GE VERNOVA

OSCILLATIONS IN POWER SYSTEMS

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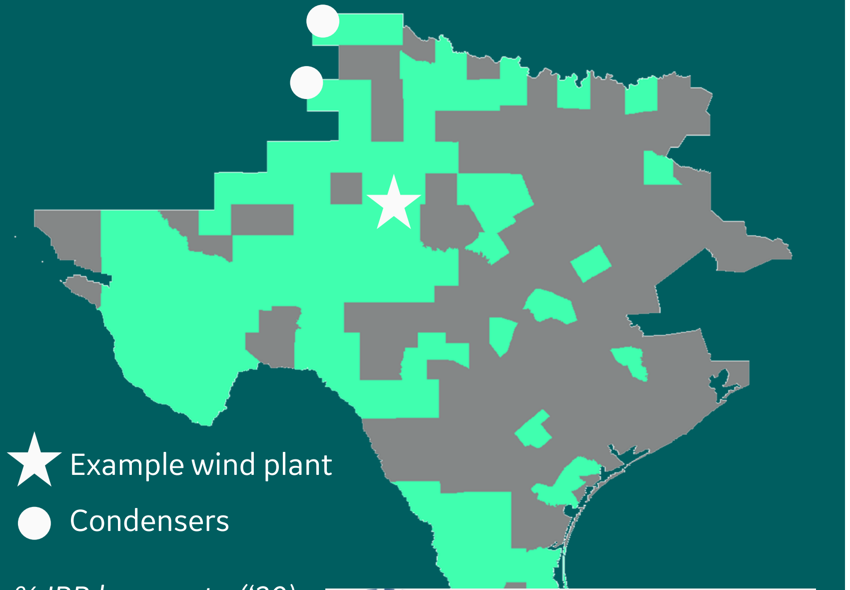
Dynamic voltage stability: Voltage can swing and collapse after a weak grid disturbance

e.g. Onshore wind plant in West Texas

e.g. ERCOT: **LOW %SM IN PANHANDLE WEAKENS VOLTAGE REFERENCE**



★ Example wind plant

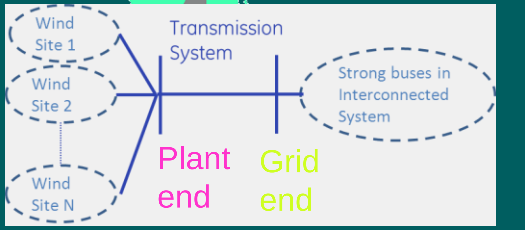
○ Condensers

% IBR by county ('20)

● <30%

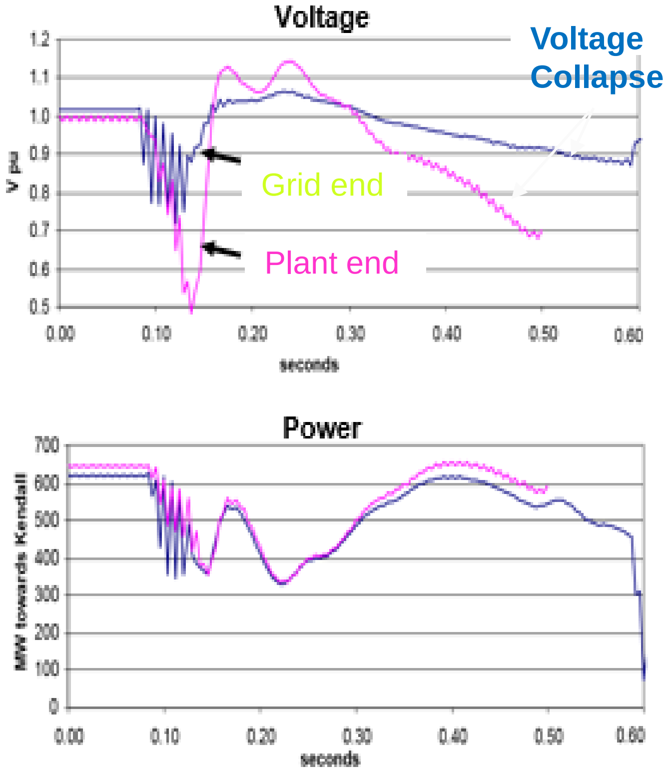
○ 30-60%

🟩 >60%

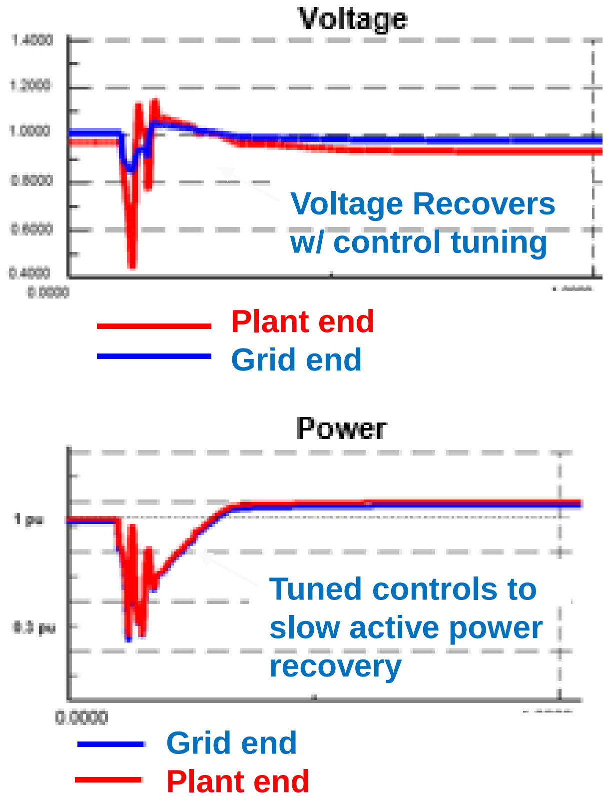


Ref: ABB, ERCOT

Field measurements: Voltage collapse due to weak grid



Simulated mitigation: Tuning controls to avoid voltage collapse



- Extremely weak application cause risk of voltage collapse
- Stable at fault clearing, collapse during power pickup before improvements
- Time frame of collapse is dictated by active power recovery

Topics

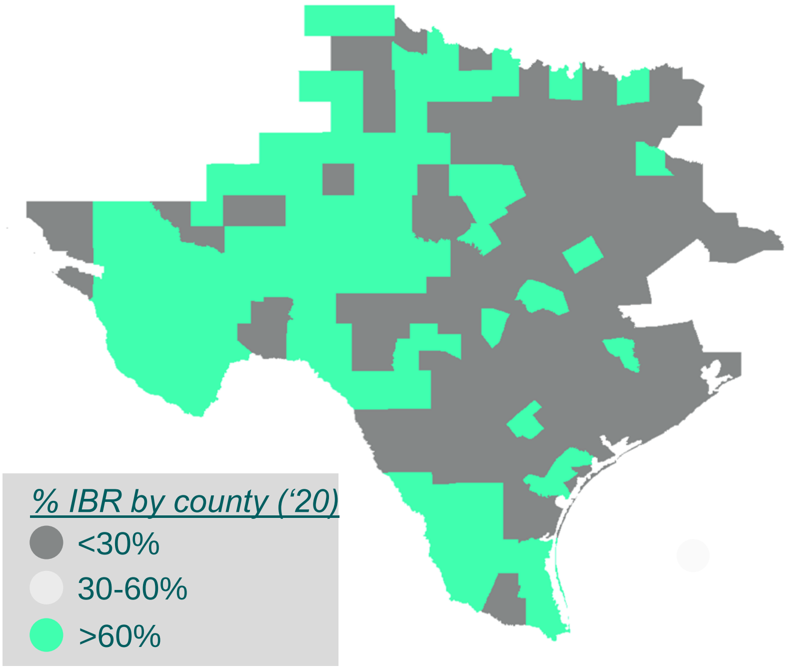
Oscillations due to…

- ✓Instabilities related to weak grids
- ✓Sub-synchronous oscillations
- ✓Control interactions
- ✓Small and large signal instabilities

Weak grid: High IBR / low SM penetrations weaken grid reference voltage

Risks of controls confusion, tripping & blackouts challenge new project interconnection

e.g. ERCOT: LOW %SM IN PANHANDLE WEAKENS VOLTAGE REFERENCE



IBR CONTROLS CHALLENGED IN WEAK GRIDS

Voltage collapse: Grid voltage more sensitive to power flow changes

Unwanted control interactions across multiple plants (e.g. tripping)

Converter control instability with no external influence (e.g. small signal instability)

Converter control mode cycling … introducing severe transients into the system

HOW STRONG IS YOUR GRID?

