Arizona State University

Physics-based Data-Driven Approaches for Monitoring and Mitigating Voltage Instability

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The Power Grid is a Critical National Infrastructure

- The power grid is a critical infrastructure of a nation; secure operation is key for a reliable grid – societal and commercial cost

- Stability analysis is essential for secure operation of the grid after large disturbances –classic problem in power systems

- Trends impacting grid stability & control :
  - IBR penetration
  - T&D interaction
  - Sensors

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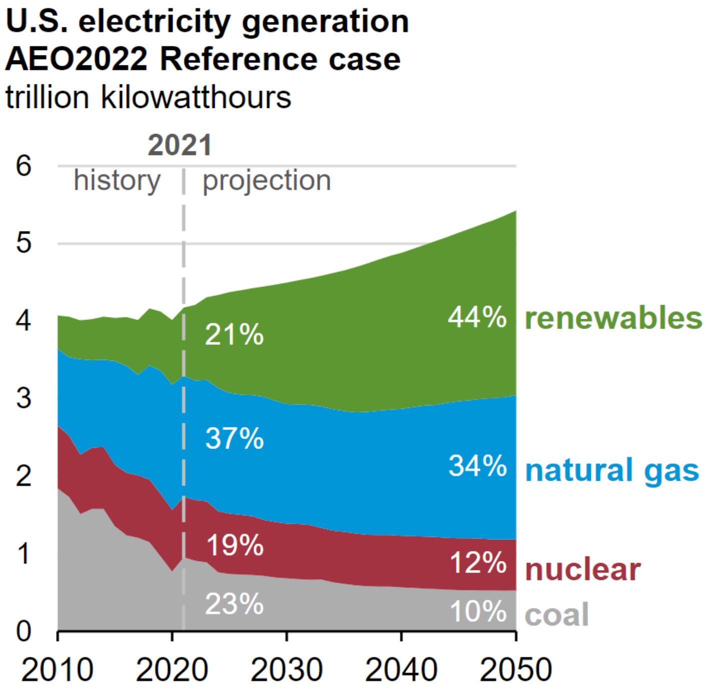
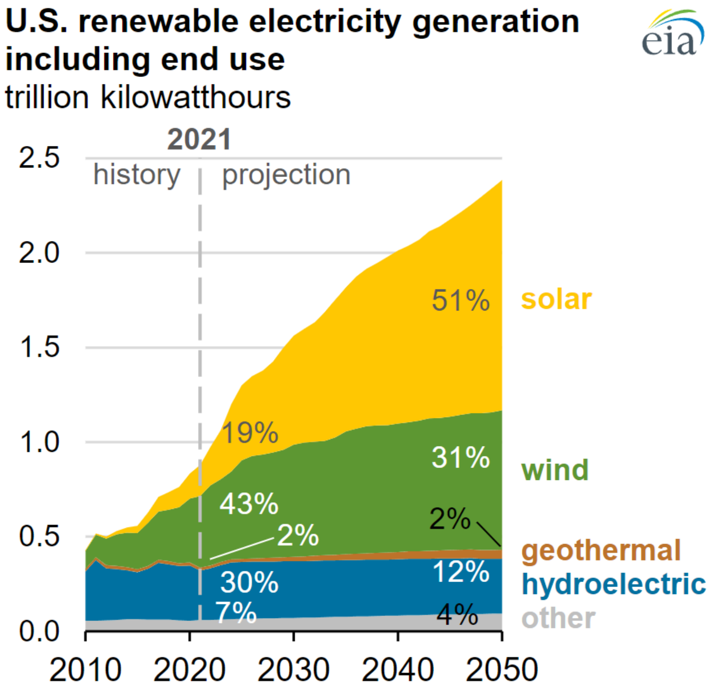
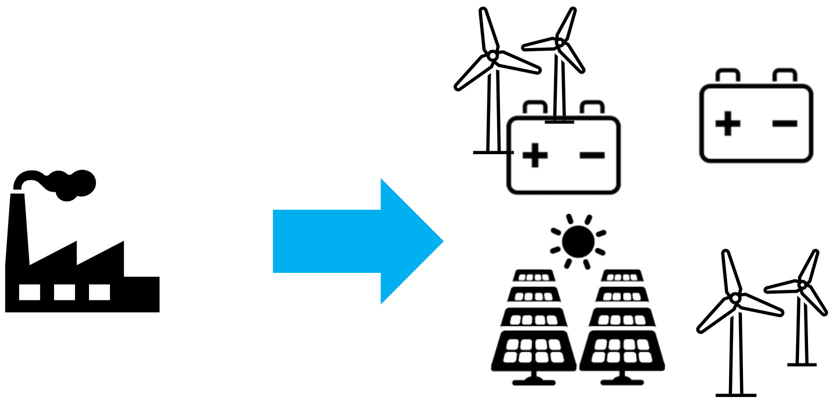
Trend 1 – Increasing Inverter Based Resources (IBRs)







Coal

10's-100's

1000's-10000's

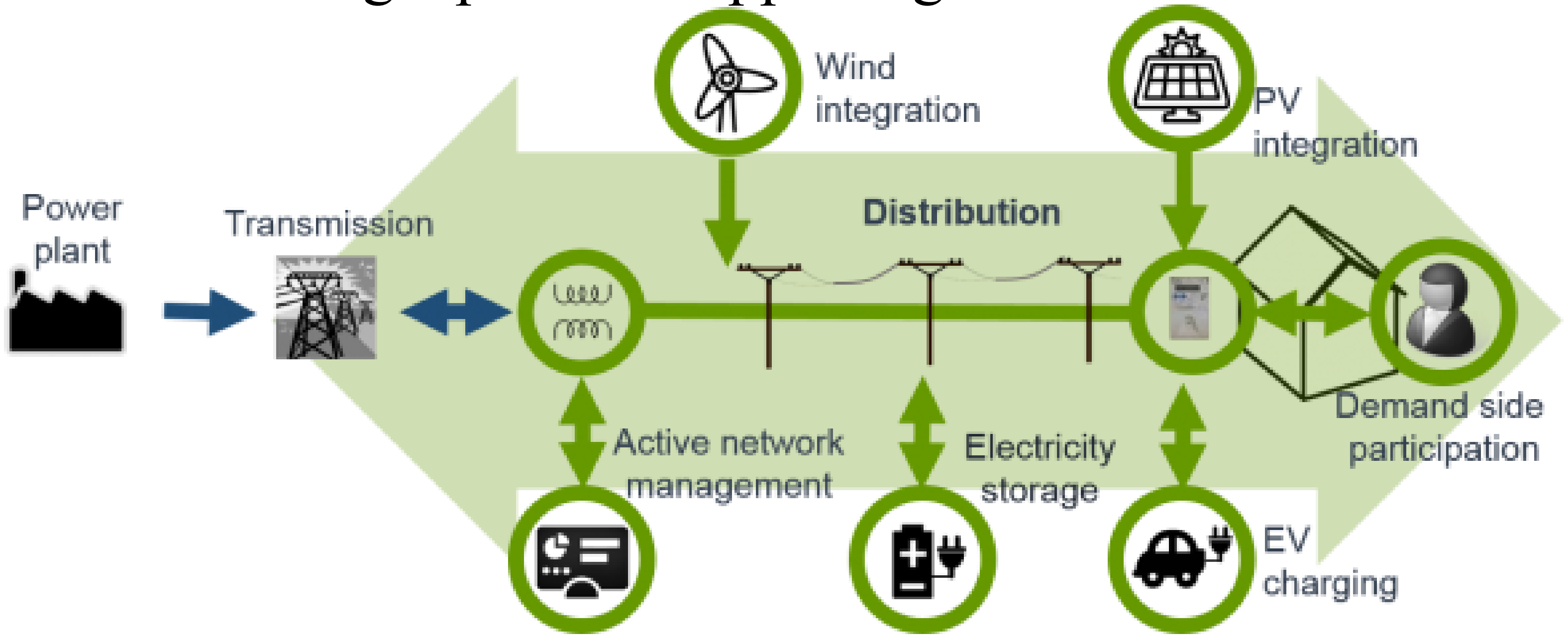
Much more dispersed

Renewables connected via inverters will rise and will be more dispersed in the grid

Source: U.S. Energy Information Administration - EIA - Independent Statistics and Analysis

Trend 2 – Rising Active Resources in Distribution Systems

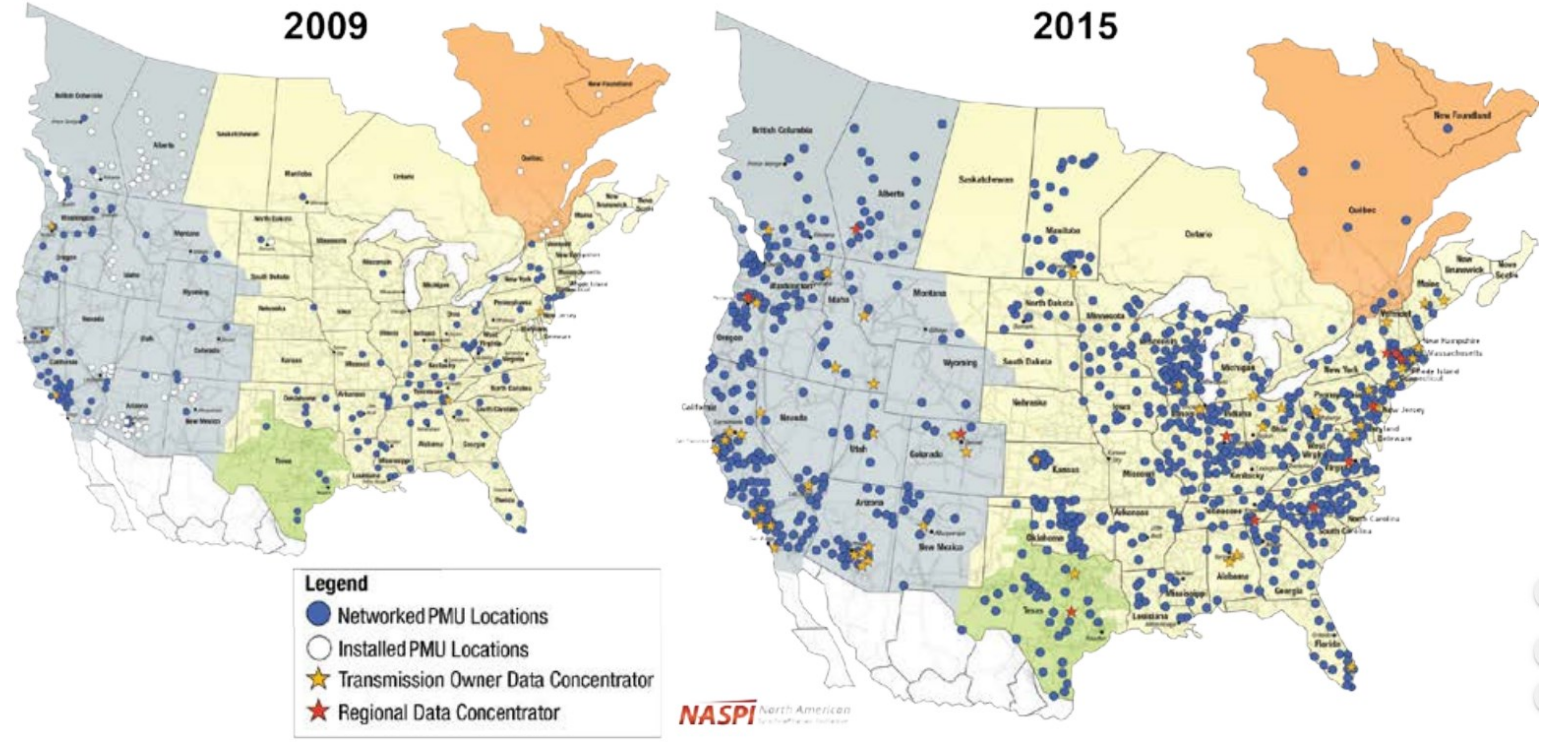
- Devices in the distribution grid are becoming active participants in the grid – Consumers to Prosumers – Referred as DERs
- FERC 2222 – DERs can get paid for supporting transmission



