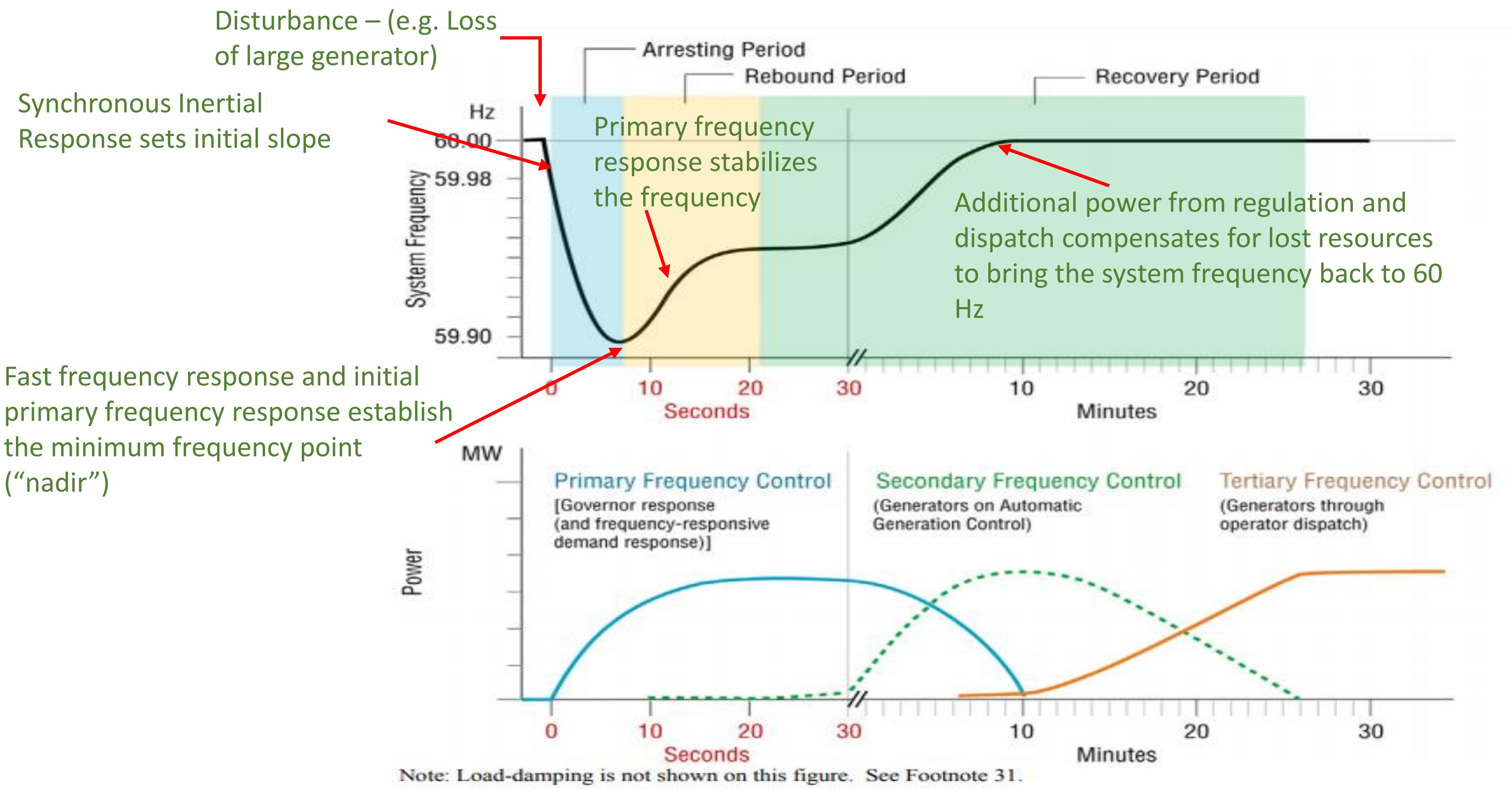
Nick Miller

Source: "Modeling of GE Wind Turbine-Generators for Grid Studies"; Clark, Miller, Sanchez-Gasca

