Novel Mitigation and Monitoring of SSR Oscillations

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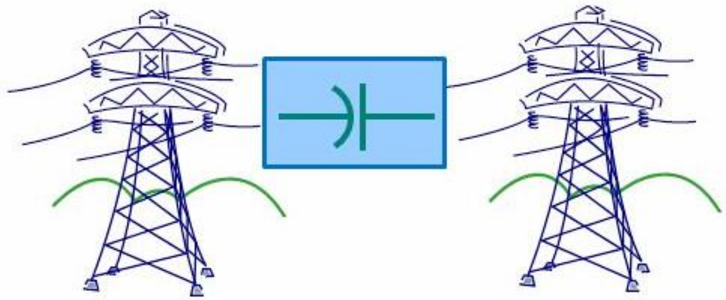
Outline

- Background
- Impact of Dynamic Loads on SSR
- Using Dynamic Loads to damp SSR
- What’ s Next?
- Conclusions



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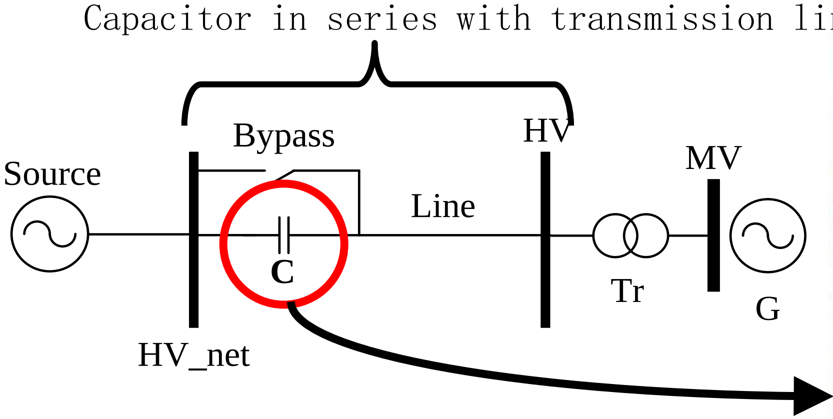
A Brief Background to My Research

Fixed Series Compensation

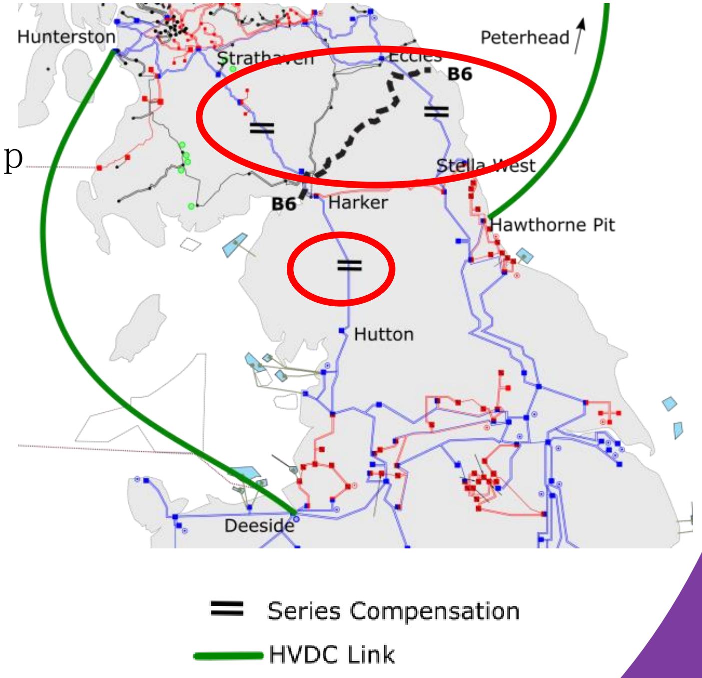
- ✓ Higher power transfers,
- ✓ Enhanced transient stability limits,
- ✓ Improved angular stability (reduced angular separation across corridors), and
- ✓ Self-regulatory and instantaneous VAr support (steady state & dynamic voltage stabi



Fixed Series Compensation

- **Facilitate increased power transfer at a lower cost**

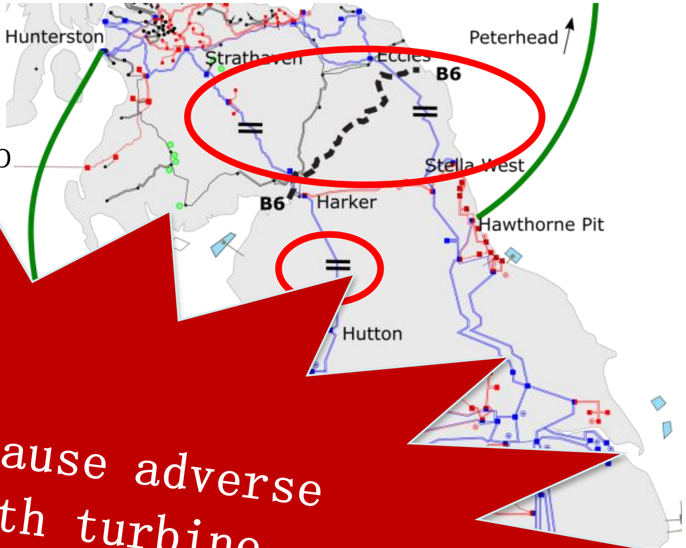
- **Great Britain** increased flow of renewable generation from Scotland to England (B6) to help meet goal of 15% renewable energy by 2020:
  - Series capacitor banks have been installed at the Eccles, Moffat and Gretna substations (Scottish Power, 2015)
  - TCSC at the Hutton 400kV substation, near Kendal in Cumbria. Enhanced power transfer capacity by around 1 GW (National Grid, 2014)
  - Also installing HVDC in parallel to the AC network.
    (National Grid, 2018)



Fixed Series Compensation

- Facilitate increased power transfer at a lower cost

- **Great Britain** increased flow of renewable generation from Scotland to England (B6) to help meet goal of 15% renewable en… by …20:
  - Series capacitor ban… have … the Eccles, Mo… and … (Scottish Power, …
  - TCSC at the … Kendal in C… capacity by a…
  - Also ins… network. (National G…