"Short circuit ratio" SCR
A measure of how much current is injected during a fault to keep voltage stable

TODAY'S MITIGATIONS

1. **Limit new IBR projects** … esp w/ inexperienced grid operators
2. **Tune grid following controls** to avoid unwanted controls confusion.
3. **Synchronous condensers:** New units or fossil units can be retrofitted.

Ref: ABB, ERCOT

Stability Issues in Weak Grids

Failure to ride through disturbances

- ✓ Weak systems make ride-through more difficult, especially following a network disturbance, leading to wider system issues, such as under-frequency or loss of voltage support. Phase-Lock-Loop (PLL) stability.

Converter control interactions

- ✓ The weaker the interconnection, the more likely controls will be to influence each other and interact negatively with each other

Converter control instability

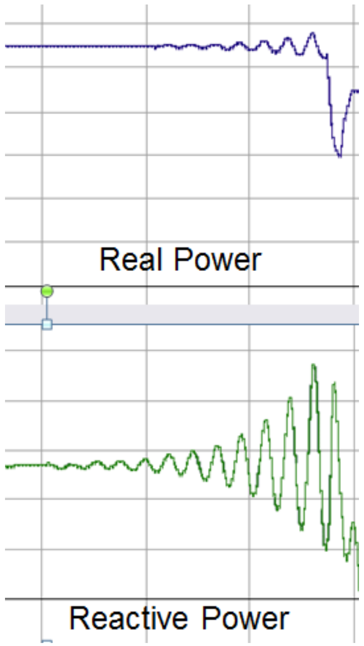
- ✓ If the network is weak enough, controls may enter unstable region with no external influence needed (small signal instability)

Cycling between converter control modes

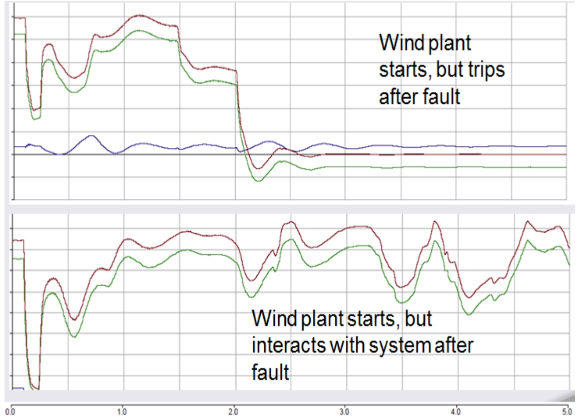
- ✓ If system is weak, various turbine control modes may cycle multiple times as turbine attempts recovery, introducing severe transients into the system

Steady-State Voltage Collapse

- ✓ Voltage collapses more sensitively as real & reactive power flows through weak grid (non-source dependent)

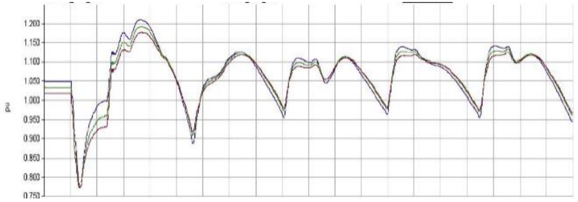


Failure to ride through

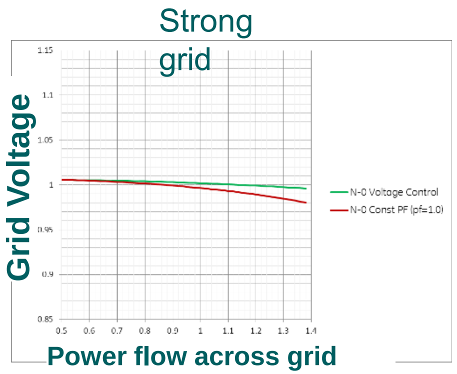


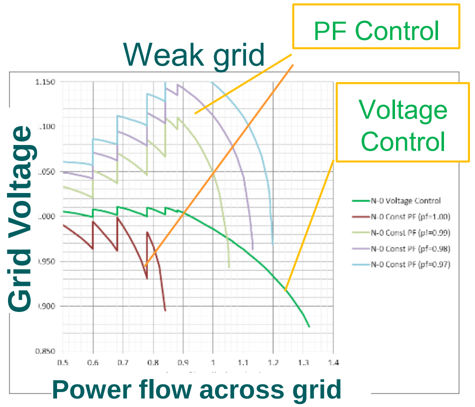
Control Interactions

Control mode cycling



Voltage transients caused by cycling





Controls stability: IBRs have multiple control layers & control modes that depend on voltage reference … weak reference → interaction

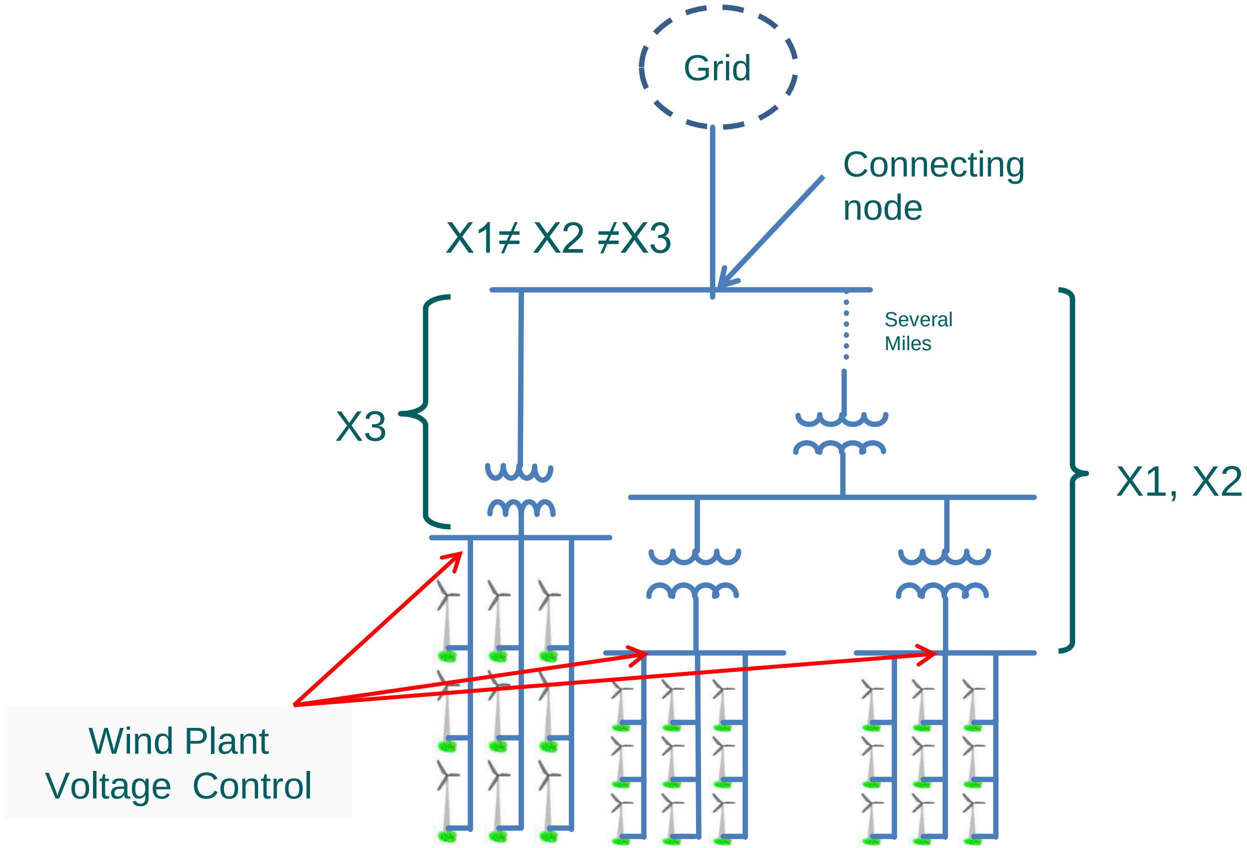
	RESPONSE TIME	POWER FLOW	DYNAMICS	TRANSIENTS
LAYERS OF WIND PLANT CONTROL				
1. Turbine level	1-10 sec	Only models a static output vs. a change in output	✓	✓
2. Converter level Inner loop	200 ms		Simplified	✓
Outer loop	1 sec		✓	✓
3. Plant level	10-20 sec		✓	✓
4. Plant to plant level	10-20 sec		✓	✓
CONTROL MODES OF OPERATION				
1. Turbine level 1) Normal 2) Ride-thru torque control 3) Ride-thru energy management	10s – 100s ms	Only models a static output vs a change in output		✓
2. Converter level 1) Normal 2) Under/over freq ride-thru 3) Under/over voltage ride-thru 4) SSCI damping	10 – 100s ms			✓