New T&D interactions over Multiple Timescales

Trend 3 – Increasing Sensors

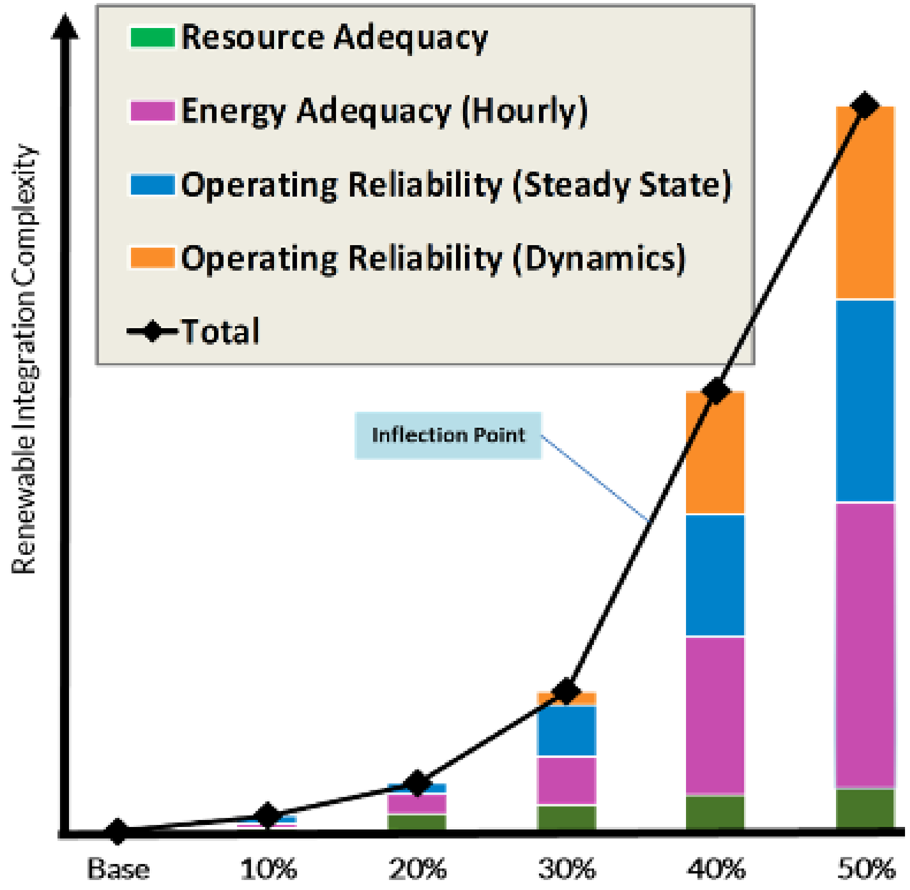
- Phasor Measurement Units (PMUs) provides real-time measurements of grid dynamics – also being introduced in distribution systems (μPMUs)



↑ Sensors in Transmission and Distribution
– Online Monitoring & Control

Renewable Integration Impact Assessment Study

- The 2021 Renewable Integration Impact Assessment study by Midcontinent Independent System Operator (MISO) found that beyond <u>30% IBR penetration</u>:
- System wide **voltage instability is the main driver of dynamic complexity**
- The system is prone to **oscillations during peak renewable conditions -** Reduced Damping & Inertia



Source: Midcontinent Independent System Operator, "Renewable Integration Impact Assessment", RIIA report [https://www.misoenergy.org/planning/policy-studies/Renewable-integration-impact-assessment]

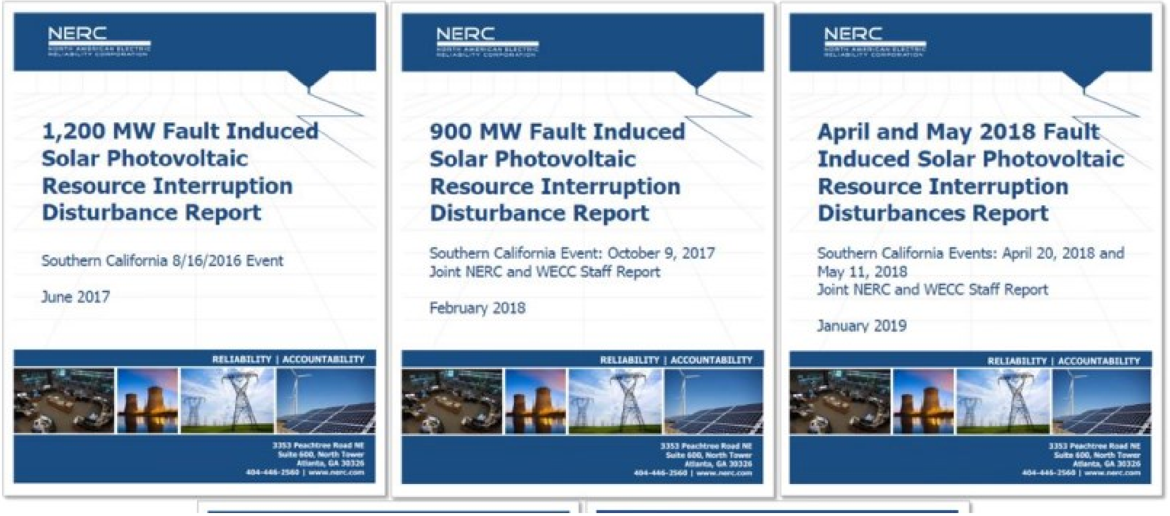
Challenges and Opportunities

The increasing IBRs reduce damping, inertia while introducing variability

Dynamics of the system is more complex due to increasing IBRs

Use the flexibility of bulk IBRs+DERs to provide support – P2800 & FERC 2222

Use sensors to monitor and analyze the dynamics to quickly identify & control instability



Fast Frequency Response, Q-V control, etc.

Focus on Online Short-Term Voltage Instability Monitoring & Mitigation

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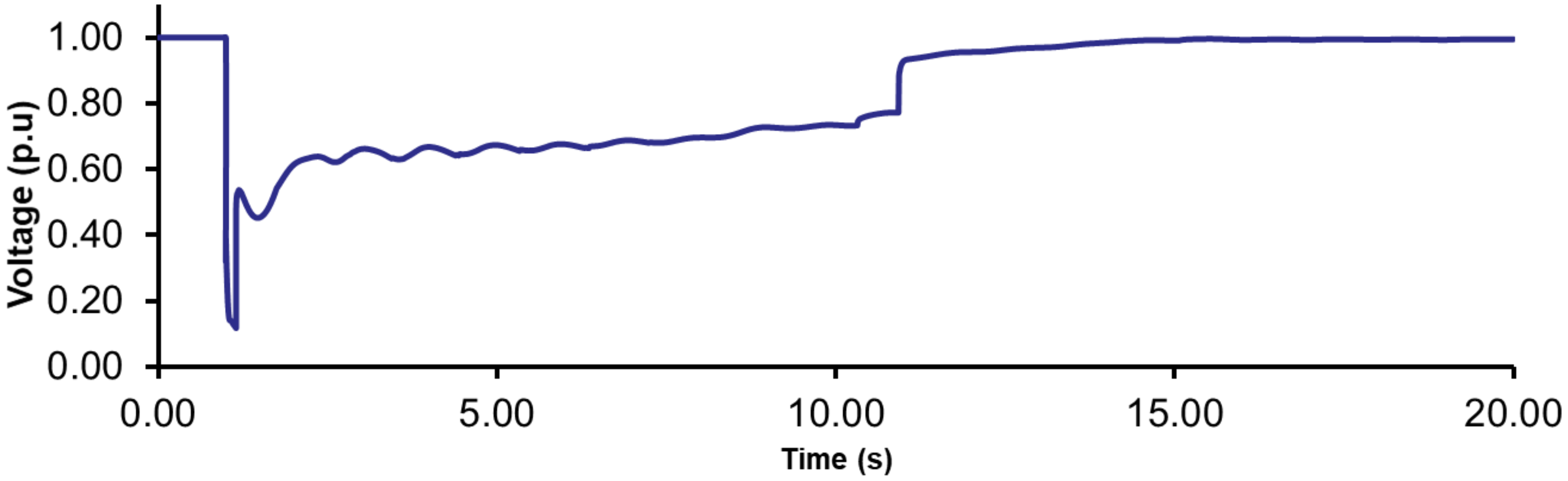
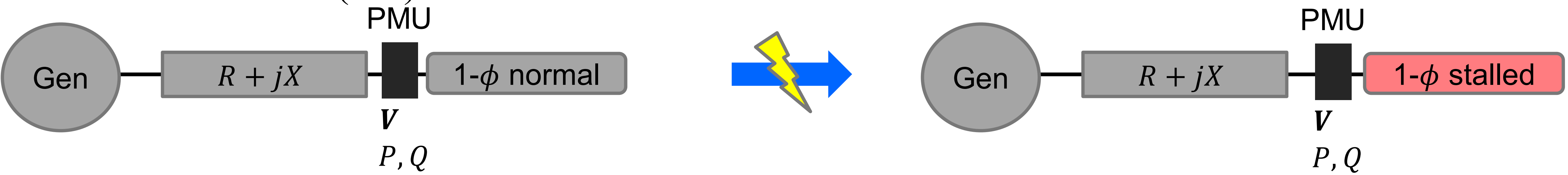
Fault Induced Delayed Voltage Recovery (FIDVR) in Transmission Systems



[J1] **Ramapuram Matavalam A.R.;** V. Ajjarapu, “PMU based Monitoring and Mitigation of Delayed Voltage Recovery using Admittances," IEEE Transactions on Power Systems, vol. 34, no. 6, pp. 4451-4463, Nov. 2019, doi: 10.1109/TPWRS.2019.2913742

Fault Induced Delayed Voltage Recovery (FIDVR)

- Caused due to motor stalling during and after fault – mainly occurs in 1-ϕ Air Conditioner (AC) dominated loads – such as Arizona and Texas



- Stalled motors are connected to grid but are not rotating - are essentially "<u>shorted transformers</u>" – high admittance

Source: Department of Energy, "DOE - NERC FIDVR Workshop", April 22 2008.

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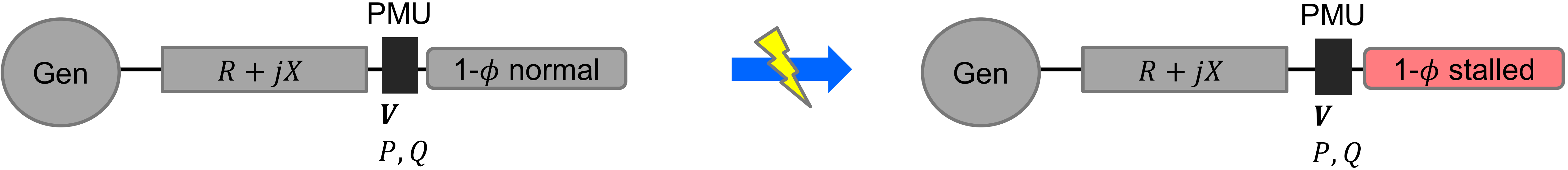

- Stalled motors are connected to grid but are not rotating - are essentially "shorted transformers" – high admittance

Stalled motor draws high current ⇒ High current causes heat to build up ⇒ Thermal protection disconnects motor when temperature limit is reached ⇒ Voltage recovers as the motor load is disconnected

Stalled motor draws high current ⇓ High current causes low voltage at terminal

Source: Department of Energy, "DOE - NERC FIDVR Workshop", April 22 2008.

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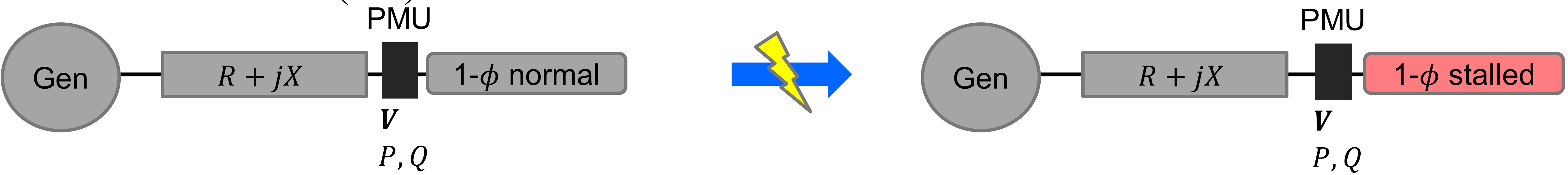