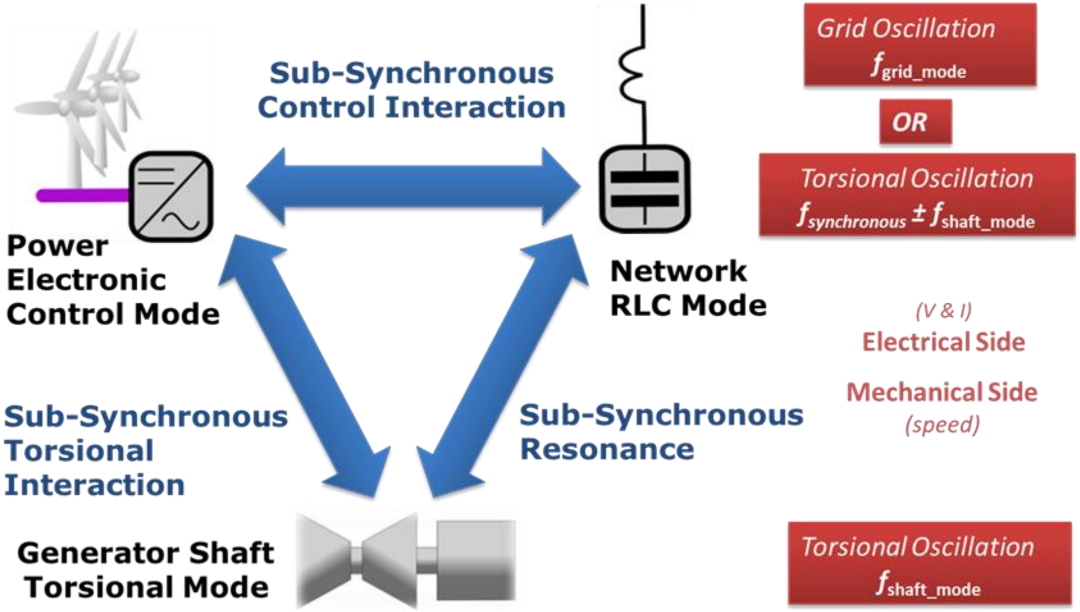
FSC is known to cause adverse interactions with turbine generators resulting in the phenomenon of Subsynchronous Resonance (SSR)

Subsynchronous Interactions: A Definition

SSR is defined by IEEE as "the electrical power system condition where the electric network exchanges energy with a turbine generator at one or more of the natural frequencies of the combined system below the synchronous frequency of the system"

[Source: IEEE SSR Working Group, "Proposed Terms and Definitions for Subsynchronous Resonance", IEEE Symposium on Countermeasures for Subsynchronous Resonance, IEEE Pub. 81TH0086-9-PWR, 1981, p 92-97]

Shaft failure at Mohave (1970)



SSR: The Physics

- Natural frequencies occurring due to series capacitor compensation are below the nominal frequency of the network applied voltages

$$i(t) = K[A\sin(w_1 t + \psi_1) + Be^{-\varsigma w_2 t}\sin(w_2 t + \psi_2)]$$

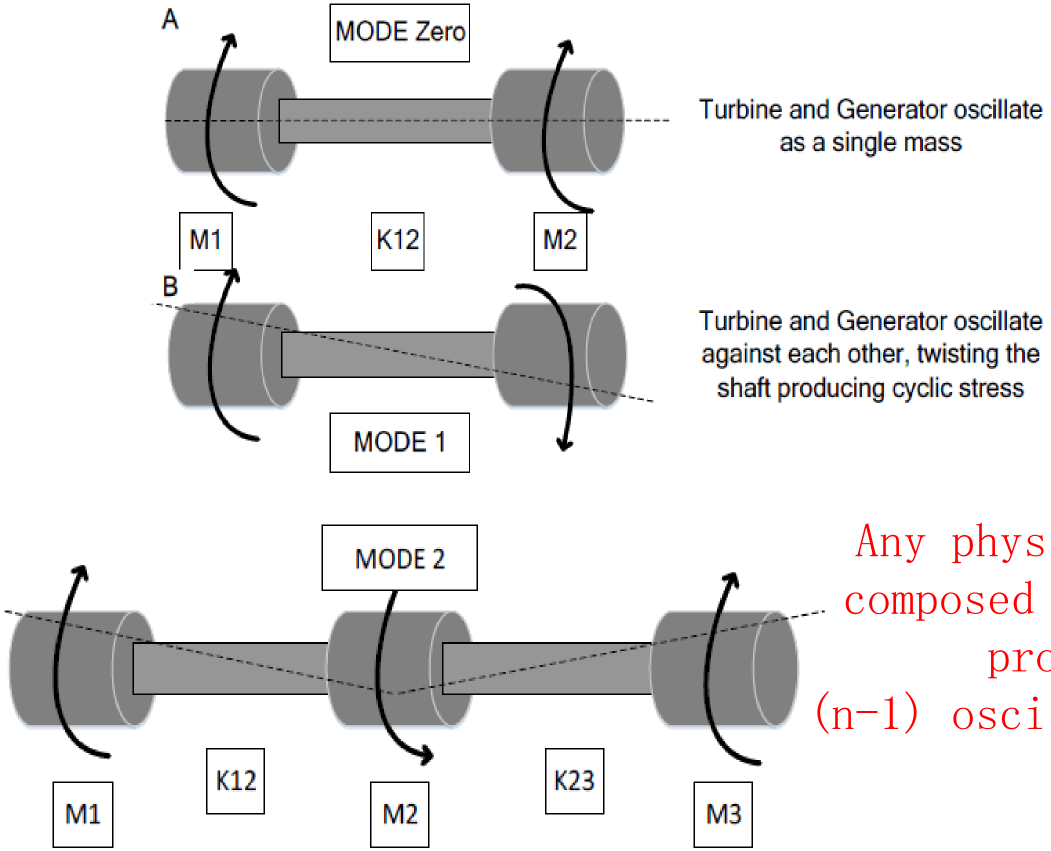
  - w1 at the frequency of the driving voltage
  - w2 is dependant on the network parameters

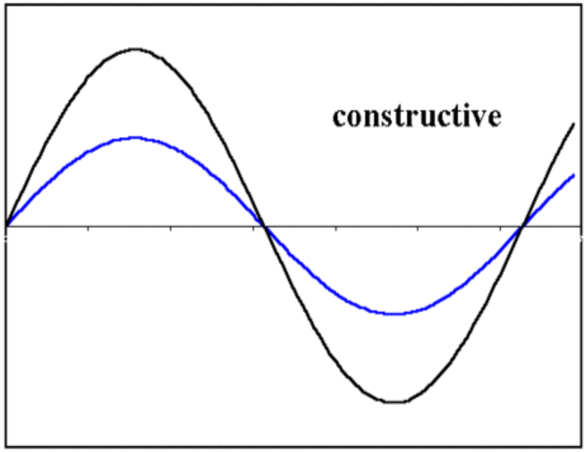
- Currents of frequency w2 are reflected onto the rotor as
  - Sum, (w1+ w2) and difference (w1- w2) components

