Arizona State University

Localizing and Mitigating Delayed Voltage Recovery in Distribution Systems via DER & Load Control

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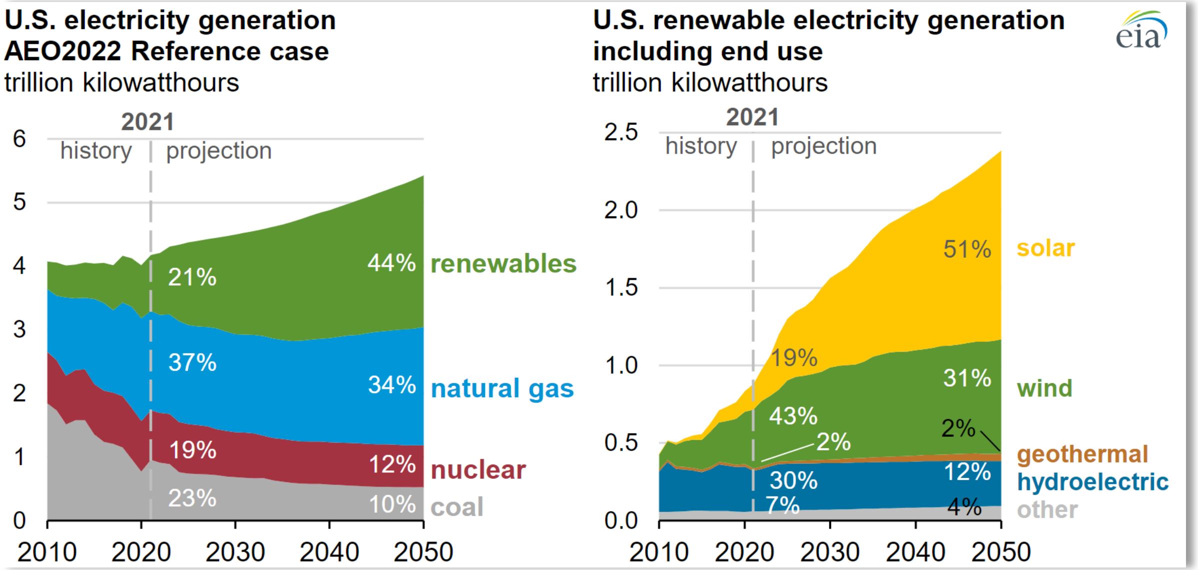
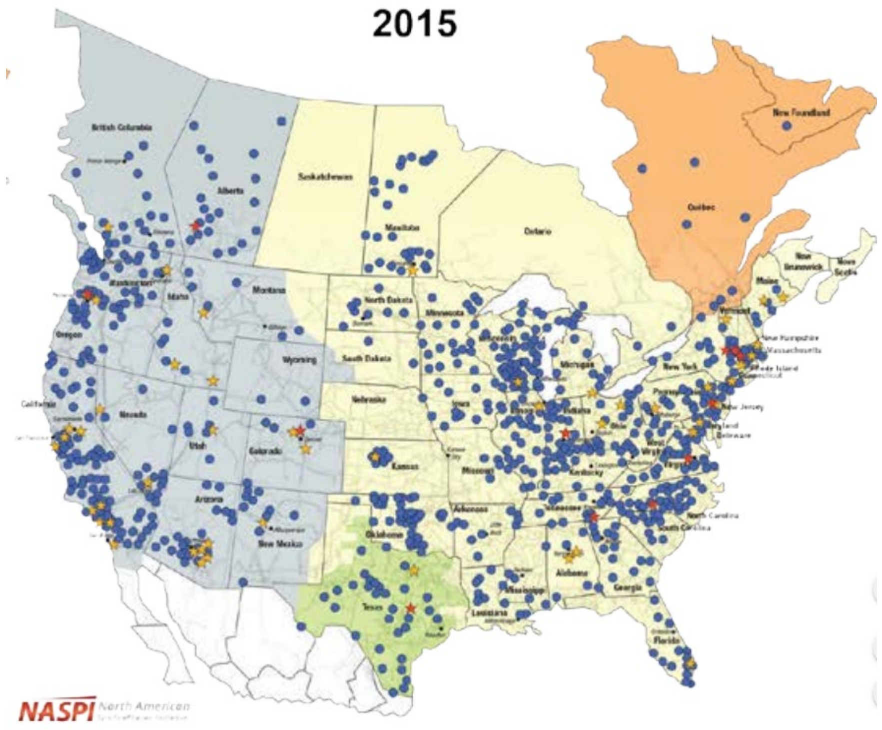
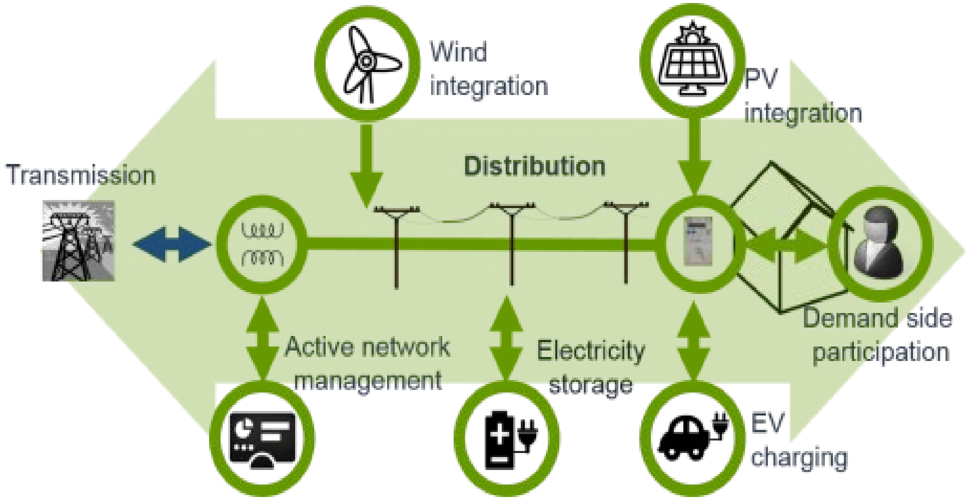
PSERC