Different modes ensure turbine safety

Different modes provide grid reliability services

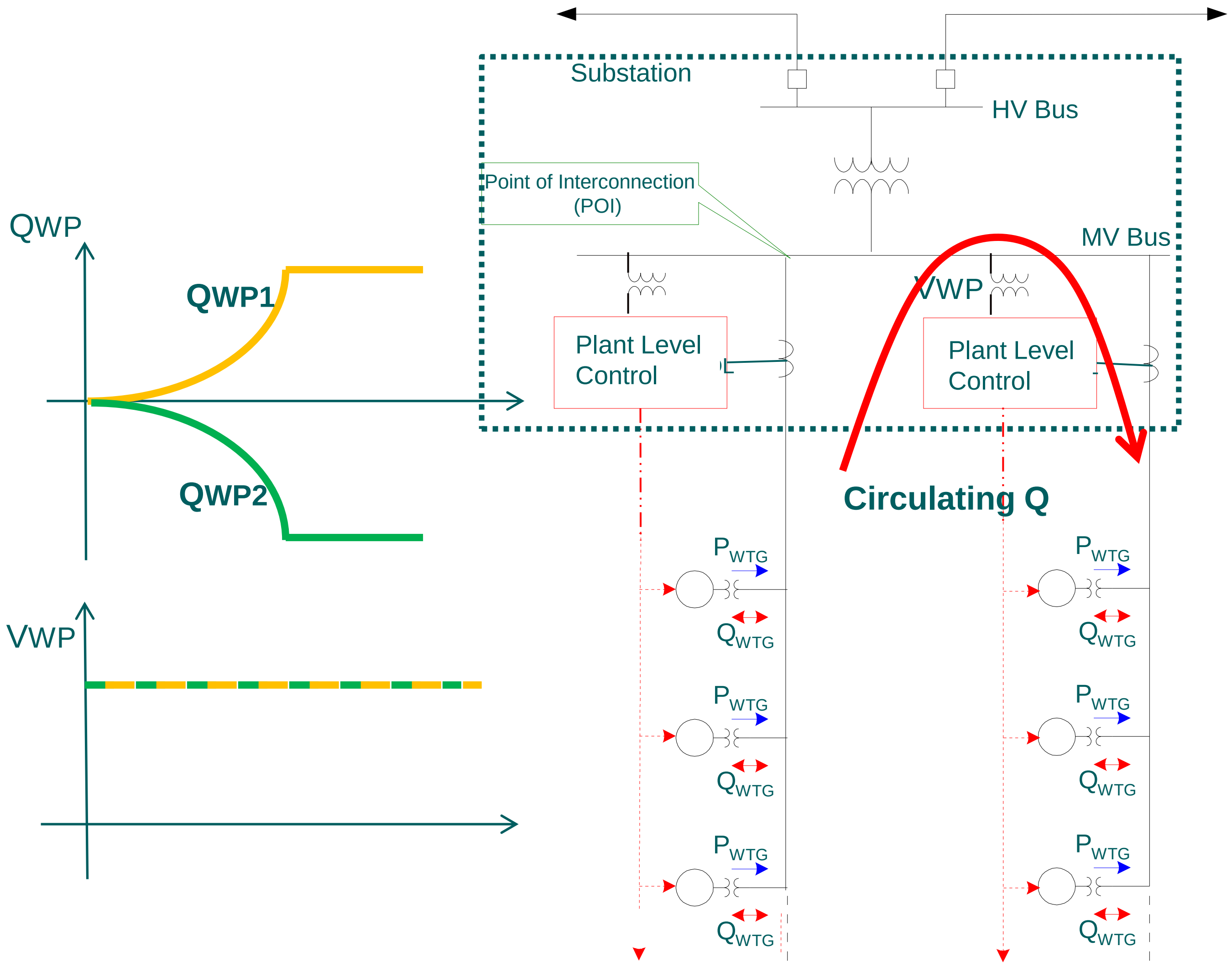
- Turbines and converters switch control modes based on grid voltage and frequency
- In weak grids, large voltage fluctuations may lead to confusion across plants, control layers and/or control modes

Multi-Plant Voltage Control Coordination



Plant Level Control Interactions

Mandatory in Bonneville
Use droop to fix



Plant Level Control Interactions Solution: Voltage Droop

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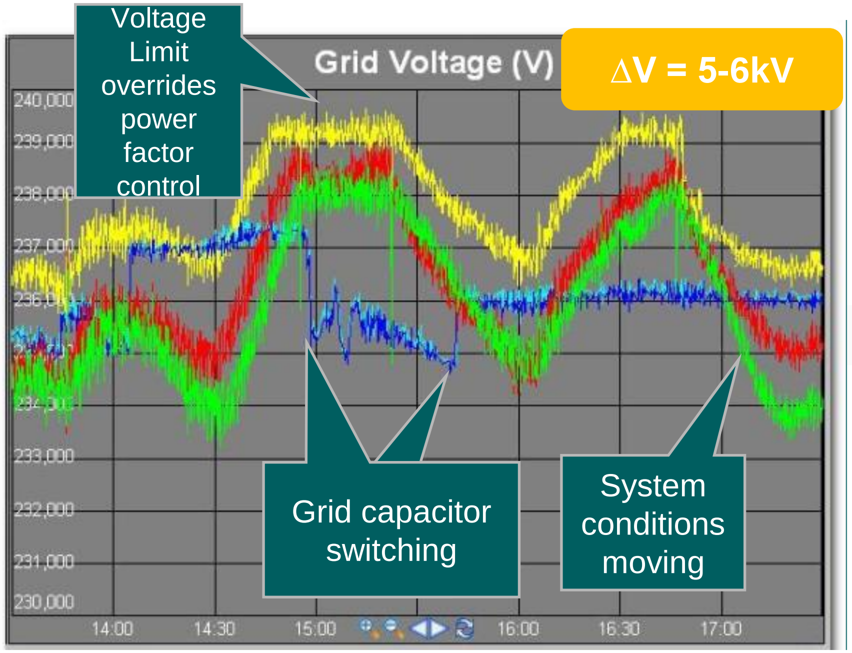
PF Control



ΔV = 5-6kV

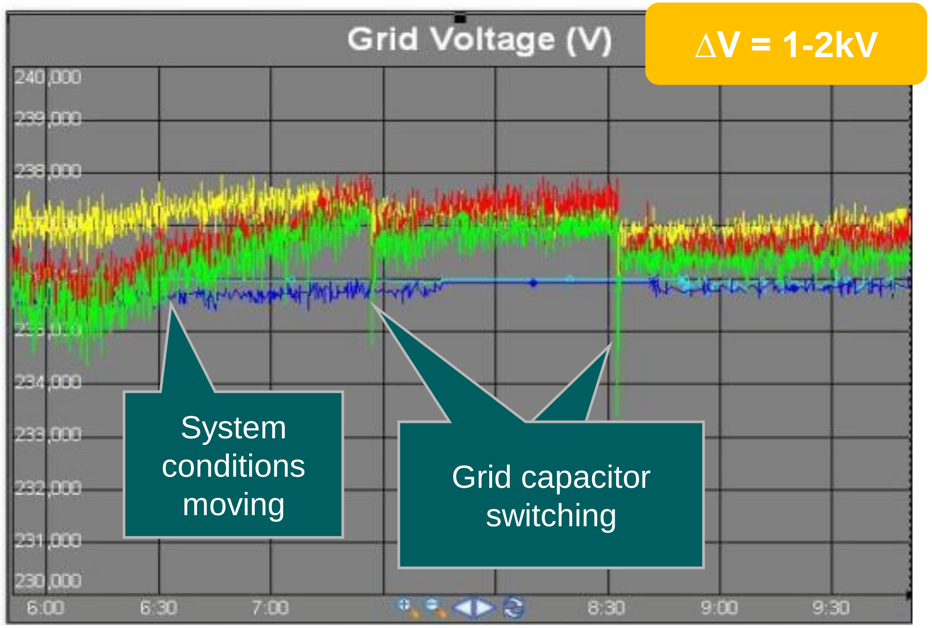
Voltage Limit overrides power factor control