- Difference or subsynchronous component of current induces subsynchronous frequency shaft torque
  - Torque oscillations mean torsional stress and fatigue

Generator rotor as multi-mass

Mode zero represents the condition where the masses all move in phase and the entire shaft system behaves as a solid mass (Classical generator rotor model) with a common mode of oscillation

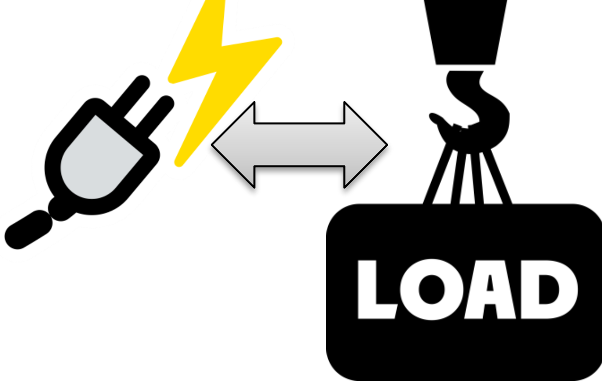




Any physical system composed of n masses produces (n-1) oscillatory modes

Impact of dynamic loads on torsional interactions

Load and SSR: EMT Studies



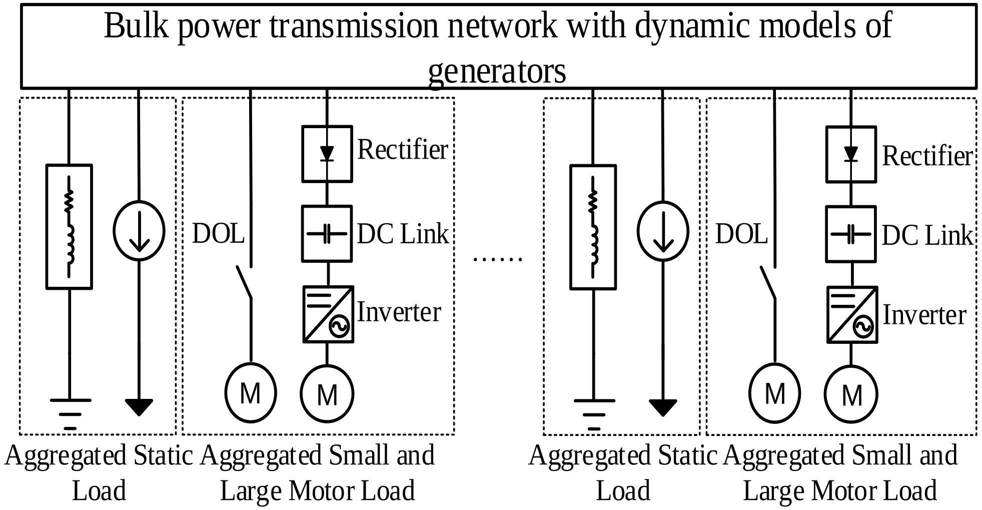
- Generation station modelled in detail
  - turbines, generators, speed governors, excitation systems
- Network is modelled in detail using algebraic and ordinary differential equations

But impact of LOADS is either neglected (IEEE Benchmark models) or assumed as constant Impedance (STATIC) models (throughout the years of SSR research)

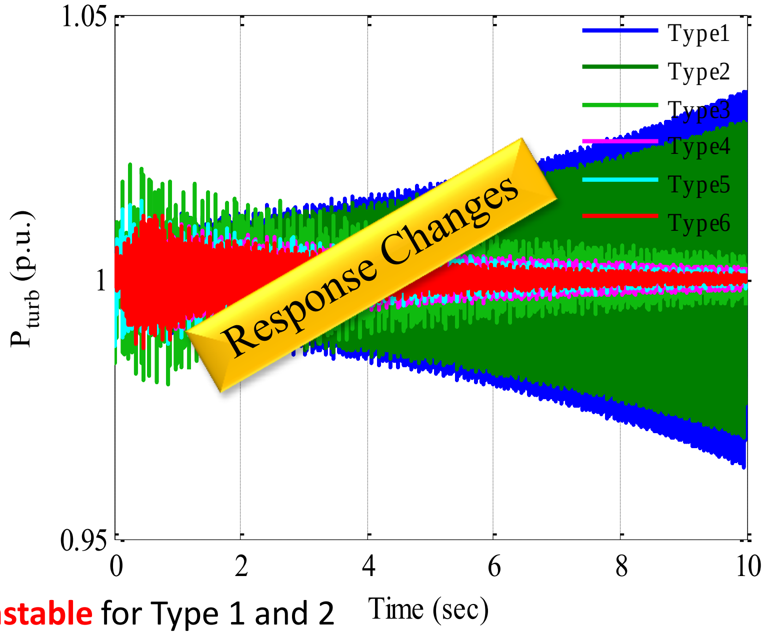
- The impact of loads on system dynamics has been widely investigated for the classical stability studies but not for torsional interactions
- Load modelling for assessment of SSR becomes critically important when the load center is in close electrical proximity to a generation center

In the absence of appropriate load models, simulations may over or underestimate the risk of SSR, which may cause the protection or mitigation to be over/ under-designed

Loads and SSR Damping



Aggregation of loads at the transmission level



unstable for Type 1 and 2

stable for Types 3, 4, 5 and 6

Table I. List of load types considered

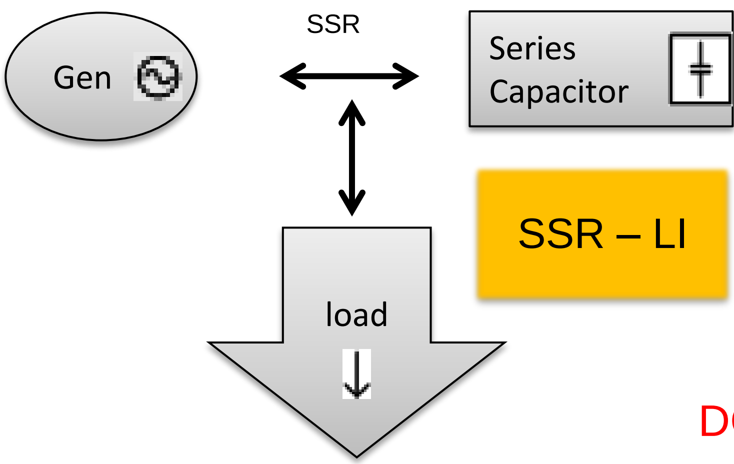
Load Type	Description
Type 1	Loads neglected
Type 2	100% Const. Impedance
Type 3	50% DOL and 50% VFD based Motor loads
Type 4	100% DOL connected Motor load
Type 5	30% Const. Impedance 30% Const. Current 40% DOL connected Motor load
Type 6	50% Constant Impedance 50% DOL connected