Power and Frequency



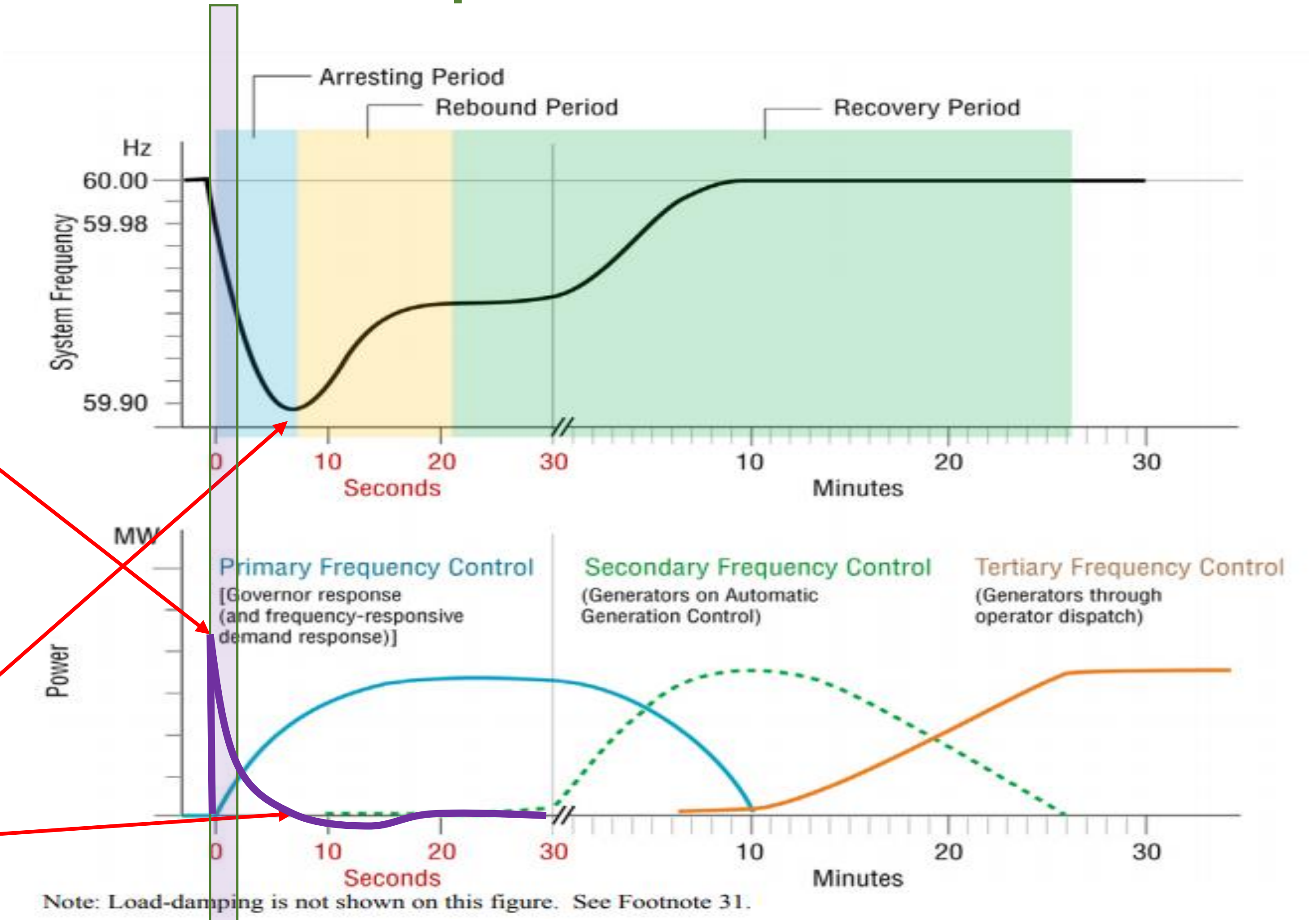
Courtesy J. Eto, J. Undrill, M. O’Malley et al, “Use of Frequency Response Metrics to Assess the Planning and Operating Requirements for Reliable Integration of Variable Renewable Generation”, 2010

Annotations by M. Ahlstrom, Nextera

https://www.ferc.gov/industries/electric/indus-act/reliability/frequencyresponsemetrics-report.pdf

Power and Inertial Response

Synchronous Inertial Response is "instant", uncontrolled, and dominated by accelerating power which is proportional to dω/dt



Inertia response, BY DEFINITION, is zero when speed is steady (dω/dt = 0.)

Courtesy J. Eto, J. Undrill, M. O'Malley et al, "Use of Frequency Response Metrics to Assess the Planning and Operating Requirements for Reliable Integration of Variable Renewable Generation", 2010