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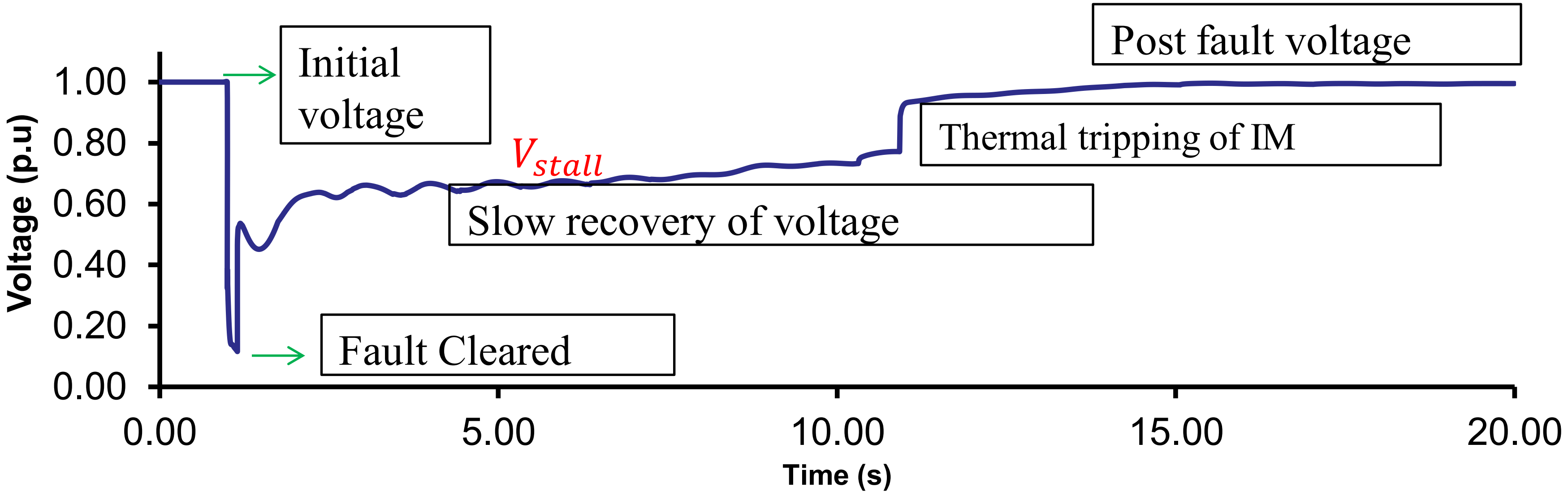

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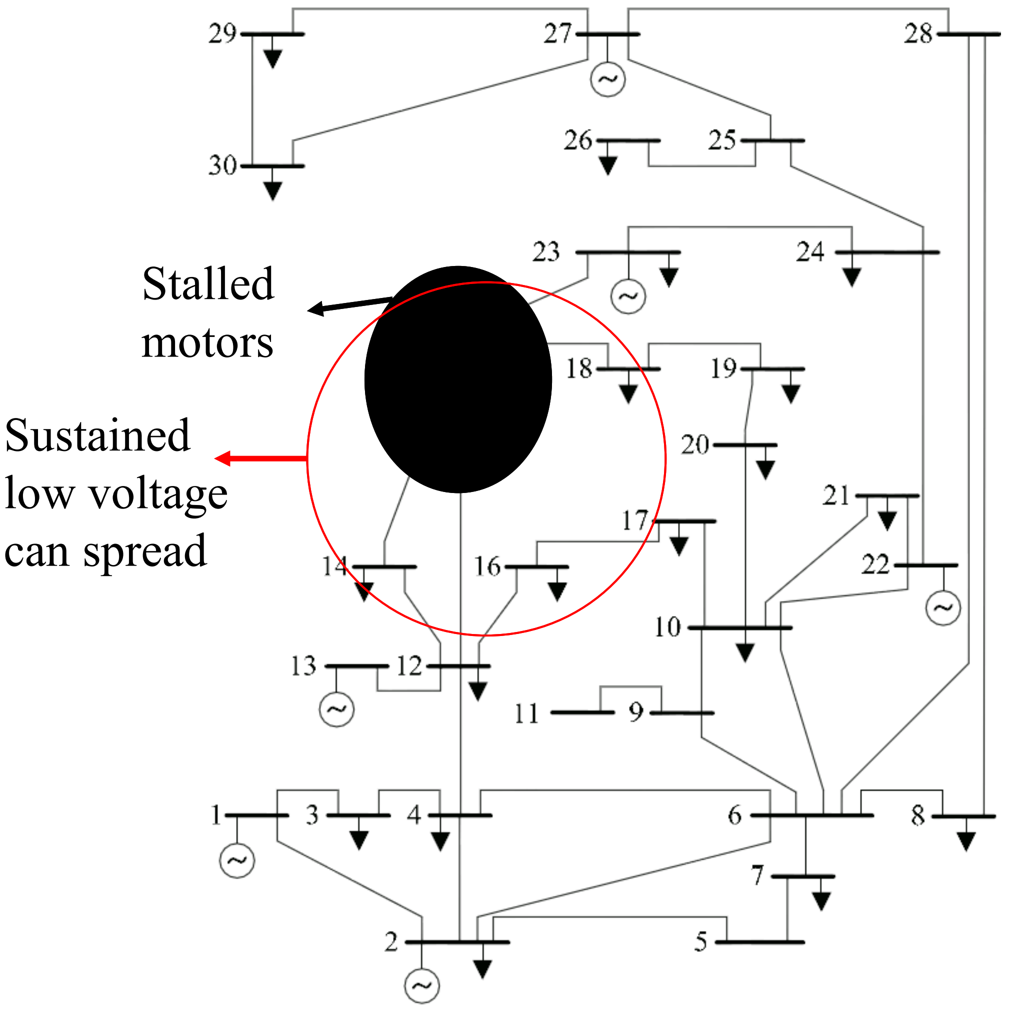
FIDVR in transmission system

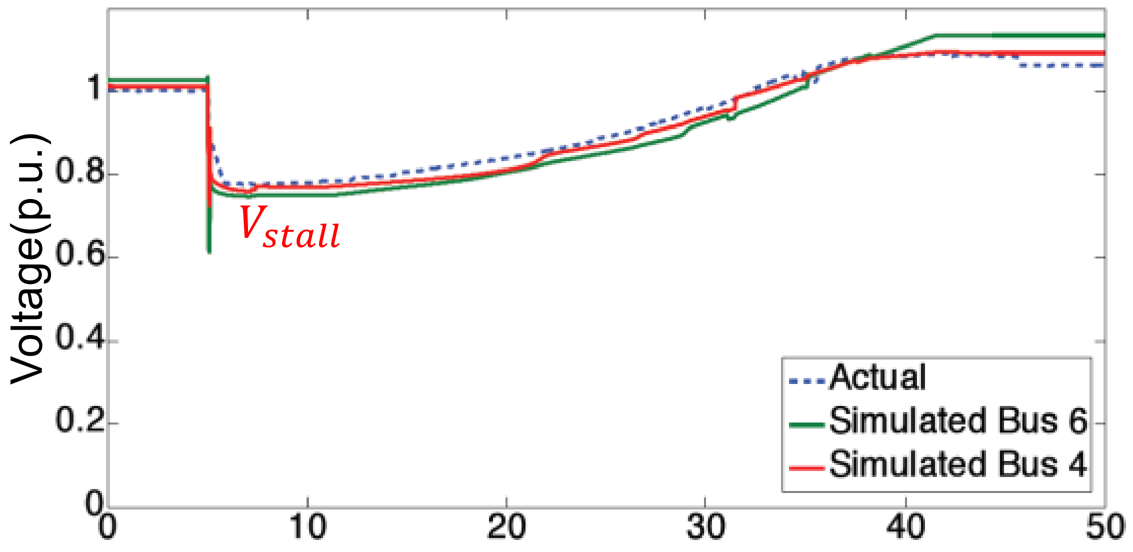
- Sustained low voltages may cause devices in nearby regions to trip – DERs can get disconnected
- Many hundreds of stalled AC motors
- Prefer a local method at substation PMU to monitor and control



How do we characterize and mitigate FIDVR locally?

FIDVR with high & low system damping

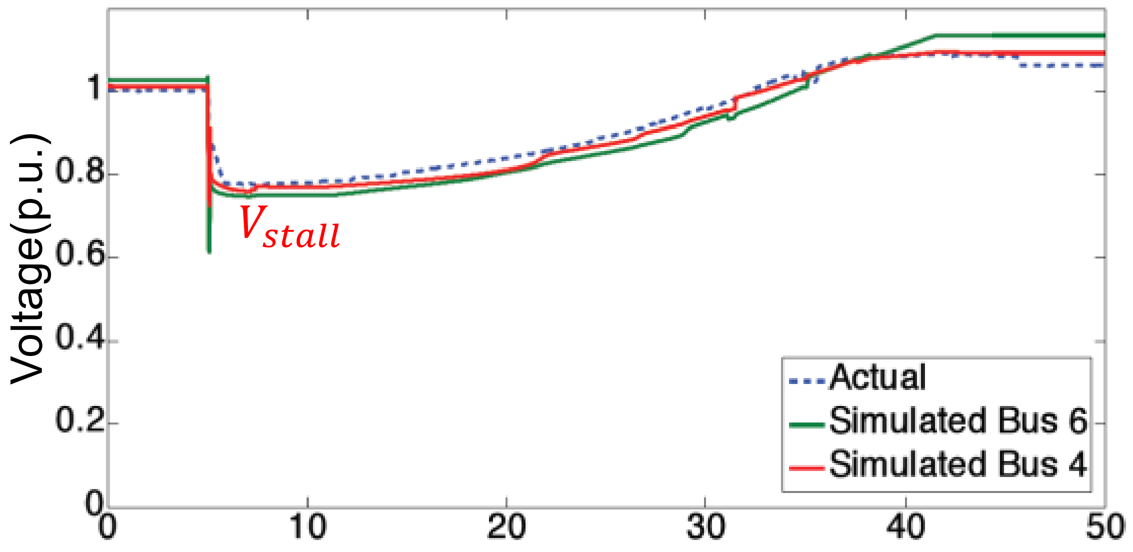
- Existing online monitoring & mitigation methods use voltage to monitor FIDVR
- In high damping scenarios, voltage is a reasonable indicator of severity (Halpin 2008, Kolluri 2015)

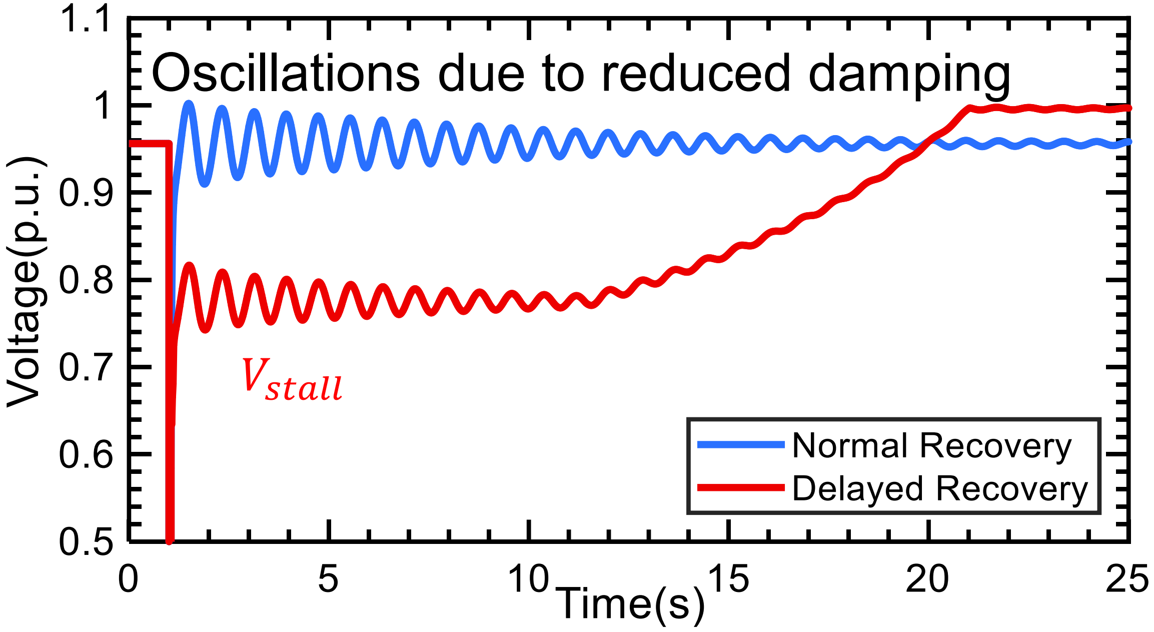


Source: Workshop Presentations Fault-Induced Delayed Voltage Recovery (FIDVR).pdf (nerc.com)

FIDVR with high & low system damping

- Existing online monitoring & mitigation methods use voltage to monitor FIDVR
- In high damping scenarios, voltage is a reasonable <u>indicator of severity</u> (Halpin 2008, Kolluri 2015)
- In simulations with poor damping in system - observed that the voltage is not a reliable metric for monitoring FIDVR
- System operation in regions where control gains are not tuned ⇒ poor damping