Conservative results impact decisions

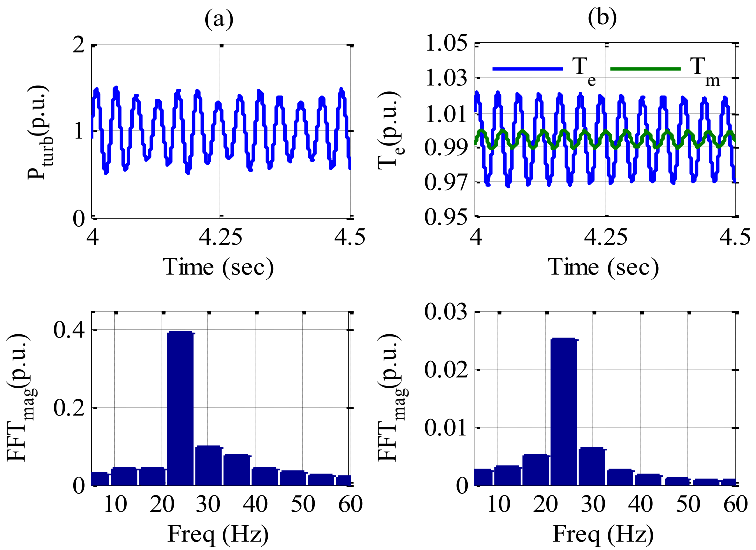
- at the planning stage (regarding location and/or degree of compensation)
- during operation (setting improper thresholds for online alarms against dangerous interactions).

Do Loads Interact with SSR?

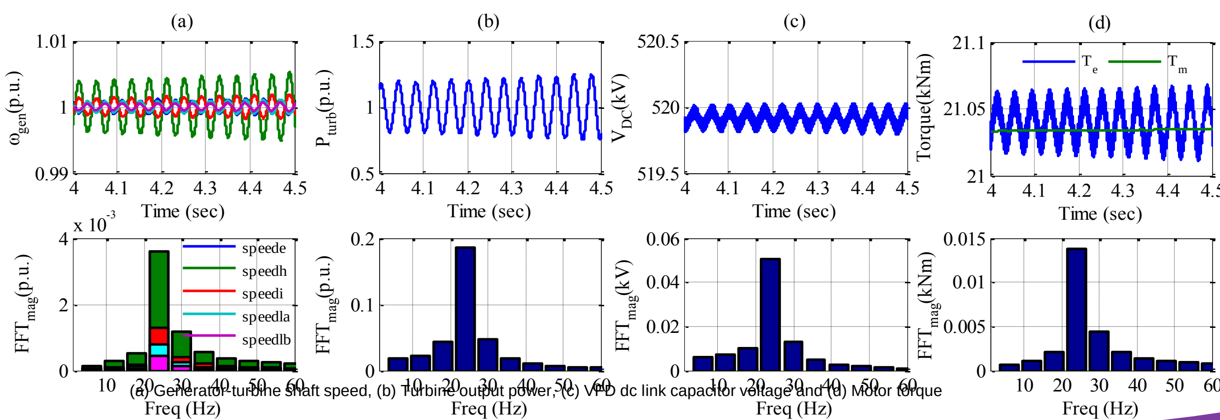
Subsynchronous Resonance Load Interactions



DOL



In the presence of SSR – DOL and VFD loads exhibit sympathetic oscillations



(a) Generator-turbine shaft speed, (b) Turbine output power, (c) VFD dc link capacitor voltage and (d) Motor torque

VFD

25Hz example

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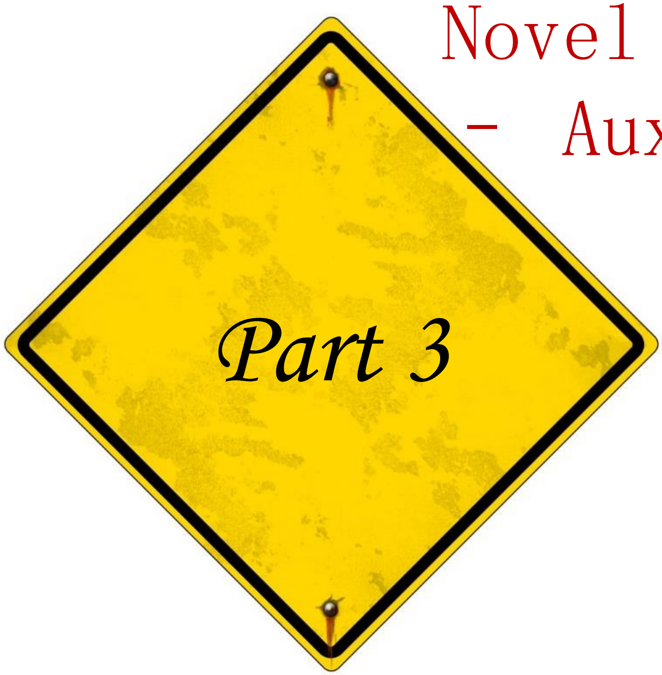
Novel SSR Mitigation – Auxiliary damping controller