Grid capacitor switching

System conditions moving

3 hours

Voltage Control with Droop



ΔV = 1-2kV

System conditions moving

Grid capacitor switching

3 hours

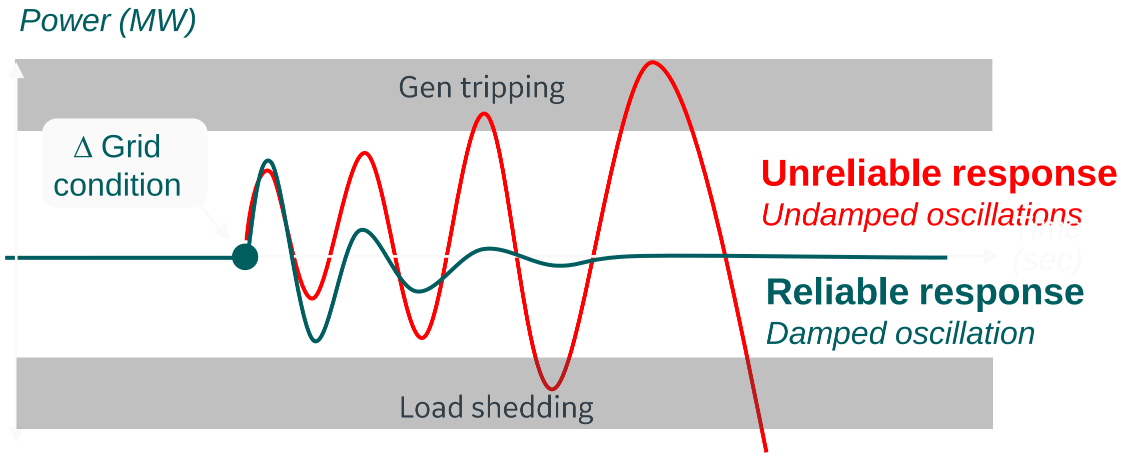
Voltage Droop mitigates plant control interactions and improves voltage regulation quality

Source: Miller, etal ; "Coordinated Voltage Control for Multiple Wind Plants in Eastern Wyoming: Analysis and Field Experience", IEEE PEMWA Denver July 2012

Small signal stability: Change in grid condition can trigger power oscillations

Grid operators often overlook this risk …. can result in equipment damage if undetected

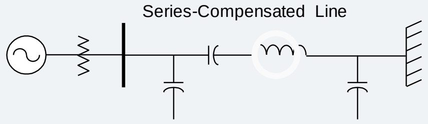
Power oscillations grow in undamped systems



Unreliable response
Undamped oscillations

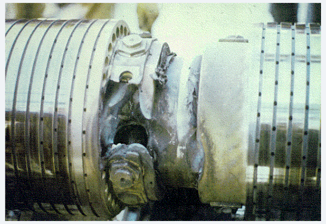
Reliable response
Damped oscillation

Ex: Sub-synchronous resonance (SSR) can break shafts



Undamped oscillations

Western US: Long radial lines use series compensation to lower reactive losses



Mohave 1971: SSR breaks 1st GE generator shaft

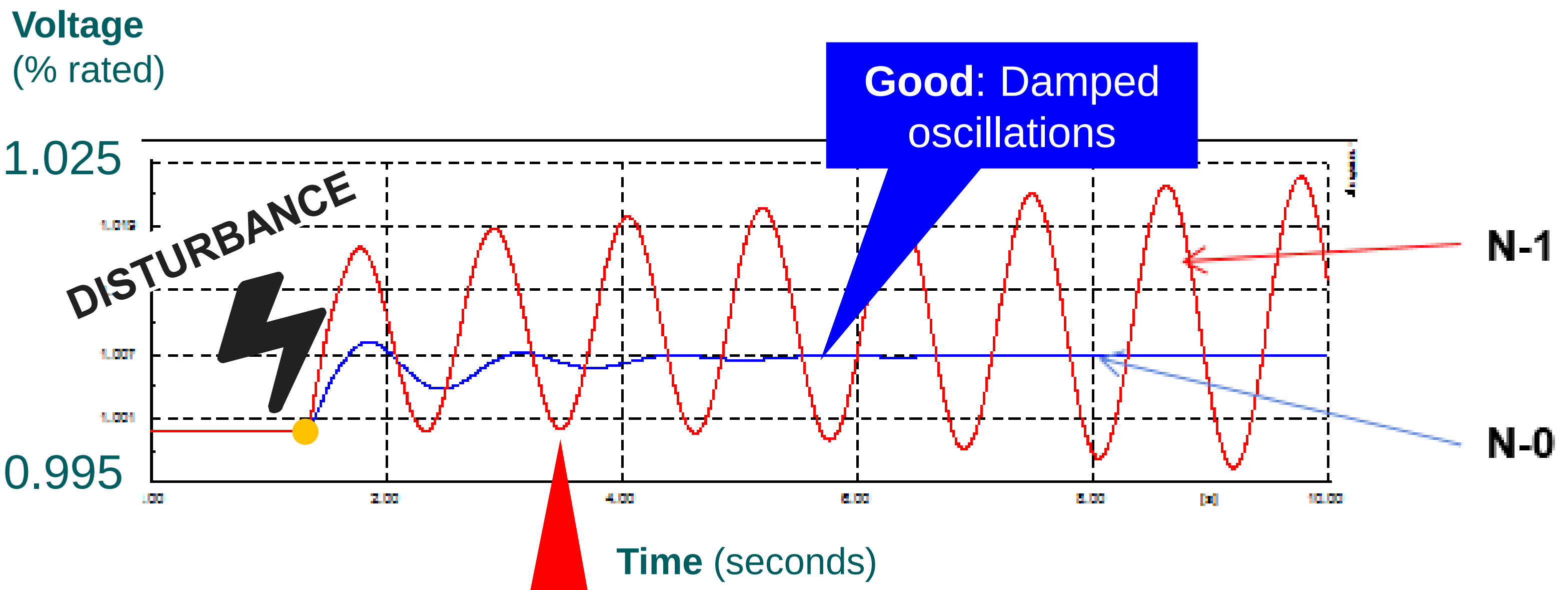
New IBRs can trigger power oscillations …

IN GRIDS WITH …	RESULT	AFFECTS	FREQUENCY
IBRs w/high AC cable shunt capacitance	Shunt resonance	IBRs	~180 - 600Hz
IBRs & HVDC (unit and plant level)	Controls interaction (e.g. due to SSO, weak grids, poorly tuned controls)	IBRs, SMs	~10 - 40 Hz ~ 0.1 - 1 Hz
Series capacitors	Sub-synchronous resonance (SSR)	Synchronous machines (SM)	~ 10 - 40 Hz
High speed exciters	Local mode power oscillation	SMs	~ 3 Hz
Fast exciters/fast governor response	Inter-area power oscillation	SMs, IBRs	~1 Hz

Fast

Slow

Texas example: Voltage may be N-0 stable but not N-1



Good: Damped oscillations

Bad: Growing oscillations

Possible upgrades:

- Control tuning
- Synchronous condensers
- Line reinforcements
- FACTS devices

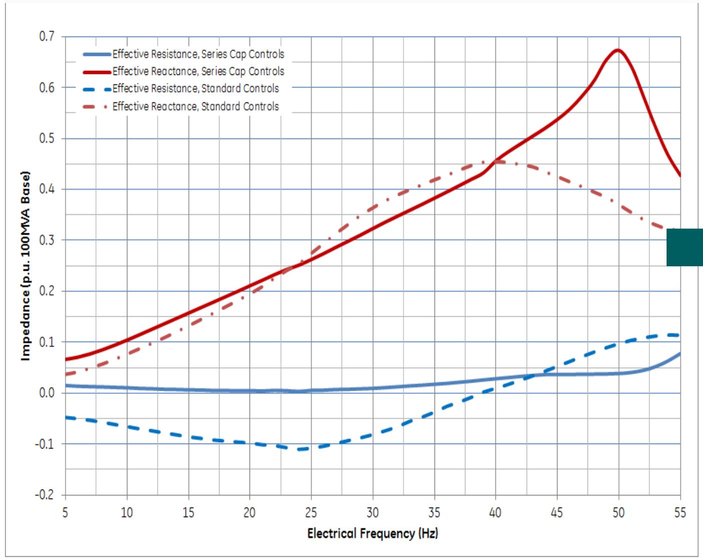
Cheapest mitigation

DISTURBANCE @t = 1s

- Interaction between wind plant control layers may create **unwanted voltage oscillations**
- **N-0 grid may be strong enough** to damp out oscillations
- **N-1 grid may not be strong enough** and oscillations may grow and lead to unit tripping/ blackouts