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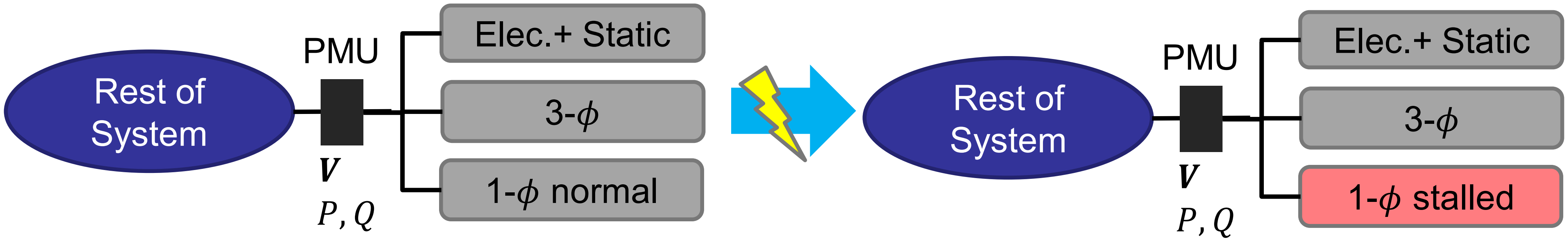
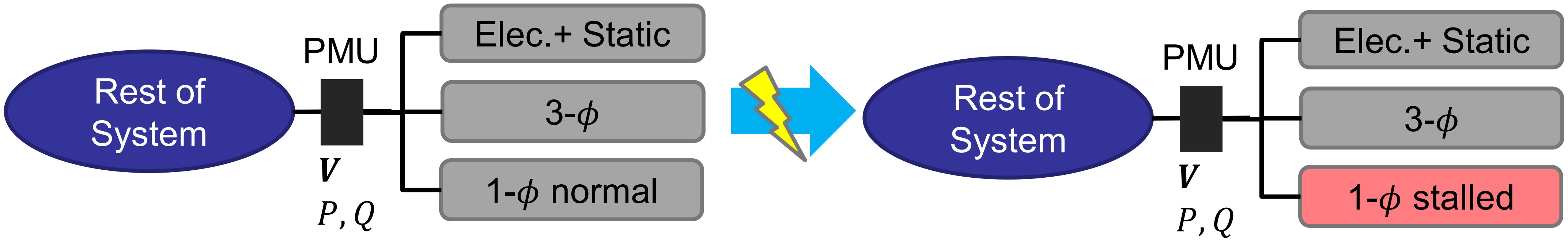
FIDVR Modelling – Composite load model



- The composite load model is the state-of-the-art model for FIDVR as it aggregates the behavior of several distribution feeders
- Challenge: The voltage is the symptom and NOT the cause of the phenomenon. The voltage behavior is a result of multiple system level phenomenon and can be oscillatory. How do we locally monitor the FIDVR in this scenario?

Source: Modeling and validation work group, "WECC Dynamic Composite Load Model Specifications," Western Electricity Coordinating Council, Technical Report

FIDVR Modelling – Composite load model



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- Challenge: The voltage is the symptom and NOT the cause of the phenomenon. The voltage behavior is a result of multiple system level phenomenon and can be oscillatory. How do we locally monitor the FIDVR in this scenario?
- Solution: The stalled 1ϕ IM is an admittance, so estimate it from measurements & model.

$$Y_{1\phi} = Y_{PMU} - (Y_{elec} + Y_{stat} + Y_{3\phi})$$

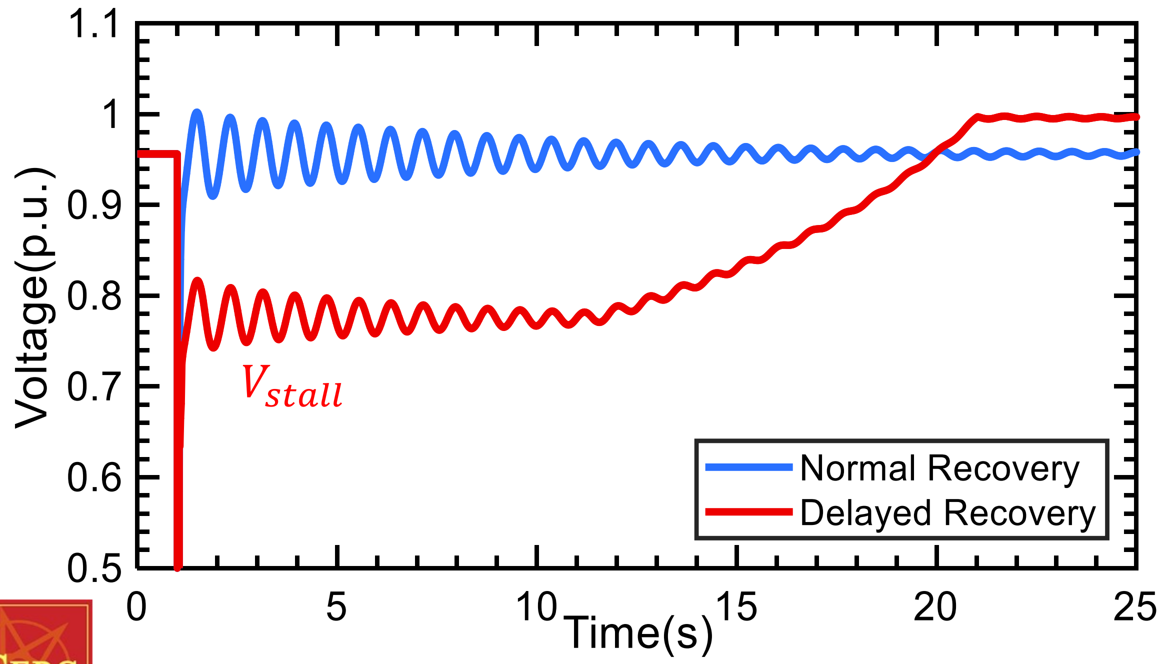
$$\boxed{\frac{P + jQ}{|\boldsymbol{V}|^2}}$$

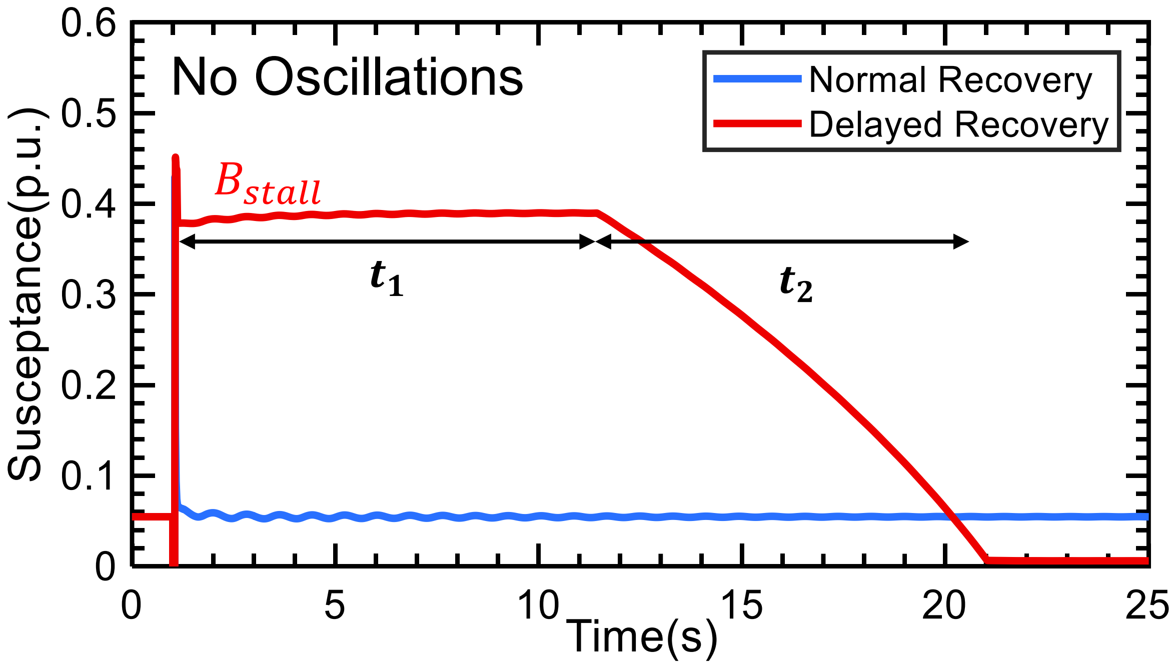
Function of Voltage and Model

Source: Modeling and validation work group, "WECC Dynamic Composite Load Model Specifications," Western Electricity Coordinating Council, Technical Report

Observations from Simulations

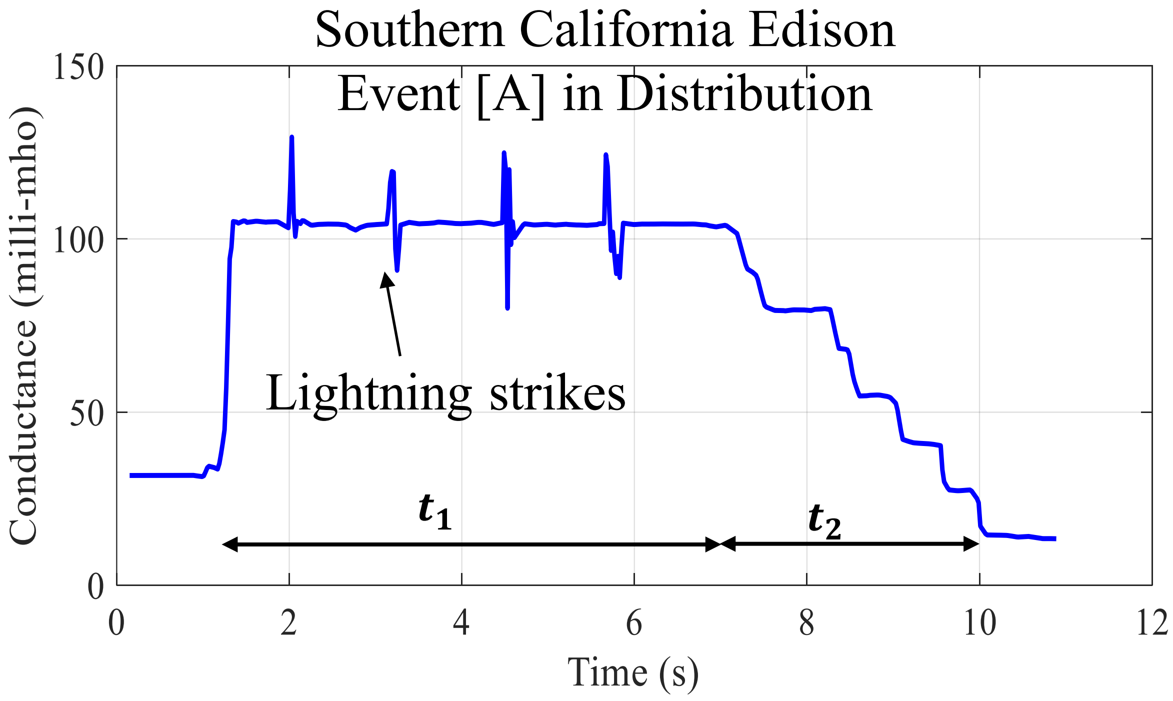
- Monitoring the stalled 1ϕ motor Admittance gave a much better understanding – unique aspect as none have looked at admittances for monitoring stability
- Susceptance (B) plot shows two distinct sections with minimal oscillations - t_1 & t_2
- Key result is to estimate the recovery time immediately after fault using B_{stall} given by $t_1 + t_2$

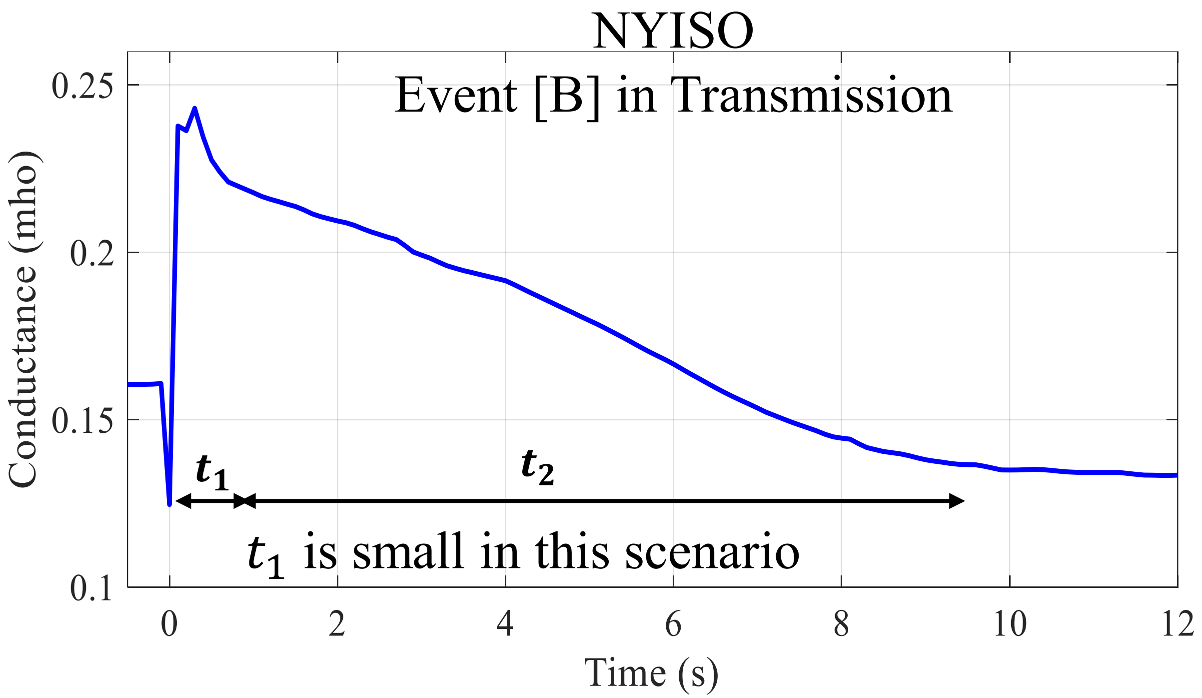




Observations from Real Data

- Reconstructed total conductance plots for real FIDVR events in distribution & transmission systems – from P and V data [A] [B]
- The overall behavior of the plots is like the simulation results – t_1 & t_2