Protection Vs. Mitigation

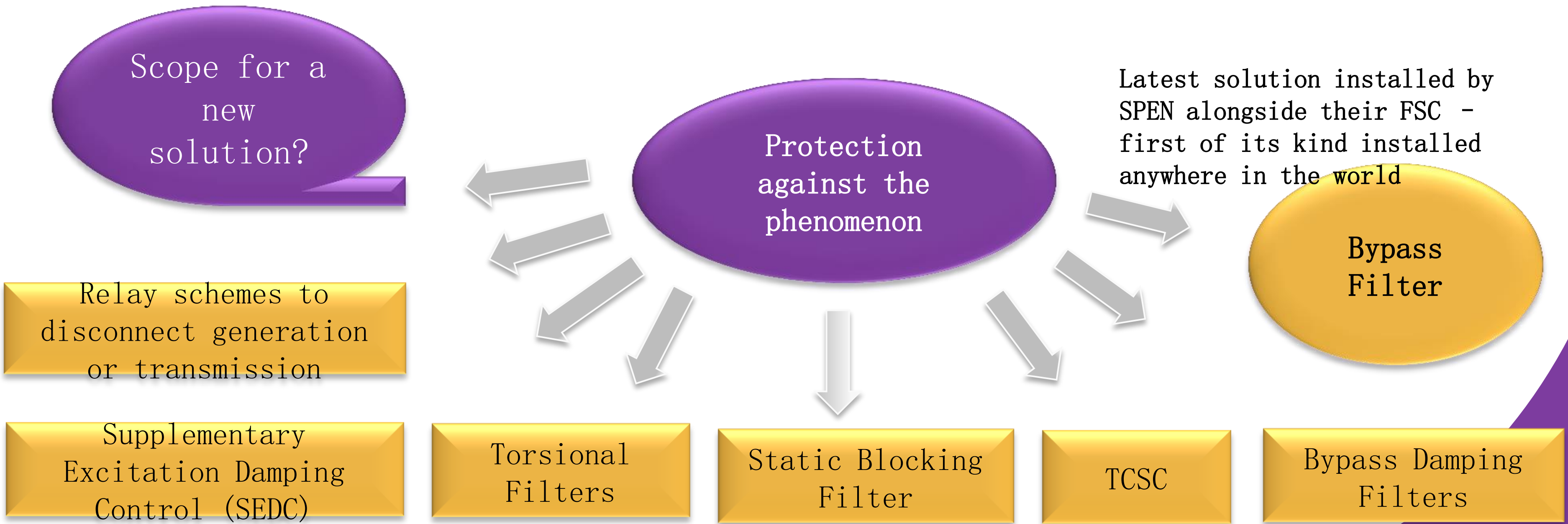
Protection involves forced tripping (removal of generator or series capacitor), which is disruptive for a system that is already in a weakened state due to outages and is generally *recommended as a backup means of defence*.

VS.

Mitigation involves reducing the exposure of the system to the risk of SSR and thus allowing the vulnerable resources to continue operating, even when outages result in stronger electrical coupling between a generator and a series capacitor. In many cases, mitigation may also be able to completely eliminate the risk of SSR.

Traditional means for Managing SSR

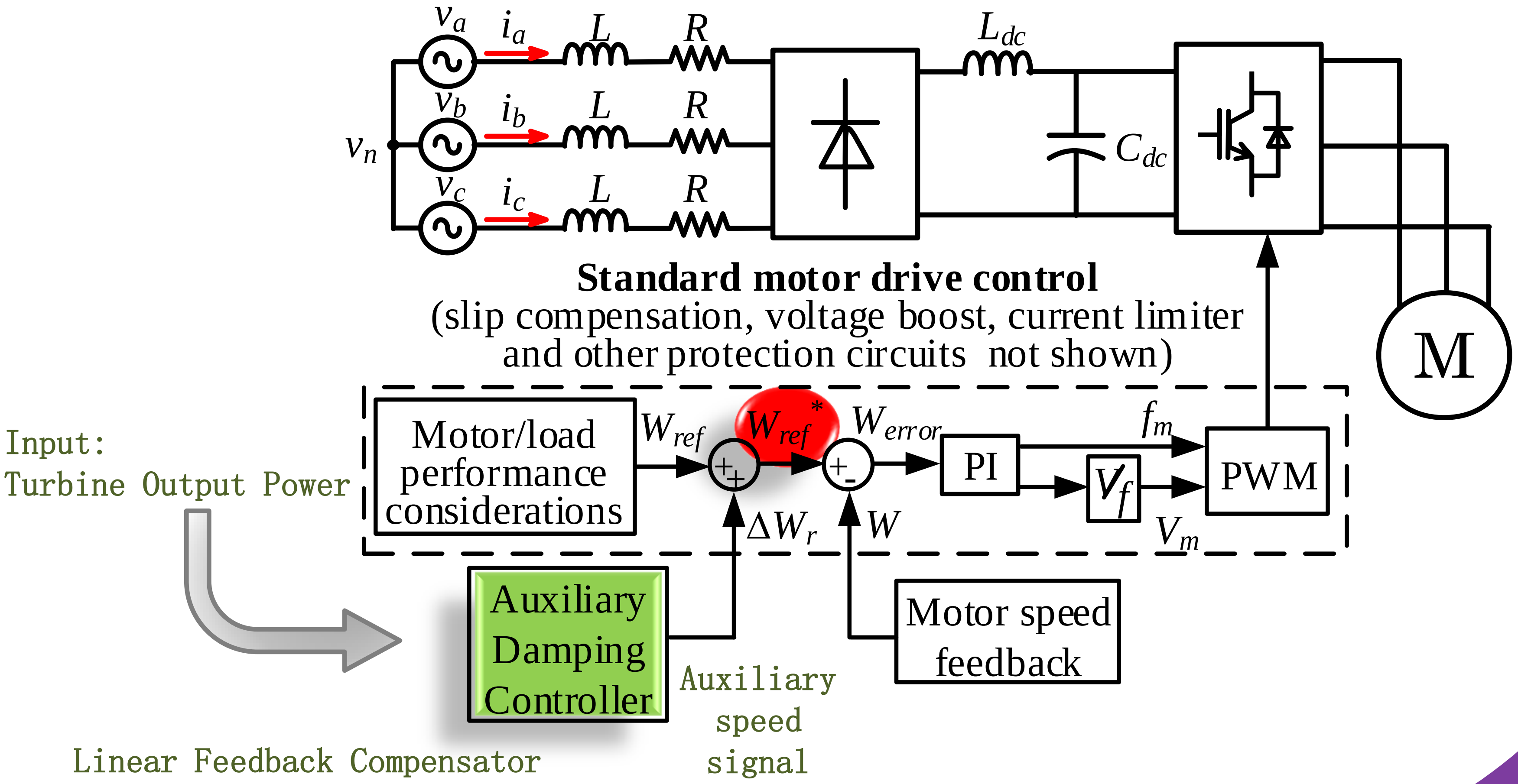
It is essential to ***detect instability*** in the subsynchronous modes of vibration and to do this ***as fast as possible*** and evaluate the need to take proactive action.