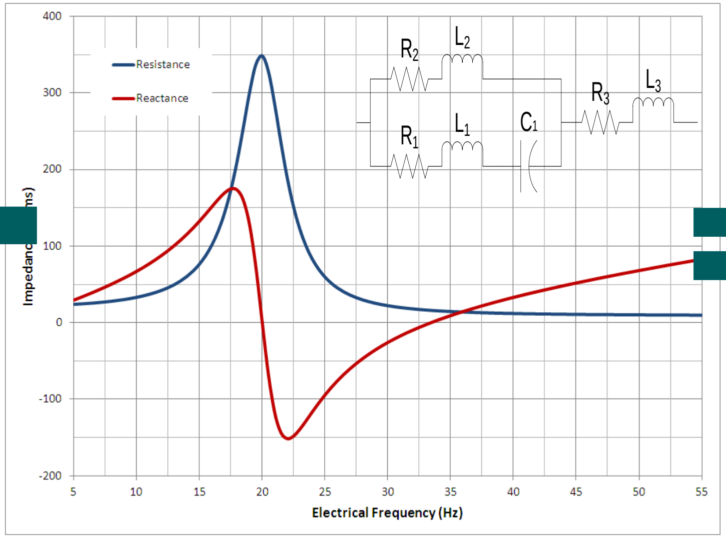
Frequency scan to screen for small signal stability risks

WIND PLANT SCAN



SYSTEM SCAN

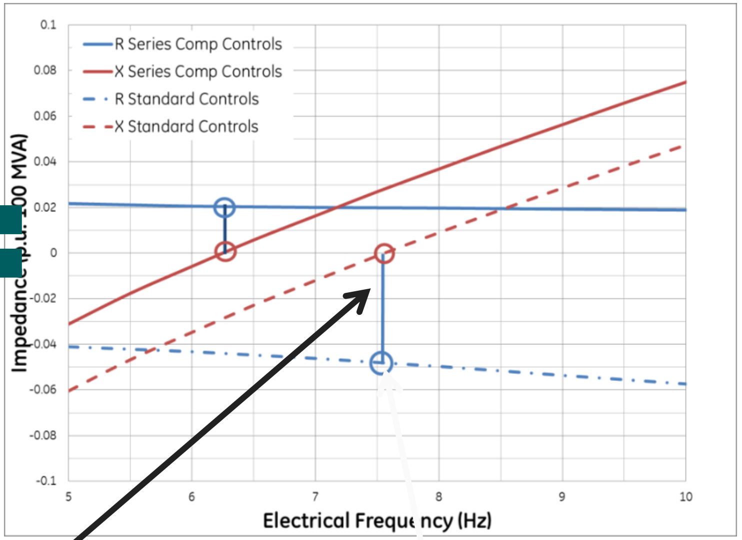
(WIND PLANT DISCONNECTED)



- - - - - - - *Standard controls*

——— *Tuned controls for small signal risk*

COMBINED SCAN



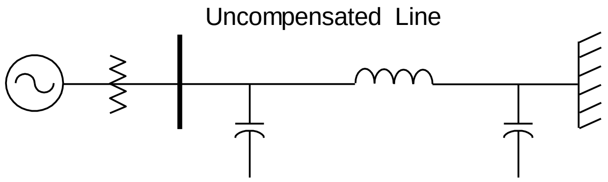
Negative resistance → **Potential Instability**
Look for rising crossover of reactance at negative resistance

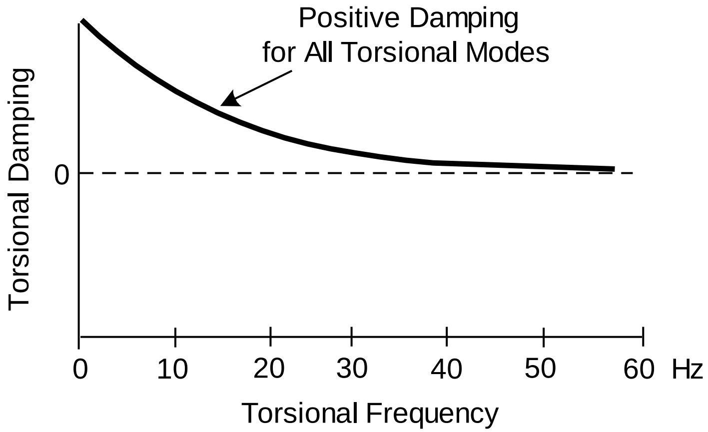
Positive damping & Stable oscillation
✓ Tuned IBR controls
✓ Positive resistance

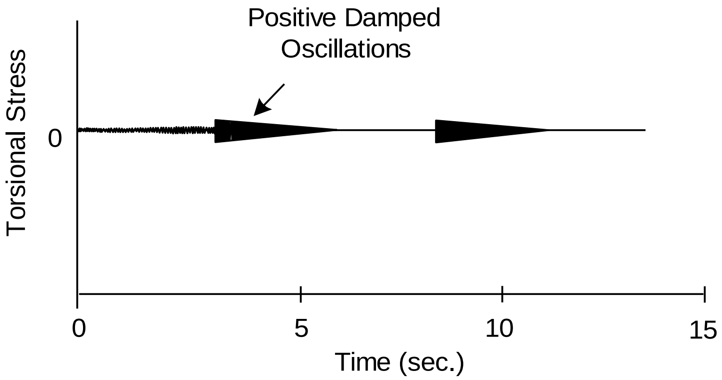
Frequency scan steps:

1. **Determine equivalent impedances** for wind plant & grid
2. **Generate plot of total reactance and total resistance** as a function of frequency.
3. **Generate combined frequency scan** by adding the effective resistance & reactance for the wind plant + system
4. **Screen for frequencies with negative resistance.** For combined frequency scan plot, frequencies at which the resistance is negative and reactance is rising correspond to unstable oscillations.

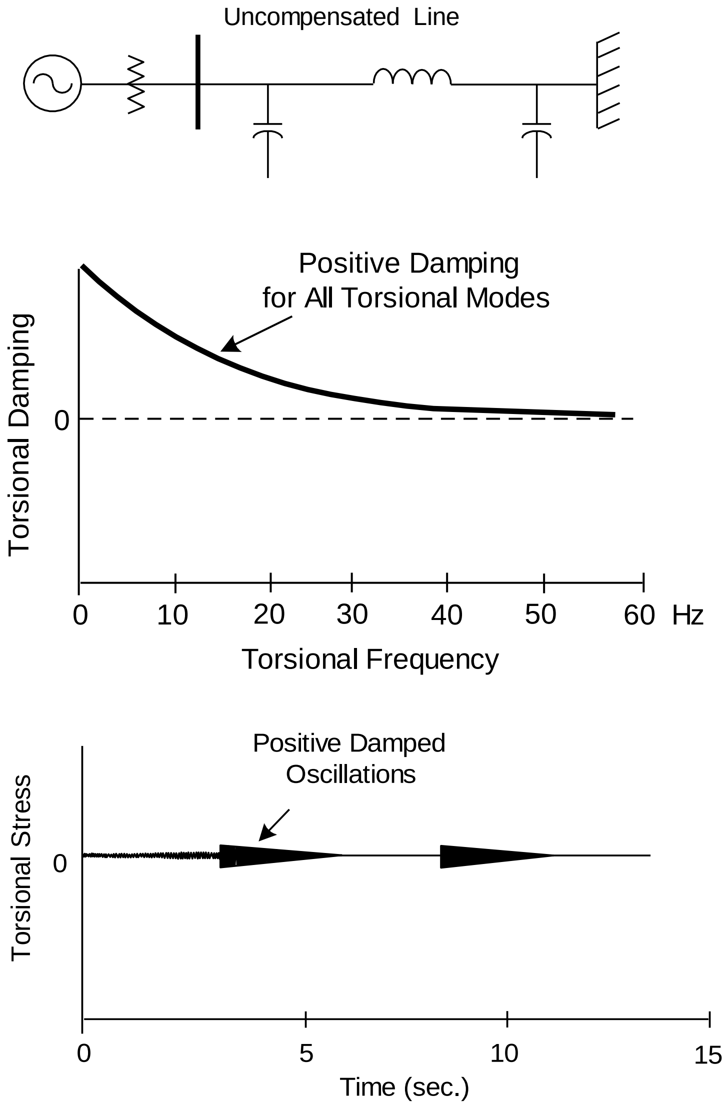
Impact of Series Capacitors on Torsional Stress