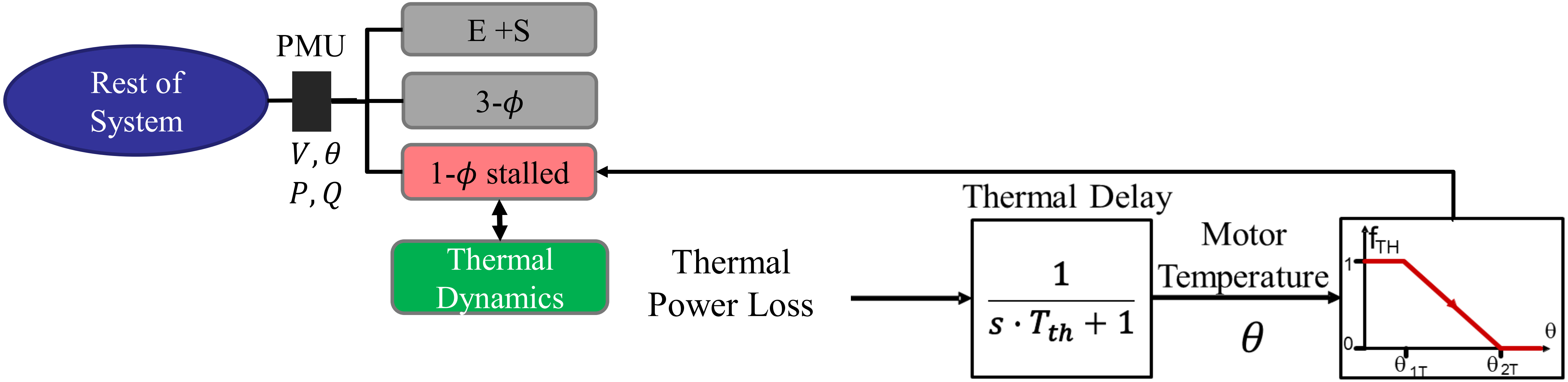




[A] S. Robles, "2012 FIDVR Events Analysis on Valley Distribution Circuits". Prepared for LBNL by Southern California Edison, 2013
[B] W. Wang, et. al., "Time Series Power Flow Framework for the Analysis of FIDVR Using Linear Regression," in IEEE Trans. on Pow. Del., vol. 33, no. 6, pp. 2946-2955, Dec. 2018

Analysis of Load Dynamics during FIDVR

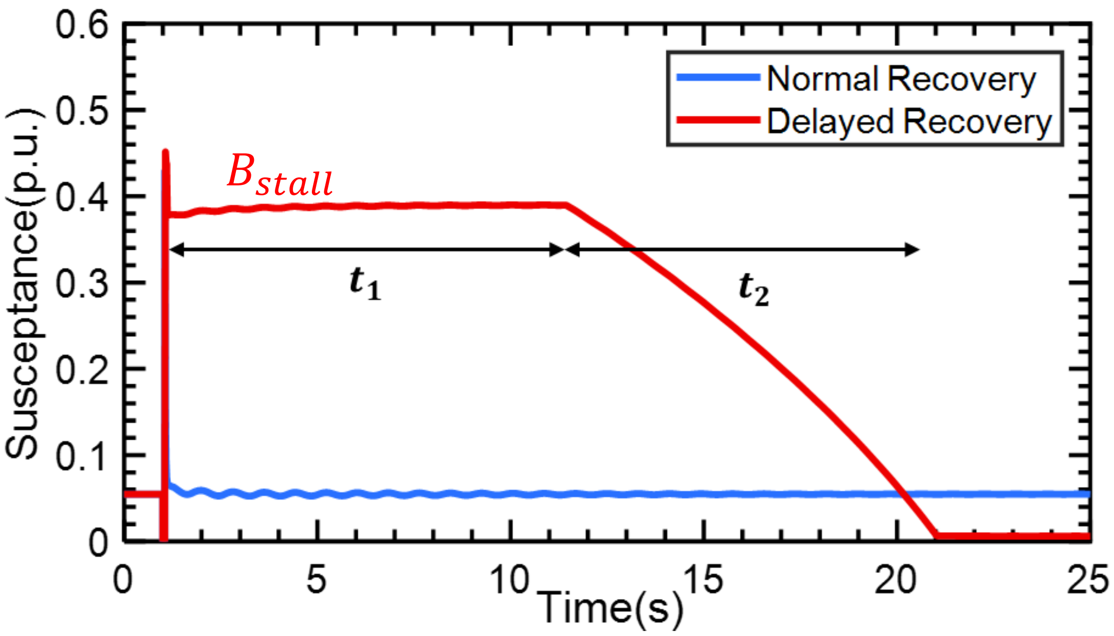
- The stalled admittance of the 1ϕ IM varies with time due to thermal protection.



- This is a physics inspired reduced model representing the key dynamics observed in FIDVR
- Represent this system by a switched non-linear differential equation for the dynamics of the motor temperature, θ, as the slowly varying state in this system

Source: Modeling and validation work group, "WECC Dynamic Composite Load Model Specifications," Western Electricity Coordinating Council, Technical Report

Analysis of FIDVR Recovery Time - I



For a <u>non-oscillatory</u> V_{stall}, we can solve the non-linear differential equations to get

$$t_1 \approx -k_0 \cdot \ln\left(1 - k_1/\left(V_{stall}^2 \cdot B_{stall}\right)\right)$$

$$t_2 \approx \frac{2k_2}{\left((V_{stall}^2 + 1)B_{stall} - k_3\right)}$$

k_0, k_1, k_2 & k_3 are functions of thermal relay parameters

Total recovery time = $t_1 + t_2$

Challenge: The t_1 & t_2 expressions include V_{stall} which is oscillatory.

[J1] **Ramapuram Matavalam A.R.;** V. Ajjarapu, "PMU based Monitoring and Mitigation of Delayed Voltage Recovery using Admittances," IEEE Transactions on Power Systems, vol. 34, no. 6, pp. 4451-4463, Nov. 2019, doi: 10.1109/TPWRS.2019.2913742

Analysis of FIDVR Recovery Time - II

- Solution: Learn an expression for the times t_1 & t_2 in terms of the measured B_{stall} at the PMU from various offline simulations
- As $V_{stall} \propto \frac{1}{B_{stall}}$, a first order approximation of the expressions leads to a linear relation between the recovery times and B_{stall}

$$t_1 \approx -k_0 \cdot \ln\left(1 - k_1/(V_{stall}^2 \cdot B_{stall})\right)$$

$$t_2 \approx \frac{2k_2}{\left((V_{stall}^2 + 1)B_{stall} - k_3\right)}$$

$$\Rightarrow$$

$$t_1 = \alpha_0 \cdot B_{stall} + \alpha_1$$
$$t_2 = \beta_0 \cdot B_{stall} + \beta_1$$

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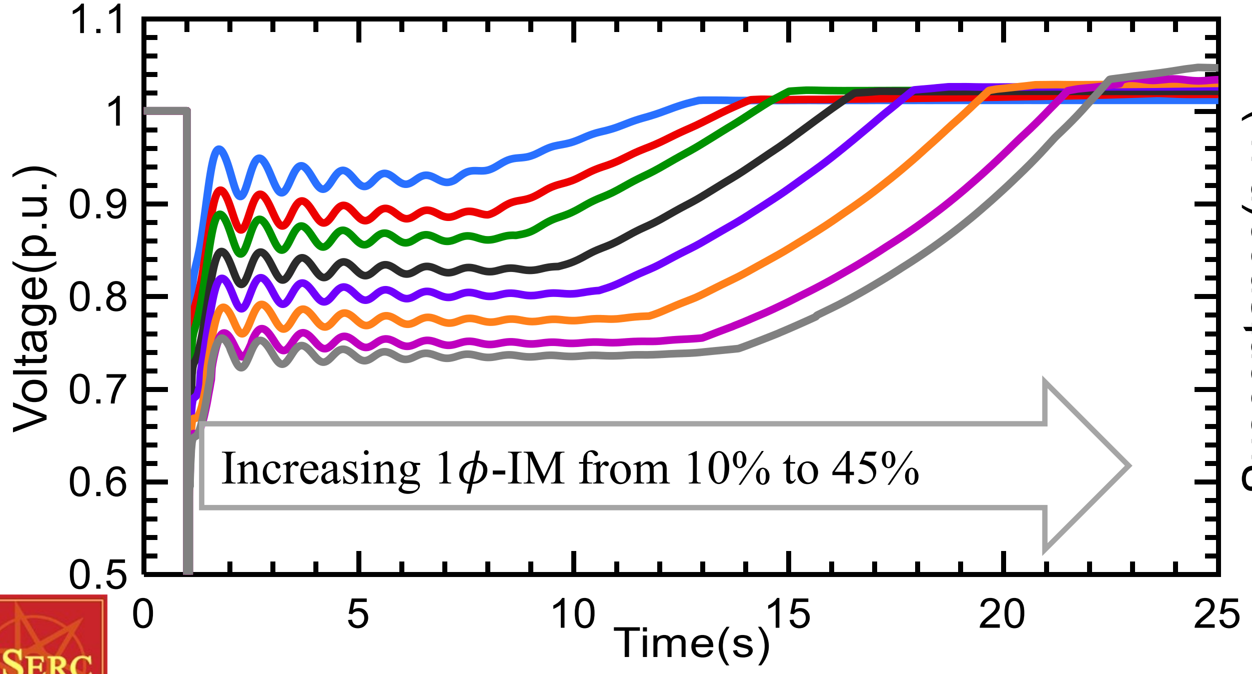
Data-driven Learning for FIDVR Recovery Time

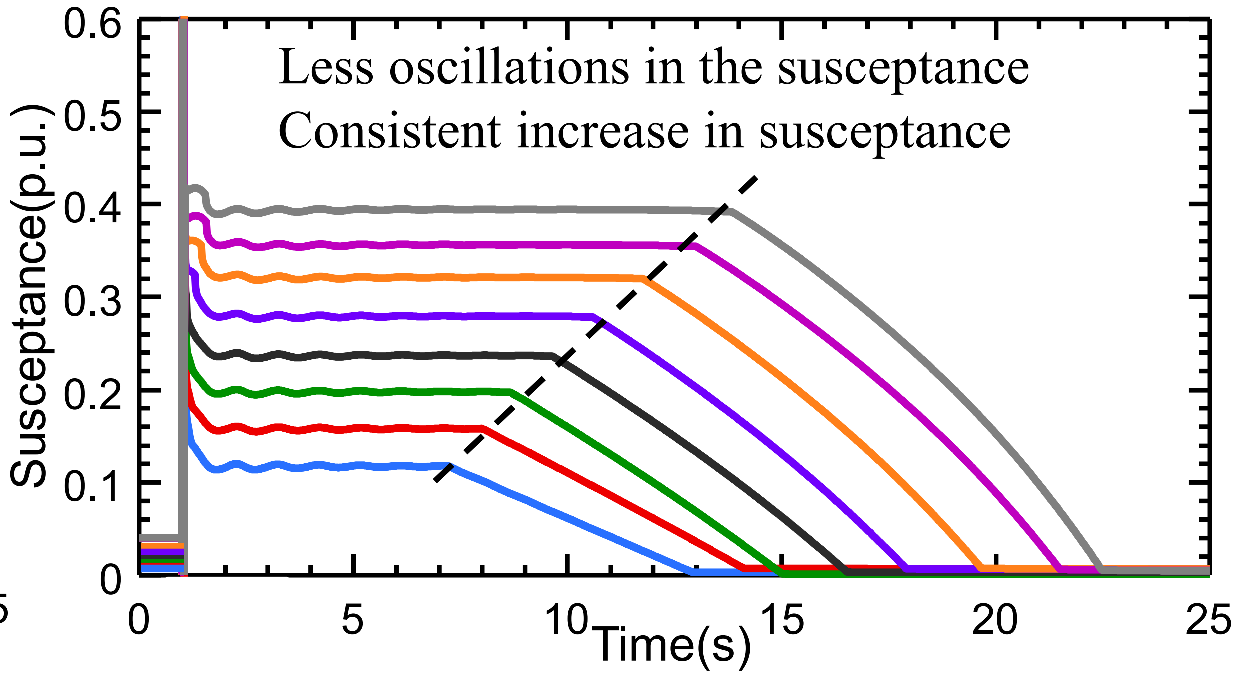
- Estimate the linear regression model for t_1 & t_2 using multiple simulations

$$t_1 = \alpha_0 \cdot B_{stall} + \alpha_1$$
$$t_2 = \beta_0 \cdot B_{stall} + \beta_1$$

Model fits the actual data with >95% accuracy for various systems

- The coefficients encode the behavior of the grid, the load and depend on the disturbance in the grid – plots below show variation for various faults





Recovery Time Prediction – Results on 162 node system

- Coefficients trained on few 1ϕ IM % and tested

1ϕ IM %	Actual $(t_1 + t_2)$	Estimated $(t_1 + t_2)$	Error %
20%	13.6	13	4 %
25%	15.1	14.6	3.2 %
30%	16.5	16.1	2.5 %
35%	18.2	17.5	3.4 %
40%	20	19.1	4.4 %
45%	21	20.5	2 %

- The values of B_{stall} just after fault are used – quick identification of severity

Admittance works for Monitoring. Mitigation ?