Proposed Control Solution

- The proposed ADC uses the **existing auxiliary power plant 11 kV VFD interfaced induction motor loads (e.g FD/ID Fans and pump loads)** that are available locally right at the generation centre
- The ADC **exploits their speed control systems** with minor modifications to the control loop, which incurs little to no additional costs and ensures easy deployment
- It uses the **turbine output power as the control system input**, which is a standard power plant control room signal and does not need additional communication or dedicated monitoring

Residue based ADC design



Three-phase controller diagram for the VFD_AD

VFD based auxiliary power plant loads

- The most important power plant auxiliary loads with variable frequency drives (VFDs) are **Boiler Feed Water pumps** (BFWs), **Induced Draft (ID) fans and Forced Draft (FD) fans**

Significant Capacity

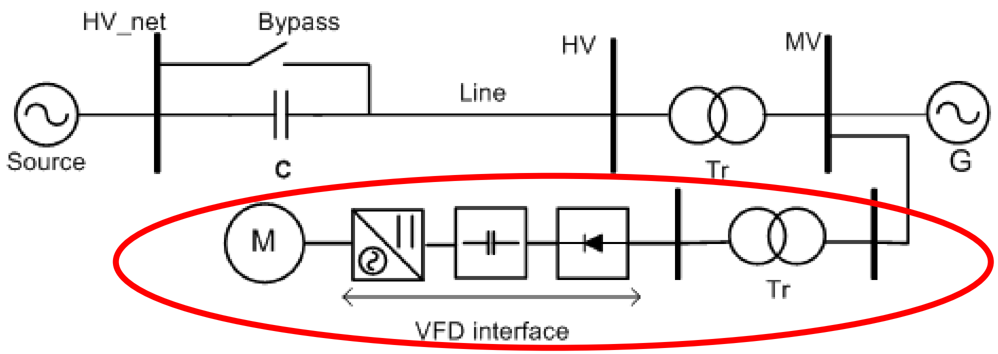
- 3.6 % in fans and 7.2 % in pumps of the plant generation capacity
- FD and ID fans, used in power plant combustion processes consume significant amounts of power with motor sizes approaching 14 to 18 MW in many large power plants.

High availability and redundancy

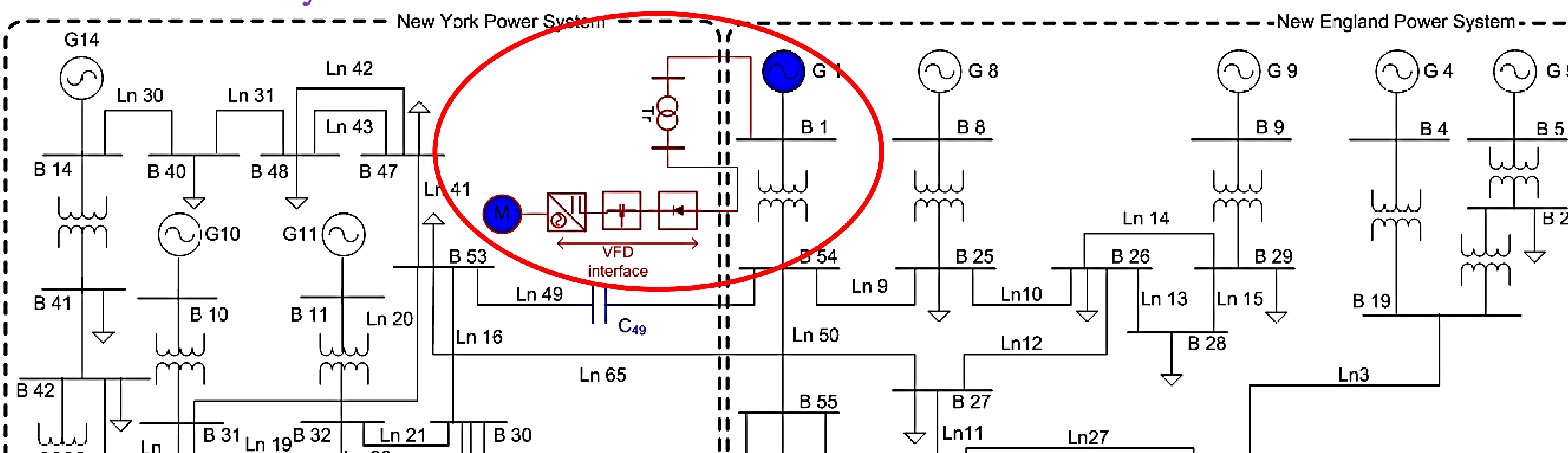
- Additional pumps/fans available as backup or two pumps/fans operating in parallel
  at 50 % of their capacity