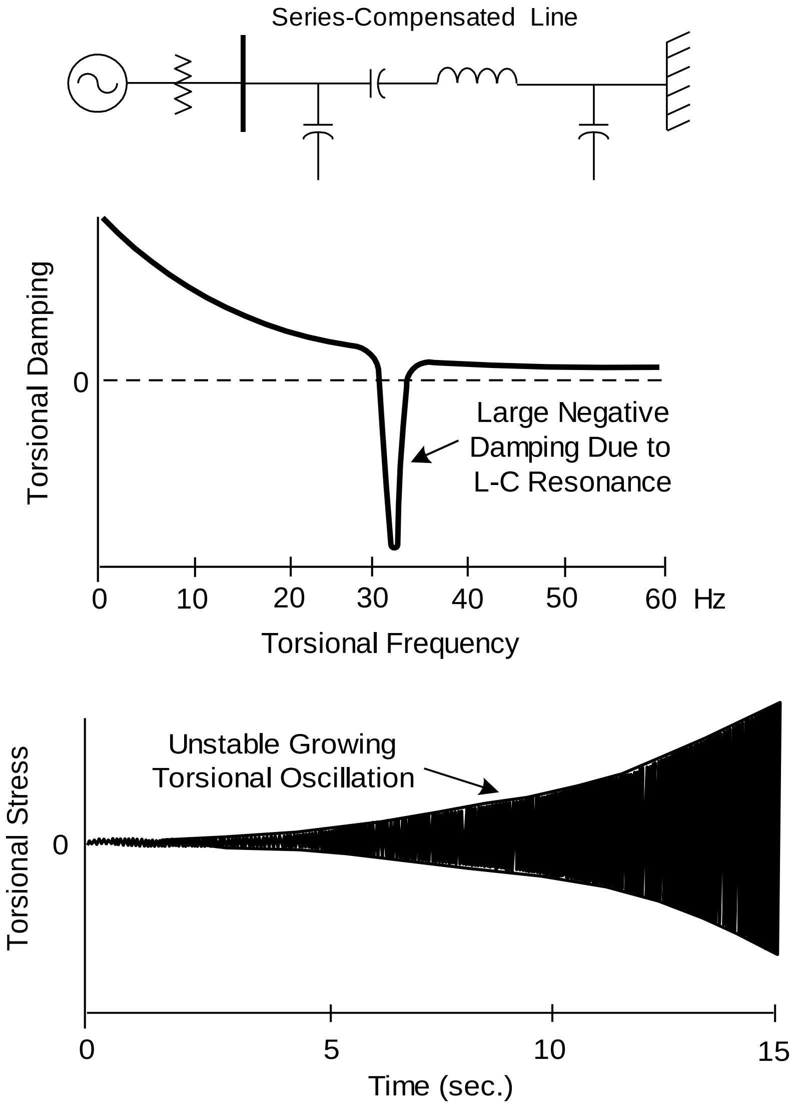




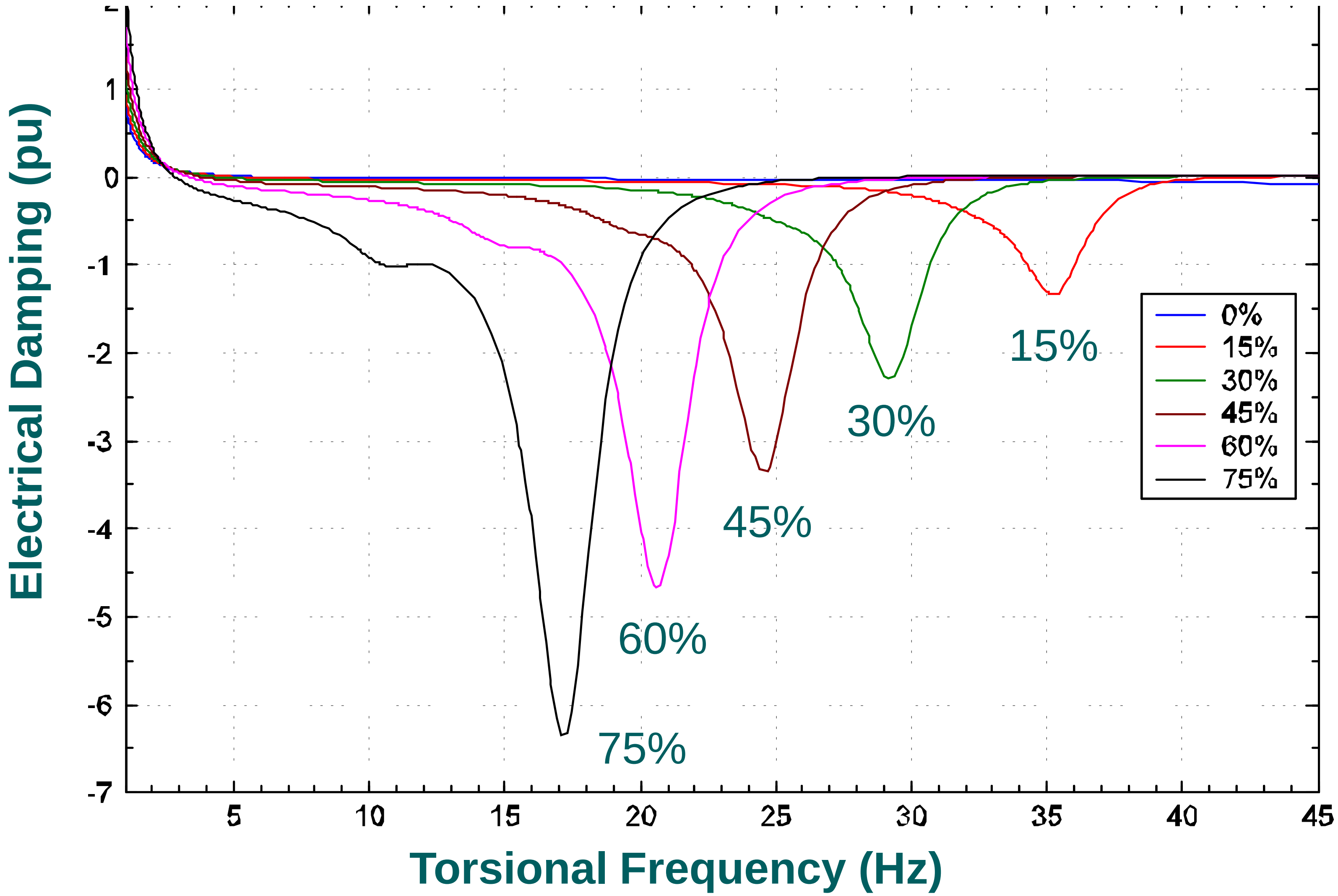


Impact of Series Capacitors on Torsional Stress



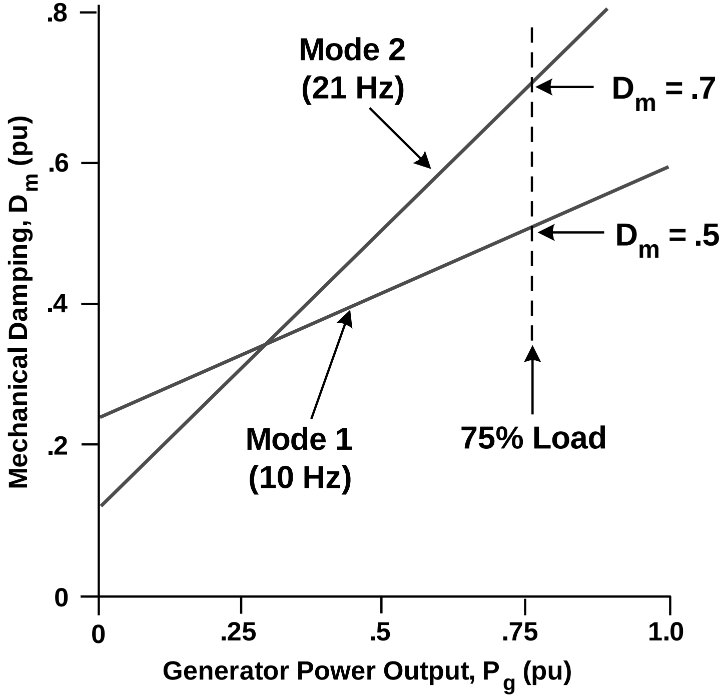


SSR Increases With % Compensation

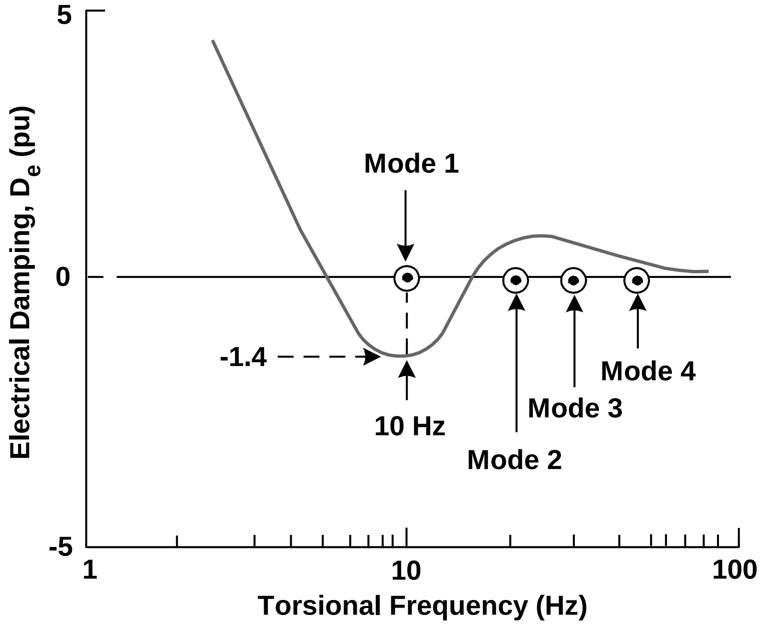


Torsional Damping

Mechanical Damping, D_m



Electrical Damping, D_e



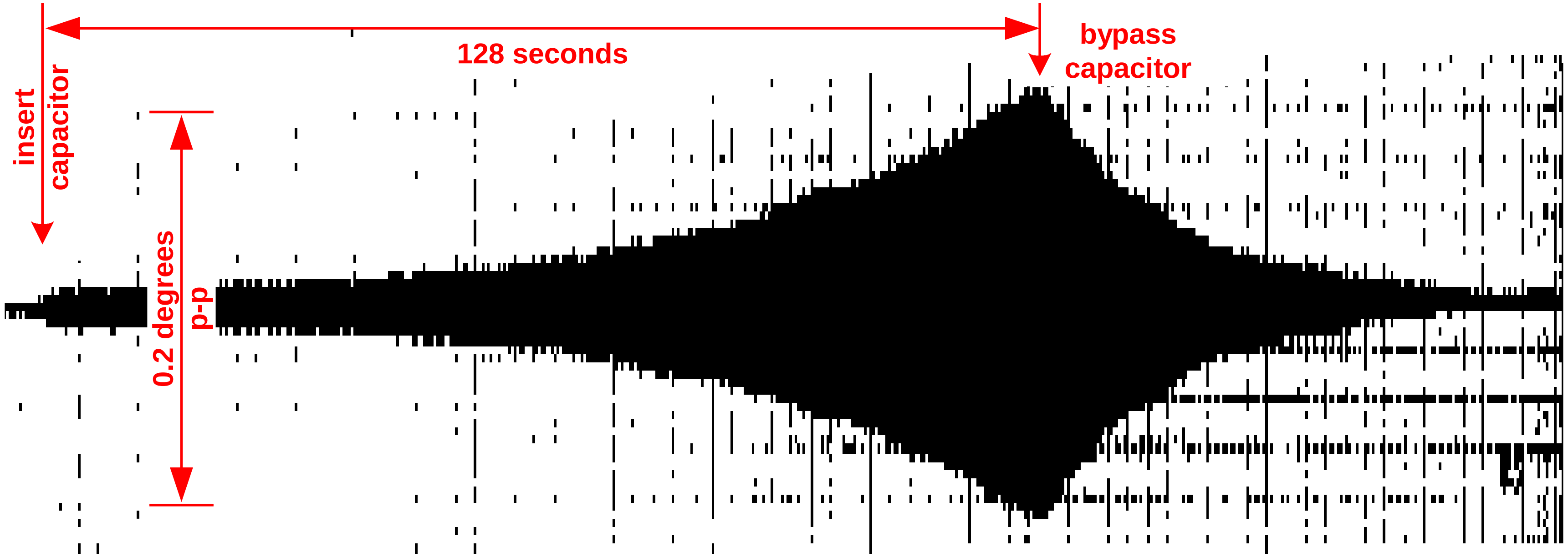