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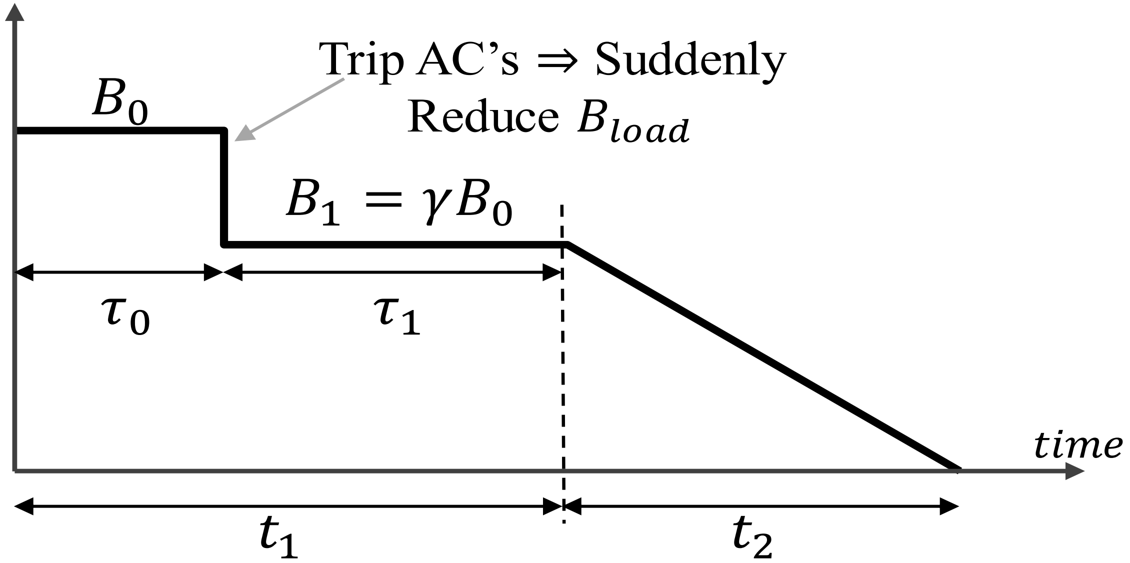
Mitigation of FIDVR using Local Controls

- AC disconnection using smart thermostats is the best approach as these motors are the reason for FIDVR – will lead to sudden drop in B_{stall}



- τ_0 is the control time of AC disconnection and includes communication latency

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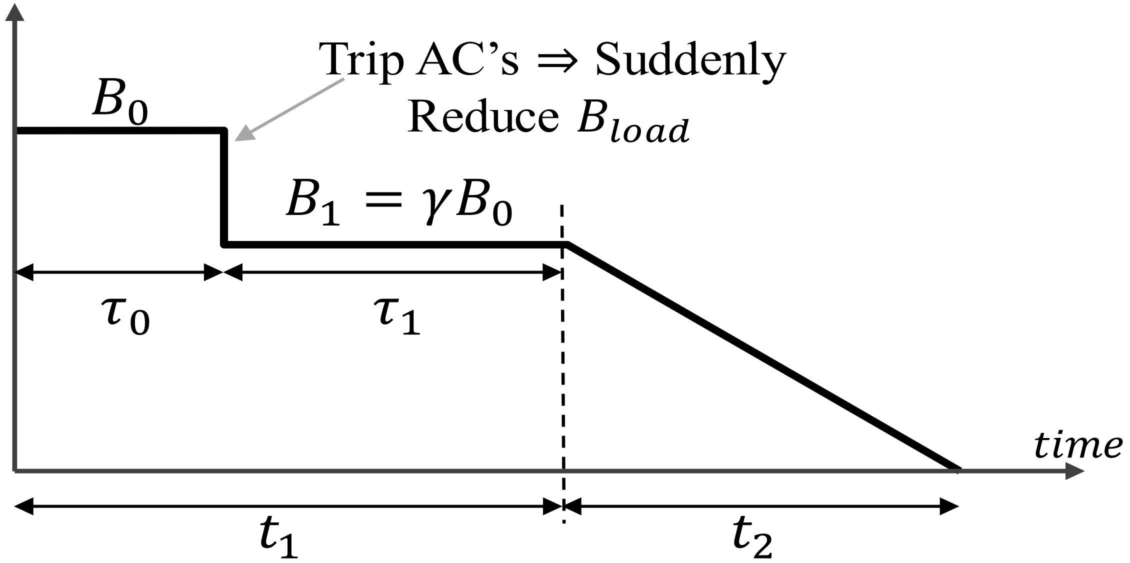
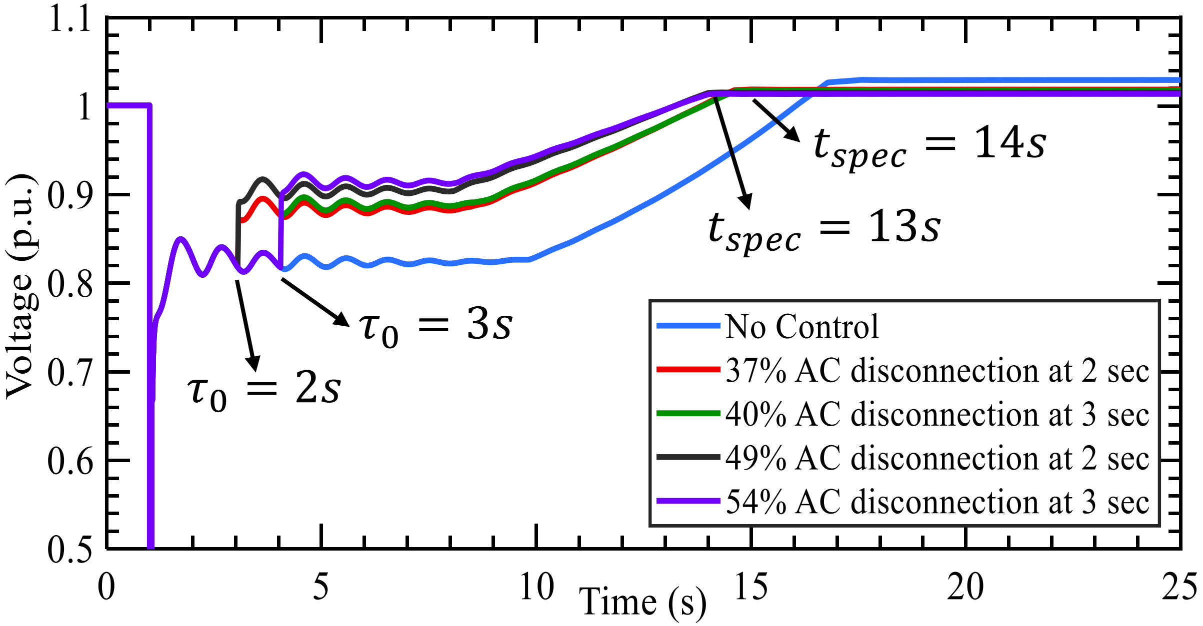


- τ_0 is the control time of AC disconnection and includes communication latency
- Determine γ so that $t_1 + t_2 \leq t_{spec}$
- γ is the solution of a quadratic equation derived from the $\alpha_0, \alpha_1, \beta_0, \beta_1, t_{spec}$ and τ_0

[J1] **Ramapuram Matavalam A.R.;** V. Ajjarapu, "PMU based Monitoring and Mitigation of Delayed Voltage Recovery using Admittances," IEEE Transactions on Power Systems, vol. 34, no. 6, pp. 4451-4463, Nov. 2019, doi: 10.1109/TPWRS.2019.2913742

Results on 162 node system in PSSE

- The actual recovery time with no control is 16 sec.
- Various specified recovery times (t_{spec}) with different AC disconnection time (τ_0) are tested.

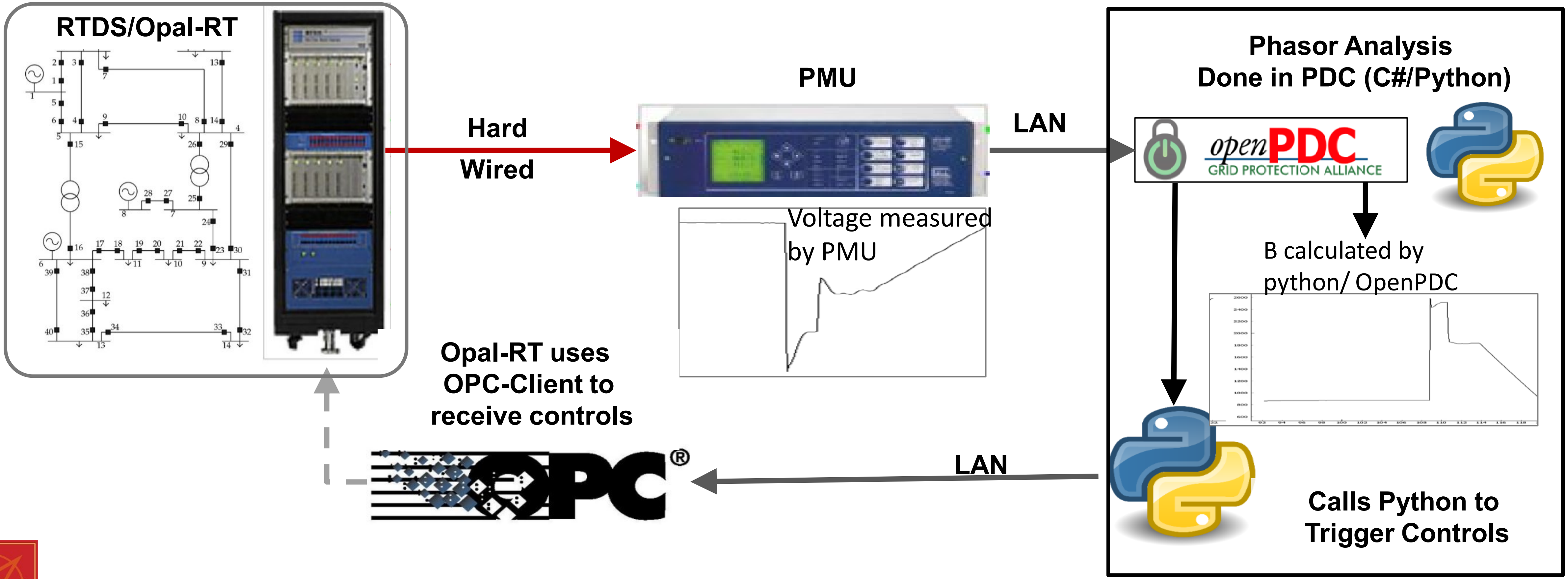


t_{spec}	τ_0	AC disconnect	Actual t_{rec}
14 sec	2 sec	37 %	13.55 s
14 sec	3 sec	40 %	13.45 s
13 sec	2 sec	49 %	12.80 s
13 sec	3 sec	54 %	12.85 s