Performance Evaluation: Test Systems

IEEE First Benchmark

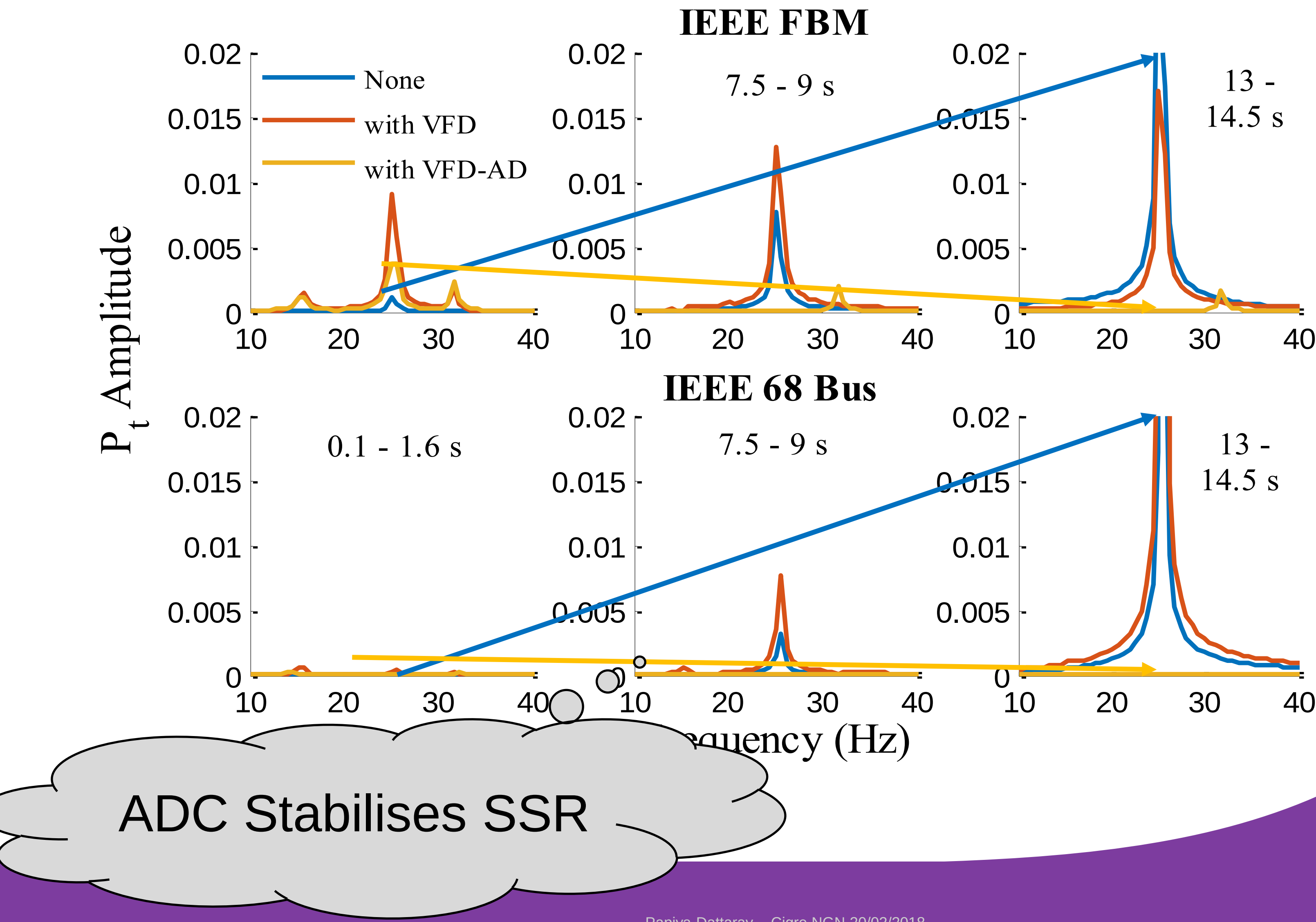


IEEE 68 Bus System

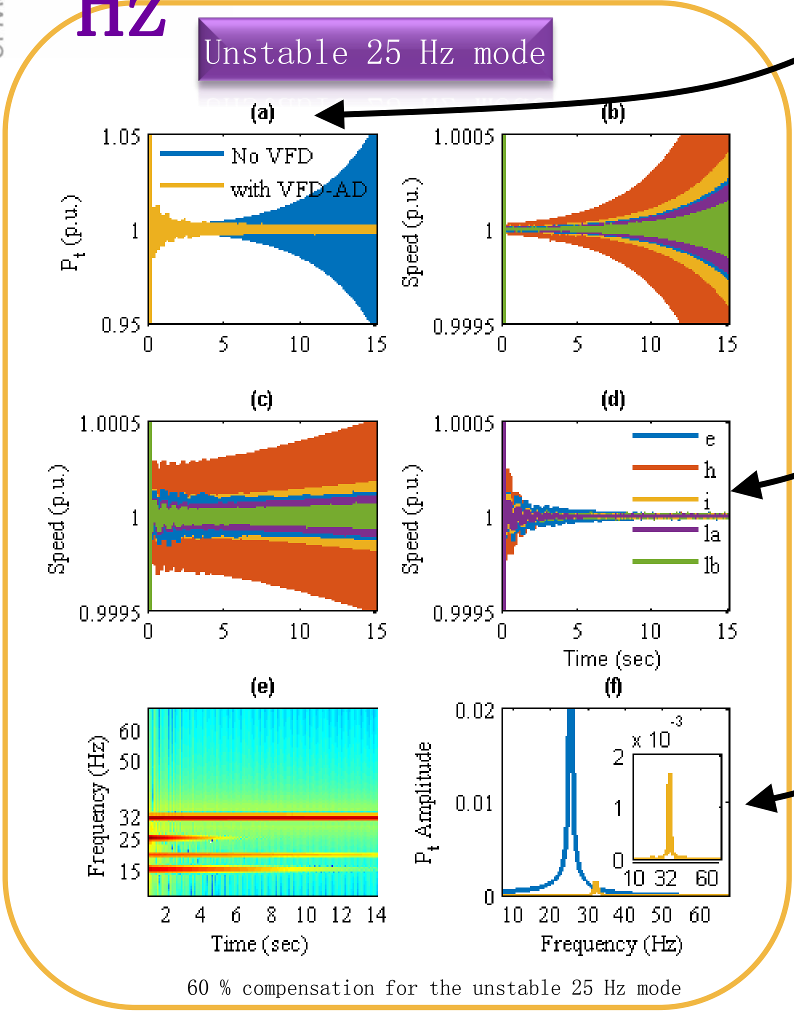


- VFD with ADC control added to two test systems
- Lines removed in 68 bus system to leave generator radial to SC
- The ADC stabilised the SSR

Performance Evaluation: FFT Analysis



Testing for different modes: 25 and 32 Hz



ADC Stabilises turbine output power

Stable shaft section speeds

Unstable SSR replaced with low level control interaction

(a) turbine output power (b) unstable SSR in turbine shaft section speeds (c) turbine shaft section speeds in the presence of VFD motor (d) stable shaft speed oscillations with ADC (e) Frequency spectrum seen in turbine output power with VFD-AD (f) FFT amplitude spectrum for Pt from 13-14.5 sec for No VFD and with VFD-AD