Example:

For 10 Hz Mode with $P_g = .75$ pu, $D_m = 0.5$ and $D_e = -1.4$

$D_{Total} = D_m + D_e = 0.5 - 1.4 = -0.9$ ***Unstable***

SSR Stability

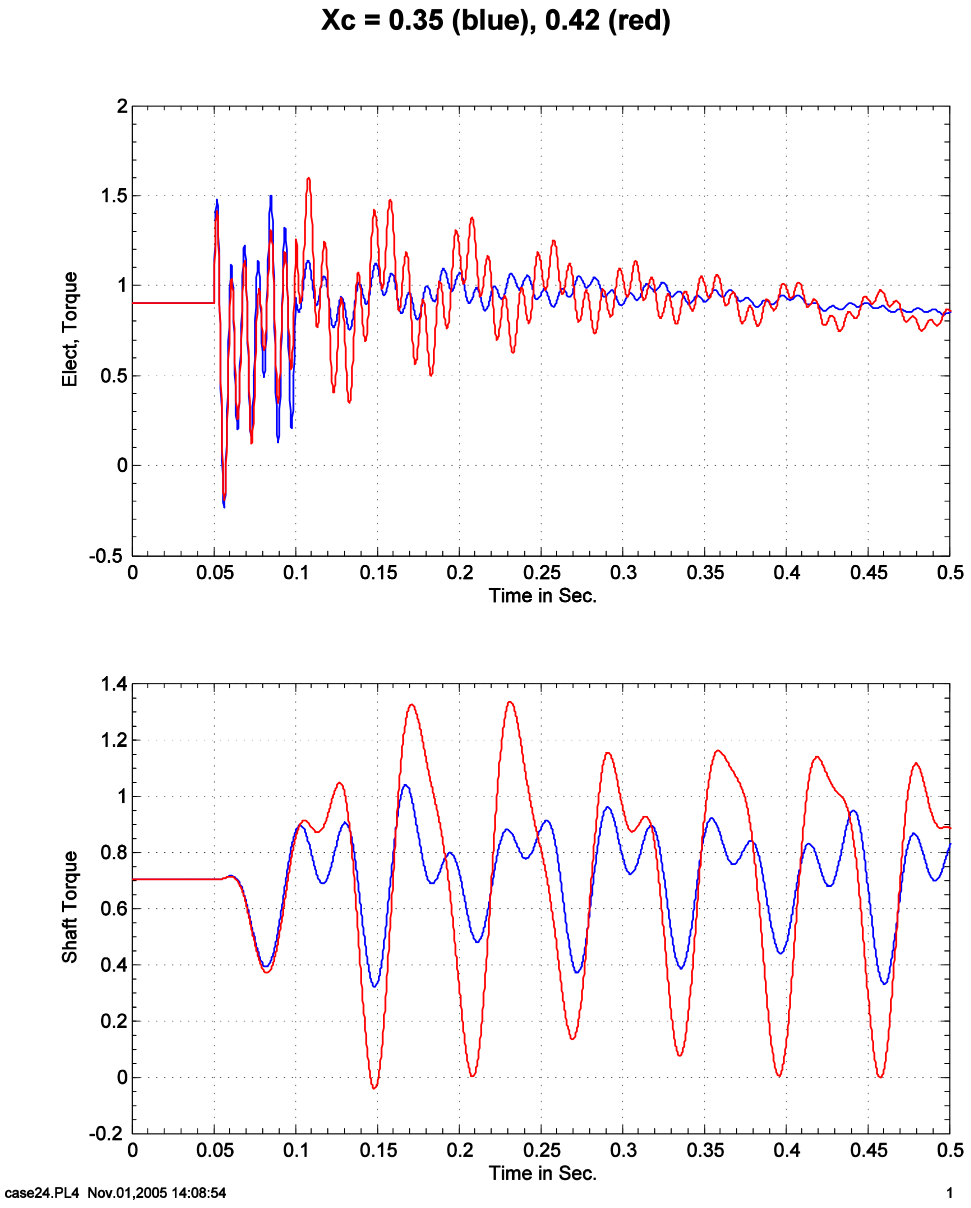
Slow growing torsional oscillations over several seconds to minutes can eventually lead to shaft failure



Measured SSR Instability: series capacitor inserted and bypassed after 128 seconds.