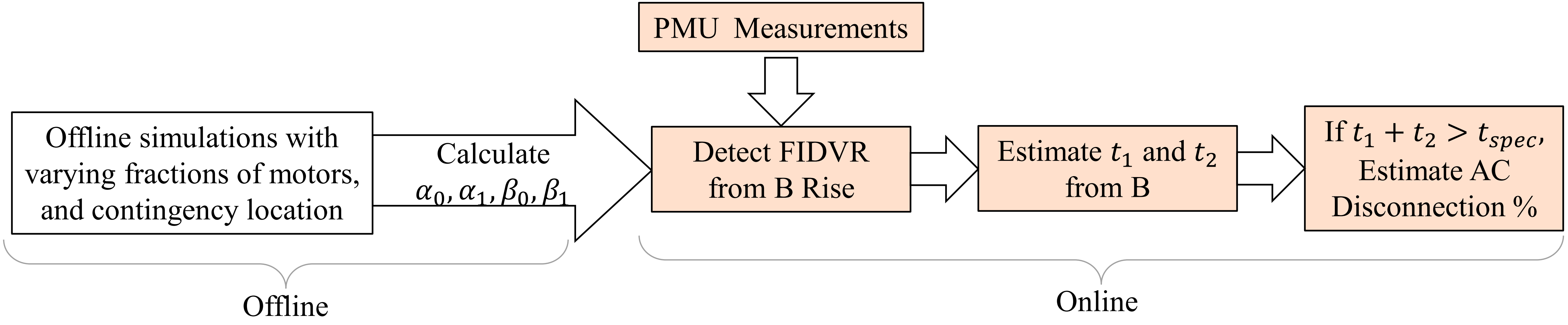
[J1] **Ramapuram Matavalam A.R.;** V. Ajjarapu, "PMU based Monitoring and Mitigation of Delayed Voltage Recovery using Admittances," IEEE Transactions on Power Systems, vol. 34, no. 6, pp. 4451-4463, Nov. 2019, doi: 10.1109/TPWRS.2019.2913742

Results - Cyber Physical Real Time Test Bed

- The Real-Time Cyber-Physical Test Bed consists of Opal-RT, RTDS, SEL-421 PMU's, OpenPDC, Python & MATLAB to perform data analysis
- Composite load model implemented as Modelica Functional Mockup Unit



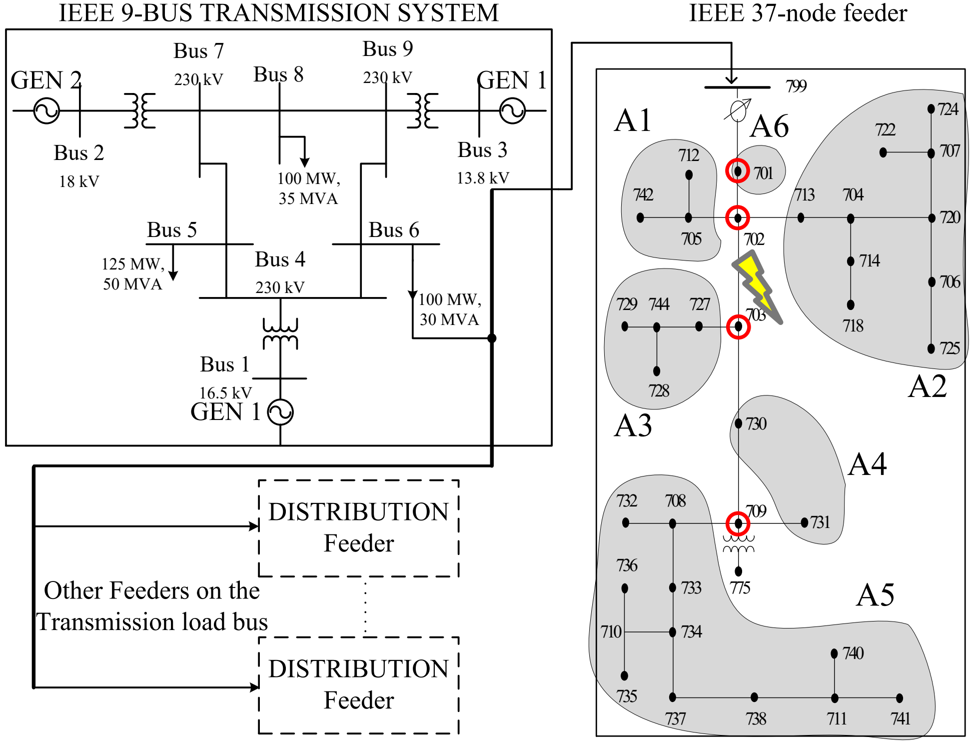
Overall workflow for FIDVR Monitoring & Mitigation



- More robust than purely voltage-based approaches for online FIDVR mitigation
- Also applicable to partial stalling of aggregated 1ϕ motor
- Can be used to systematically design remedial action schemes

[J1] **Ramapuram Matavalam A.R.;** V. Ajjarapu, "PMU based Monitoring and Mitigation of Delayed Voltage Recovery using Admittances," IEEE Transactions on Power Systems, vol. 34, no. 6, pp. 4451-4463, Nov. 2019, doi: 10.1109/TPWRS.2019.2913742

FIDVR in Distribution Feeders with DERs



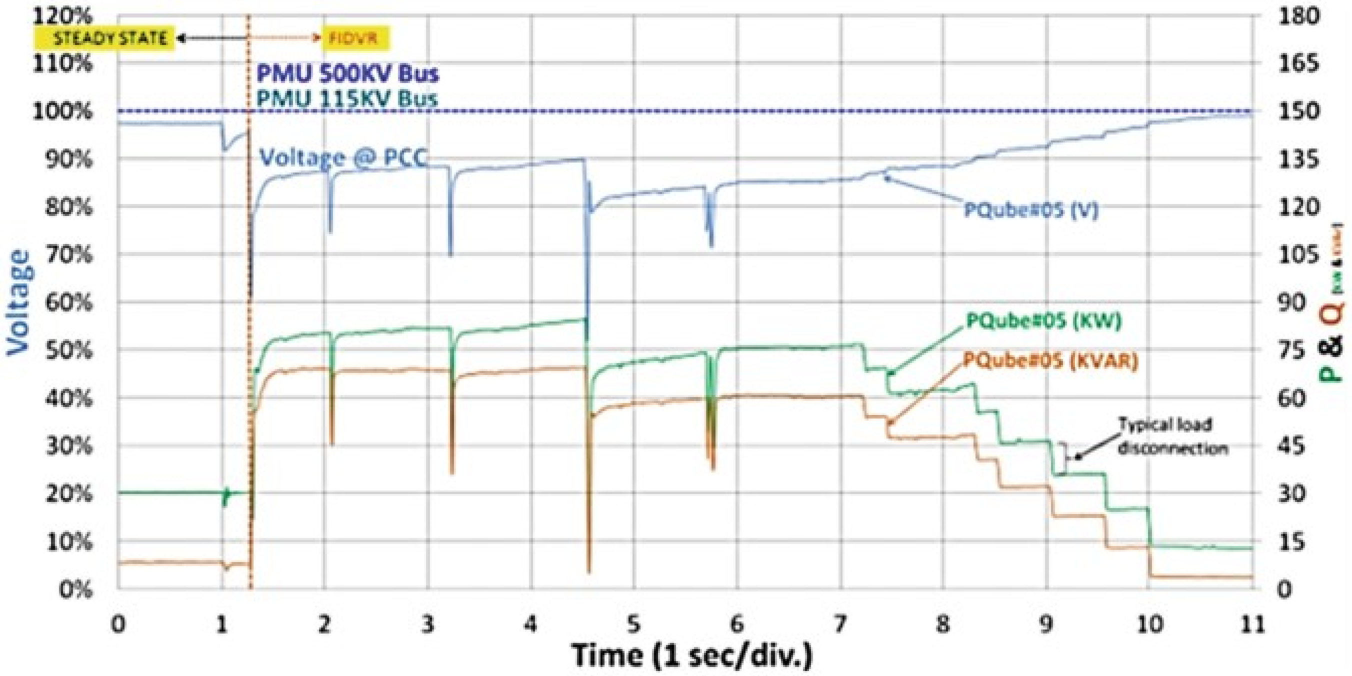
DERs can disconnect if low voltage persists

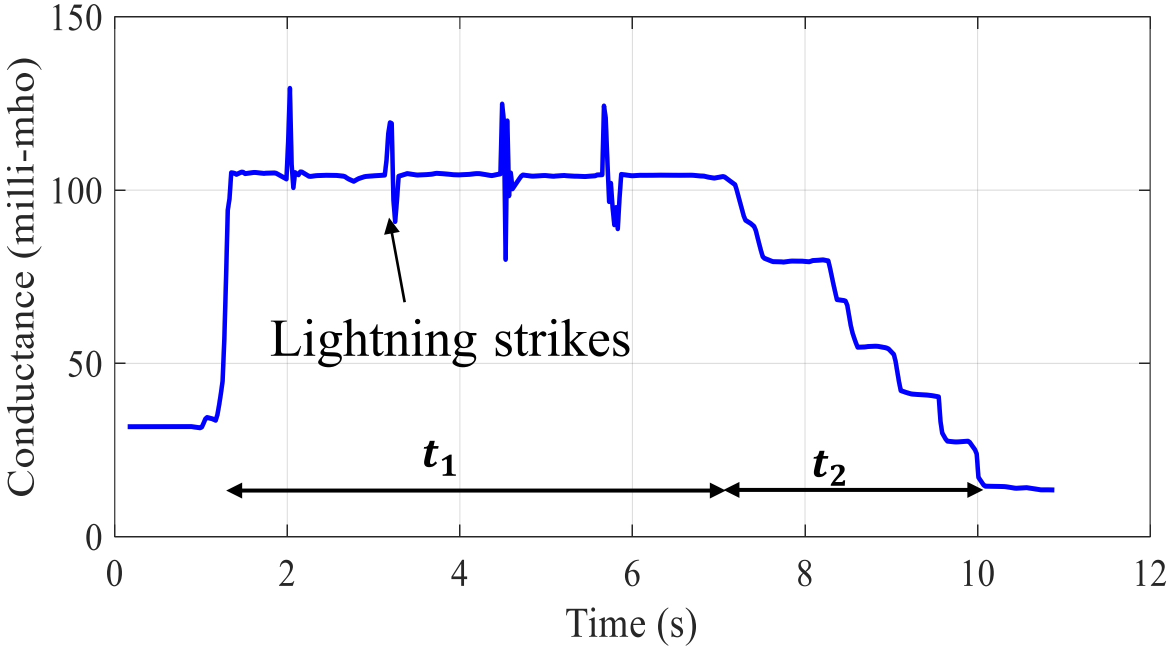
Small geographic footprint – easier for centralized control

[C1] **Ramapuram Matavalam A.R.;** R. Venkatraman; V. Ajjarapu, "Mitigating Delayed Voltage Recovery Using DER & Load Control in Distribution Systems", IEEE PES General Meeting, 2022.