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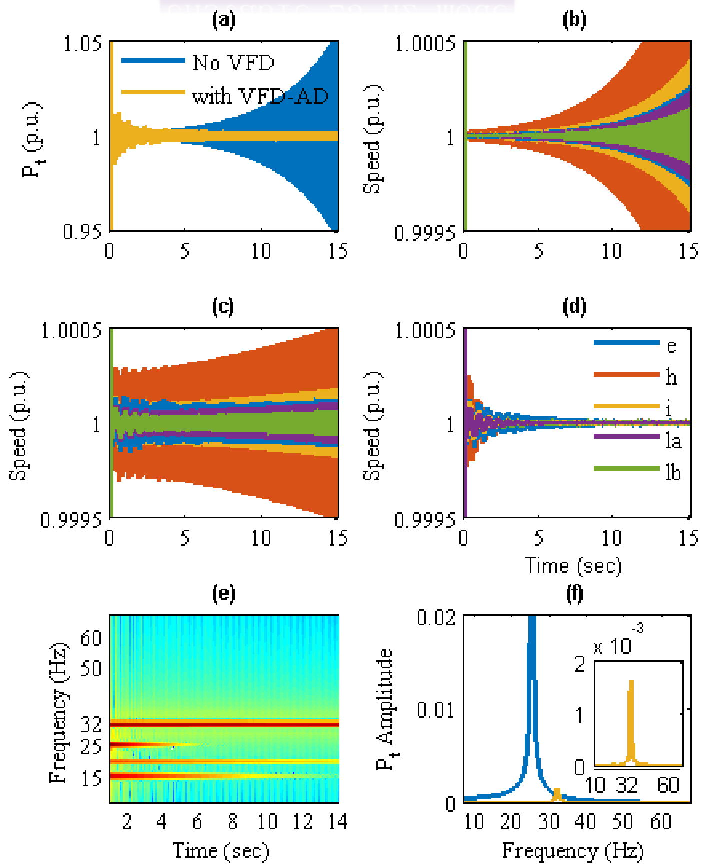
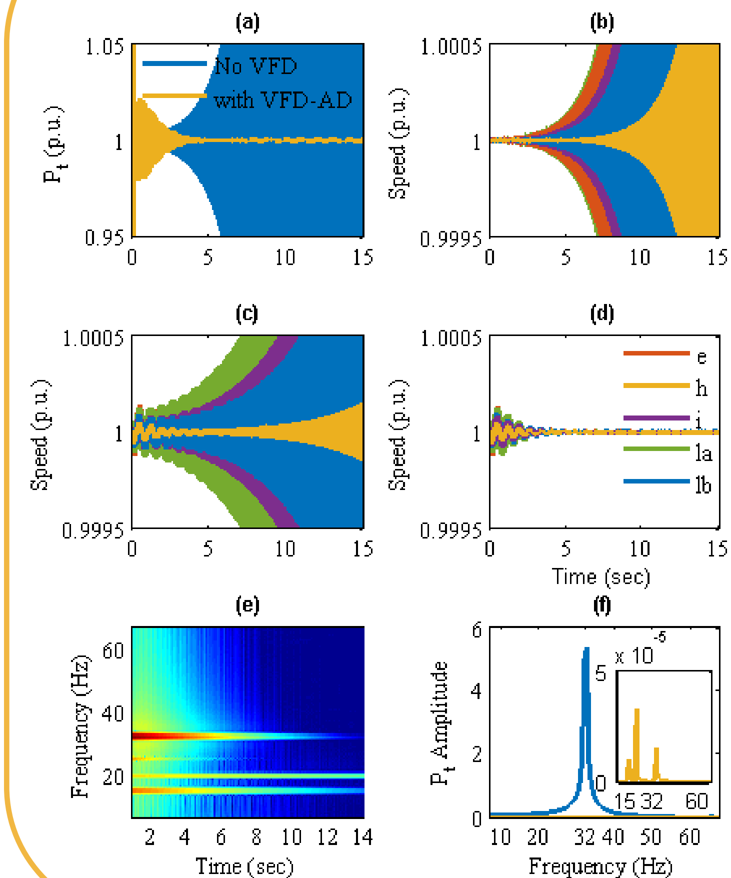
Testing for different modes: 25 and 32 Hz

Unstable 25 Hz mode



60 % compensation for the unstable 25 Hz mode

Unstable 32 Hz mode



40 % compensation for the critically unstable 32 Hz mode

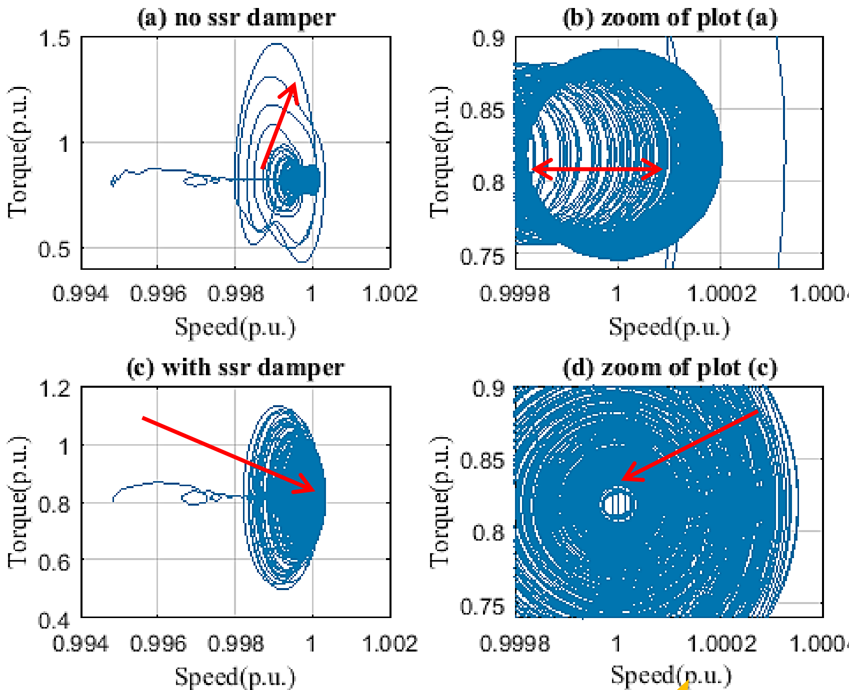
(a) turbine output power (b) unstable SSR in turbine shaft section speeds (c) turbine shaft section speeds in the presence of VFD motor (d) stable shaft speed oscillations with ADC (e) Frequency spectrum seen in turbine output power with VFD-AD (f) FFT amplitude spectrum for Pt from 13-14.5 sec for No VFD and with VFD-AD

ADC performance for TA

- ADC effective against Torque Amplification
- Three phase short circuit in IEEE FBM
- Tested for a range of fault times

Cases	Fault clearing times	P_t		W_h	
		a	ς	a	ς
No ADC	5ms	0.984	0.026	0.02	0.026
	10ms	1.072	0.024	0.022	0.024
	20ms	0.864	0.026	0.017	0.026
	40ms	0.454	0.026	0.009	0.026
	50ms	0.661	0.027	0.013	0.027
	83.3ms	0.13	0.023	0.002	0.023
With ADC	5ms	1.712	-0.21	0.035	-0.208
	10ms	1.922	-0.217	0.037	-0.214
	20ms	1.574	-0.222	0.032	-0.219
	40ms	0.821	-0.215	0.016	-0.211
	50ms	1.198	-0.216	0.024	-0.213
	83.3ms	0.243	-0.217	0.004	-0.204

SSR-LI shown through motor electrical torque versus speed plot



Dual protection for both the generator and vital auxiliaries

Challenges identified …..

- The effectiveness of the ADC and participation of the VFD based motor load in SSR damping would depend on its loading at the time of the disturbance
- When the VFD is operating at, or close to, its full load capacity the proposed ADC will not be able to provide satisfactory damping
- Simplistic control method adopted by the proposed ADC must be tuned for a specific shaft mode
- Future work will involve looking at robust control designs that may damp multiple torsional modes simultaneously.

Conclusions and Future Work

- The ADC performance is evaluated for both TI and TA types of SSR interactions in the IEEE FBM and IEEE 68 bus networks and is shown to provide effective positive damping and mitigate SSR under a range of operating conditions
- The solution is novel and practical and it incurs minimum additional costs by virtue of exploiting existing resources and provides an effective means for SSR mitigation right at the point of vulnerability (generation centre)
- A rather simplistic control architecture has been adopted here to provide a proof of concept.

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Thank you, any questions?

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