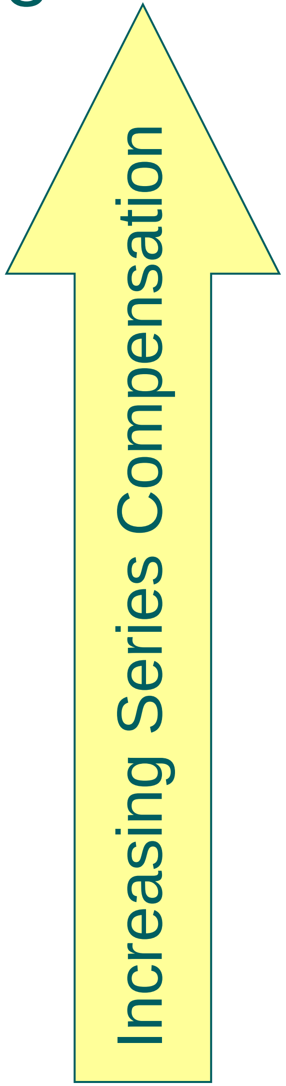
Plot shows torsional angle displacement at the turbine end of shaft.

Transient Torque Amplification



- ✓ Series capacitors can amplify shaft torques during transient
- ✓ Only when torsional and electrical resonance align
- ✓ Large transient torques cause high fatigue damage, even is system is torsionally stable
- ✓ High fatigue damage can occur in first few torsional cycles

SSR Mitigation Hierarchy



SSR Blocking Filters

Passive SSR Bypass Filter on Series Capacitor Bank

SVC-type SSR Damper at Generator Location*

Properly Tuned Thyristor-Controlled Series Capacitors in Transmission line*

Supplementary Excitation Damping Control (SEDC) at Generator Location*

Topology/Power-Based Switching Schemes

Avoid SSR with Low Level of Series Compensation

*** Highly dependent on control design and grid configuration/topology**

SSR Mitigation Hierarchy

Avoid SSR with Low Level of Series Compensation

- Torsional relays to protect turbine-generators for contingencies

Topology/Power-Based Switching Schemes

- Bypass bank for critical contingency, or
- Bypass banks when units are lightly loaded, or
- Bypass a segment of a bank

Supplementary Excitation Damping Control (SEDC)*

- Applied to Generation Unit acting through excitation controller
- Increases torsional damping
- Limited by field time constant and exciter ceiling voltage
- Saturates during large transient events
- Effectiveness depends on control design, excitation type (e.g. static vs. brushless) and grid configuration/topology

*** Highly dependent on control design and grid configuration/topology**

SSR Mitigation Hierarchy, continued

SVC type SSR Damper*

- Control of thyristor gating reduces destabilization and adds damping ***IF PROPERLY TUNED FOR EVERY GRID CONFIGURATION***
- Performance is very sensitive to control design and grid configuration
- Must be retuned if grid configuration or topology changes
- Does not mitigate transient torque amplification
- VERY CHALLENGING: Improper tuning may destabilize torsional interaction locally

Thyristor-Controlled Series Capacitors*

- Control of thyristor gating reduces destabilization and adds damping ***IF PROPERLY TUNED FOR EVERY GRID CONFIGURATION***
- Performance is very sensitive to control design and grid configuration
- Must be retuned if grid configuration or topology changes
- Does not mitigate transient torque amplification
- ***VERY CHALLENGING:*** Improper tuning may destabilize torsional interaction and can have a substantial grid-wide impact

*** Highly dependent on control design and grid configuration/topology**

SSR Mitigation Hierarchy, continued

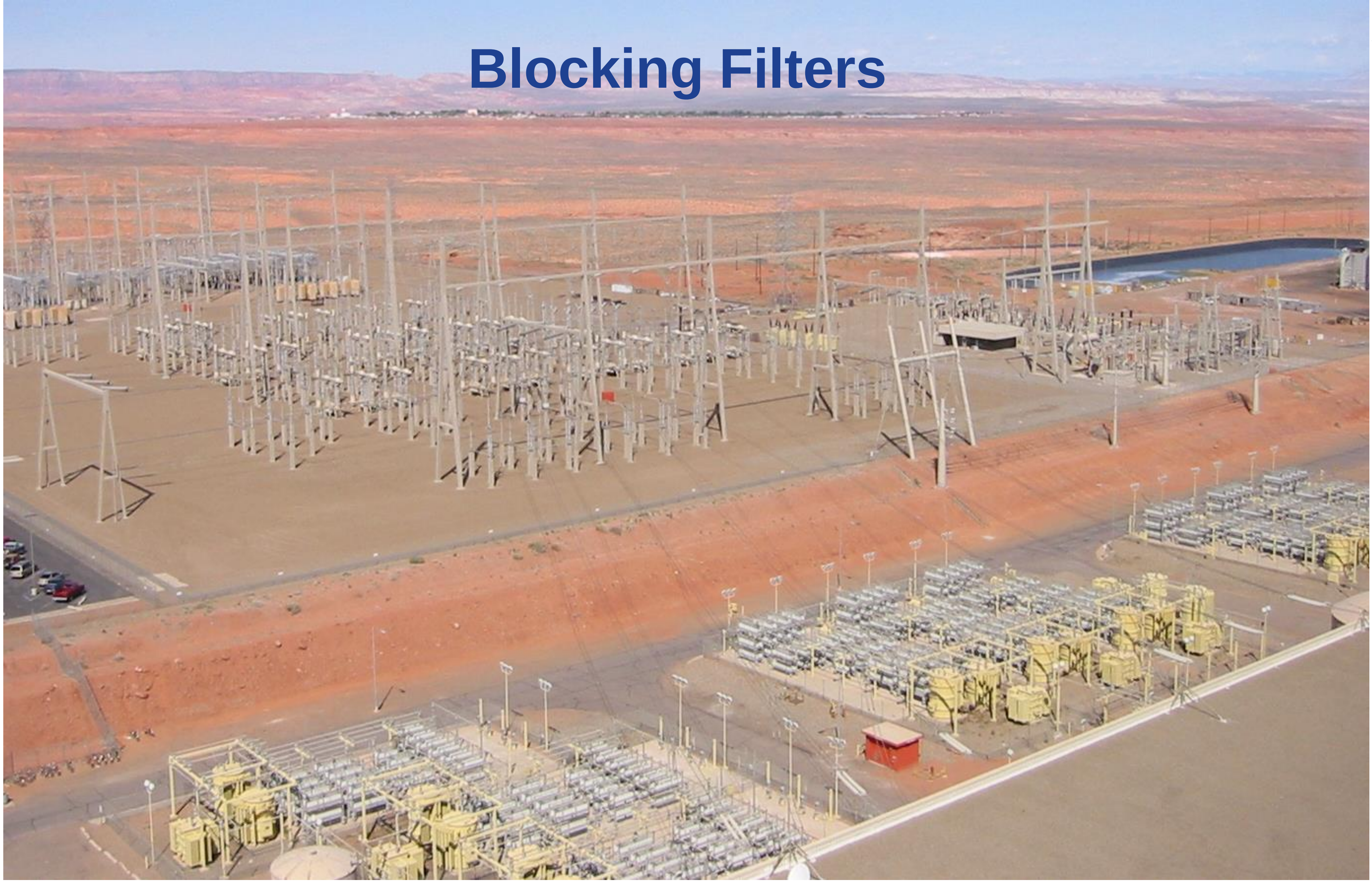
Passive SSR Bypass Filter on Series Capacitor Bank

- Detunes and damps resonance at subsynchronous frequencies
- Can eliminate both SSR stability and transient torque in some situations

Passive SSR Blocking Filters

- Located at generating station, in series with generator transformer
- Tuned to block current at complement of torsional frequencies of generating unit
  - One filter stage per torsional mode (severe SSR interactions require larger filters)
- Can mitigate both SSR stability and transient torque amplification
- Mitigation for a wide range of generation and transmission conditions
- Most effective method to mitigate torsional interaction with the grid at each plant

Blocking Filters



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