FIDVR Event in Southern California Edison

- Micro-PMUs in distribution node and PMUs at upstream Transmission substations
- Transmission voltage is mostly unaffected – distribution voltage is impacted

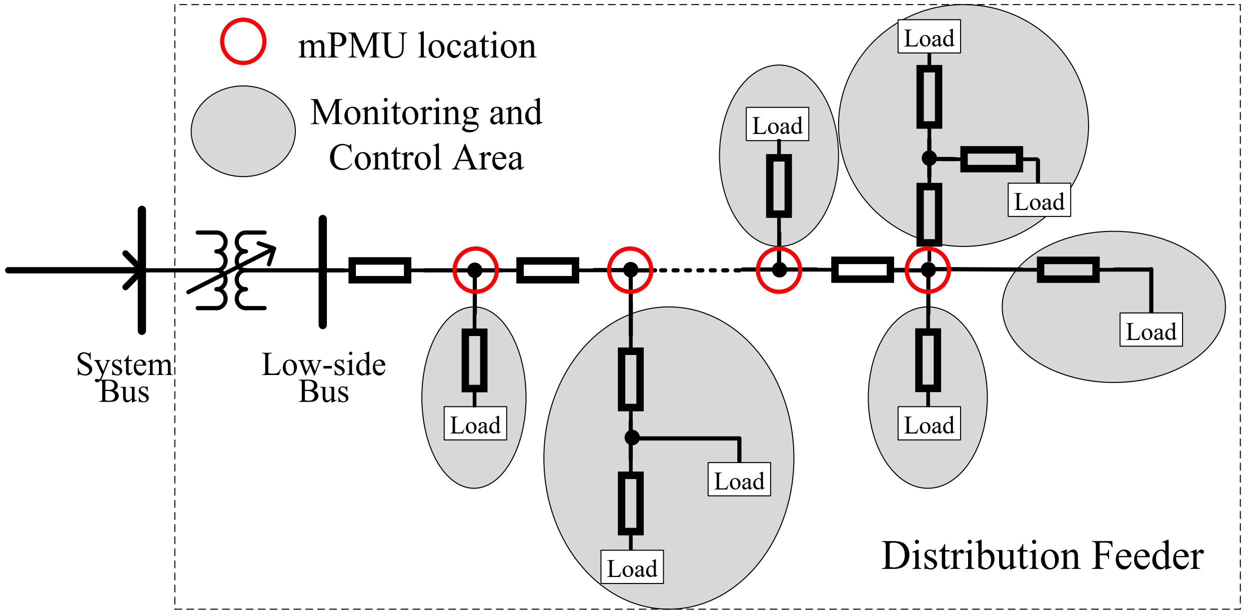




[A] S. Robles, "2012 FIDVR Events Analysis on Valley Distribution Circuits". Prepared for LBNL by Southern California Edison, 2013

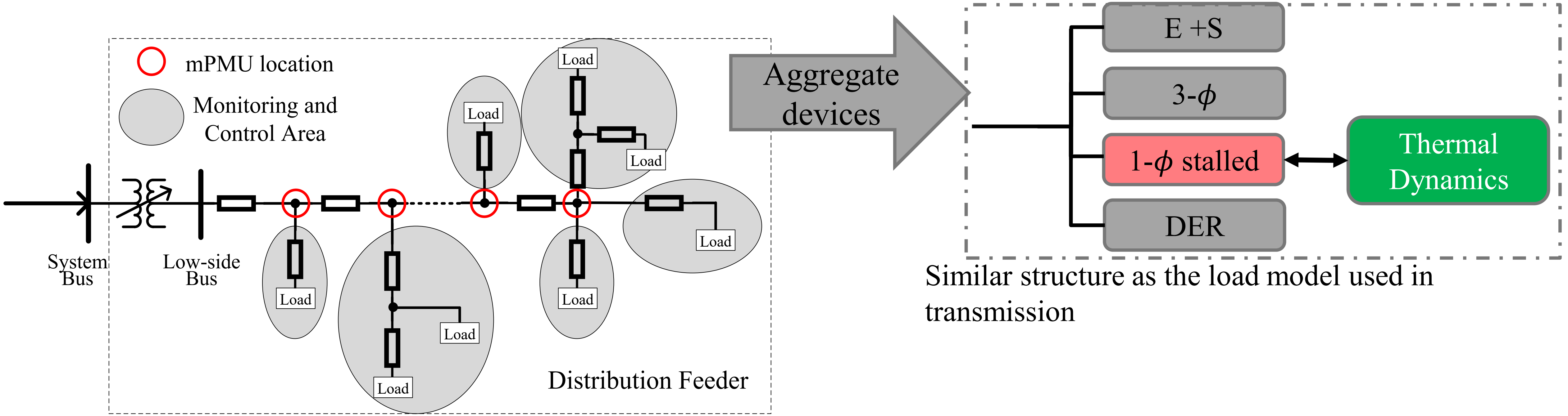
Features of the Distribution Networks

- No oscillations, <u>but voltage measurements cannot localize FIDVR</u>. <u>Admittance can localize FIDVR.</u>
- DER control ⇒ Analytical expressions of $t_1 + t_2$ should be used



Features of the Distribution Networks

- DER control ⇒ Analytical expressions of $t_1 + t_2$ should be used
- Radial nature allows aggregation of devices for monitoring with less μPMUs
- Deploy control on Full System – OpenDSS + MATLAB



Similar structure as the load model used in transmission

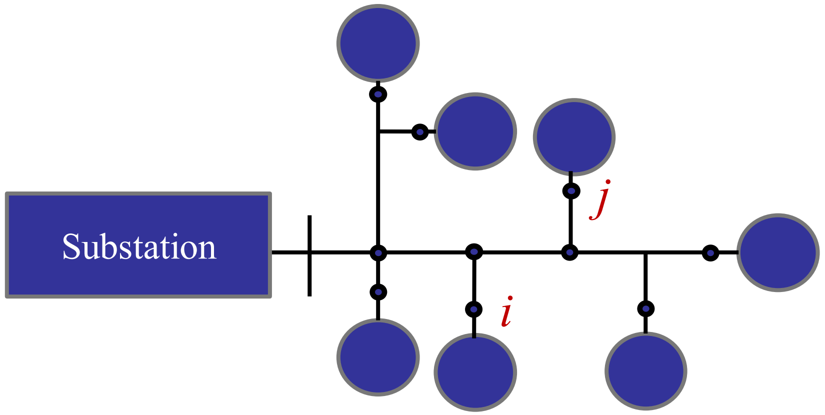
Ramapuram Matavalam A.R.; R. Venkatraman, V. Ajjarapu, "Monitoring and Mitigation of Delayed Voltage Recovery using µPMU based Reduced Distribution System Model,", https://arxiv.org/abs/1810.09510

Linear Formulation with DER + Load control

- Voltage at cluster j changes due to control (u_{AC} & u_{DER}) at cluster i

$$t_{1,\mathrm{j}} \approx -k_0 \cdot \ln\left(1 - k_1/\left(V_{stall,j}^2 \cdot B_{stall,j}\right)\right)$$

$$t_{2,j} \approx \frac{2k_2}{\left(\left(V_{stall,j}^2 + 1\right)B_{stall,j} - k_3\right)}$$



- Linear approximation for the change in recovery time

Change in FIDVR recovery time at j

Depends on load parameters

Depends on distribution system topology and load

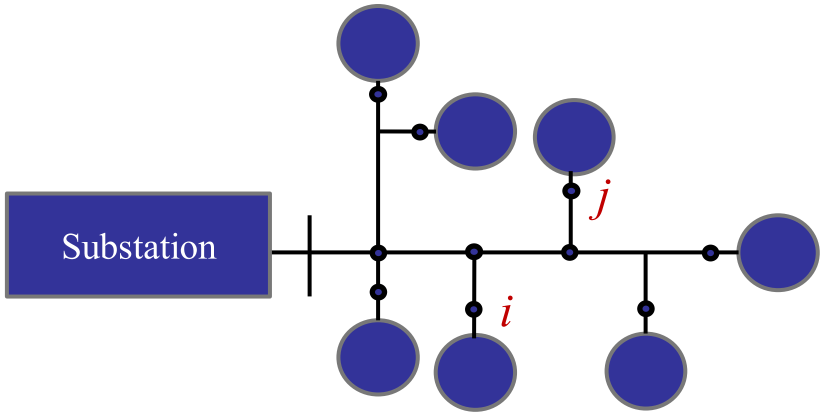
AC control at i

$$\Delta t_{rec,j} \approx \sum_{i=1}^{N} \left(\frac{dt_{1,j}}{dV_{stall,j}} + \frac{dt_{2,j}}{dV_{stall,j}}\right)\left[\frac{\partial V_{stall,j}}{\partial u_{AC,i}} \quad \frac{\partial V_{stall,j}}{\partial u_{DER,i}}\right] \cdot \begin{bmatrix} u_{AC,i} \\ u_{DER,i} \end{bmatrix}$$
$$+ \left(\frac{dt_{1,j}}{dB_{stall,j}} + \frac{dt_{2,j}}{dB_{stall,j}}\right) u_{AC,j}$$

DER Q-injection at i

Control Formulation – Linear Approximation

- Linear approximation for the change in recovery time at cluster j due to control (u) at cluster i
- More generally, $\Delta t_{rec} = A \cdot u$



$$\min c^T \cdot |u|$$

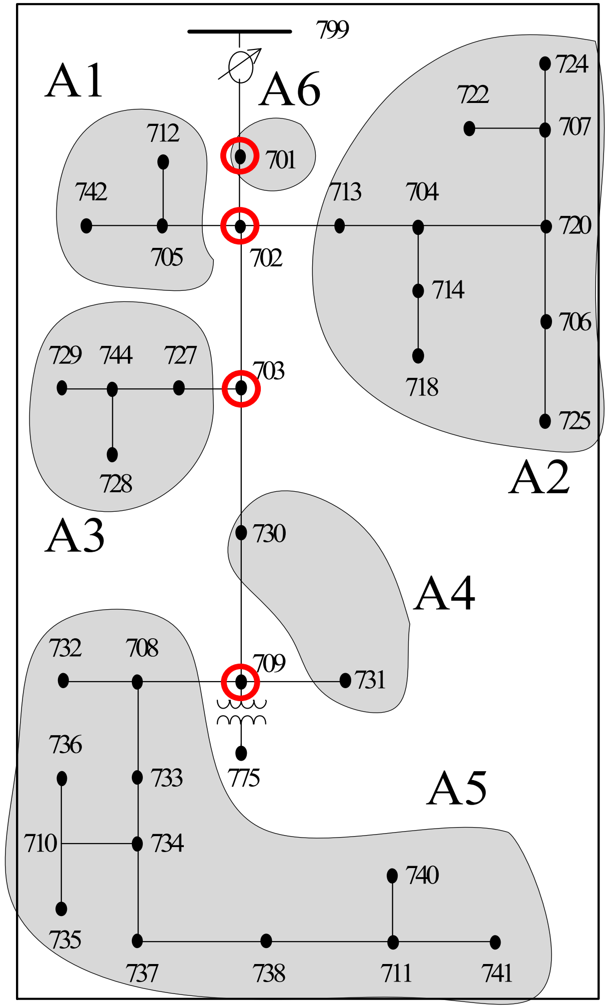
s.t.

$$A \cdot u \geq t_{spec} - t_{rec}$$

$$u_{min} \leq u \leq u_{max}$$

- Different control constraints can be applied
- Limit 50% AC disconnection in each area
- DER Q-injection up to 44% of rating as per IEEE 1547

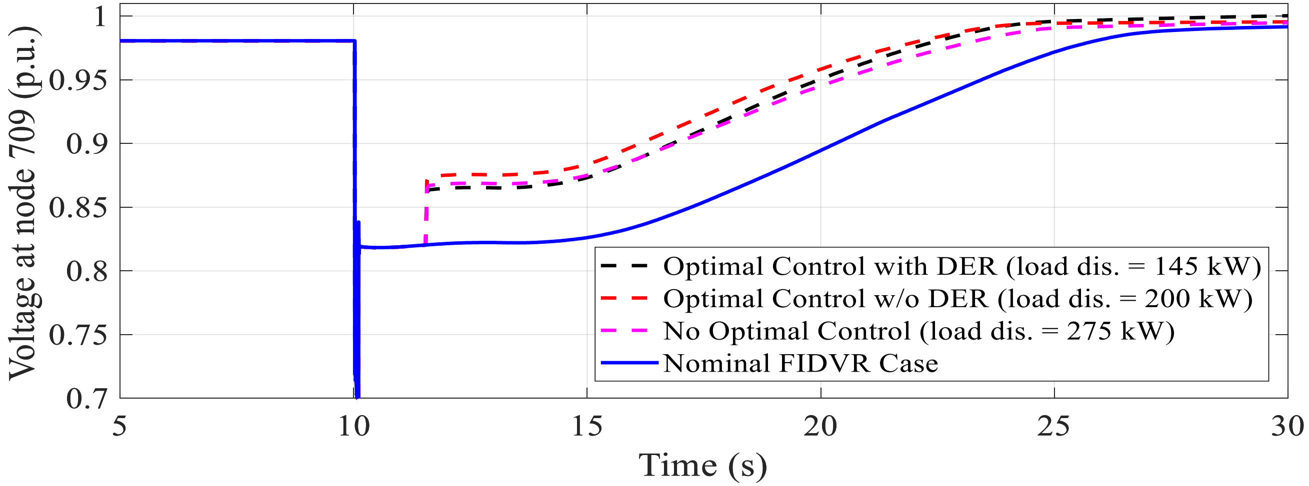
Online FIDVR mitigation in IEEE 37 node feeder – 25% DER



- Control triggered 2s after FIDVR detected, $\Delta t_{rec} = 3.5s$

Control Method	Total Load Disconnection
Uniform load control	275 kW
Optimal load control	200 kW
Optimal load + DER control	145 kW

- Load control reduction of 40%



[C1] **Ramapuram Matavalam A.R.;** R. Venkatraman; V. Ajjarapu, "Mitigating Delayed Voltage Recovery Using DER & Load Control in Distribution Systems", IEEE PES General Meeting, 2022.

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Conclusion

- The admittance-based approach can successfully *localize regions of motor stalling* and quantify the severity of FIDVR in both transmission and distribution systems
- The physics inspired reduced model based on admittances and thermal dynamics can *simplify the FIDVR* analysis and provide analytical recovery times
- The linear relation derived from the data can be used to both *monitor and mitigate FIDVR* in transmission systems
- The optimization formulation based on the recovery time sensitivities can utilize the DER Q-injection and can *reduce the load disconnection* by 40%

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Questions ?

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