Broad Trends in Power Systems – IBRs & PMUs







Increasing sensors in T&D – Online Monitoring & Control

Renewables Rising Rapidly in T&D grid

Source: EIA Annual Energy Outlook 2022, U.S. Energy Information Administration - EIA - Independent Statistics and Analysis

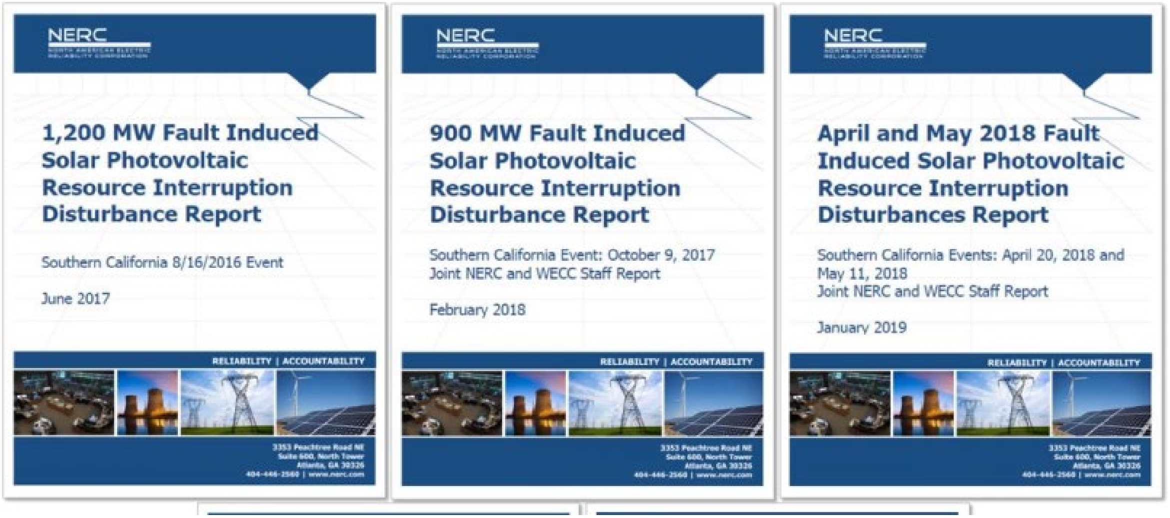
Challenges and Opportunities

The increasing IBRs reduce damping, inertia while introducing variability

Increasingly complex dynamics due to increasing IBRs, especially in D-system

Use the flexibility of bulk IBRs+DERs to provide support – IEEE P2800, IEEE 1547 & FERC 2222

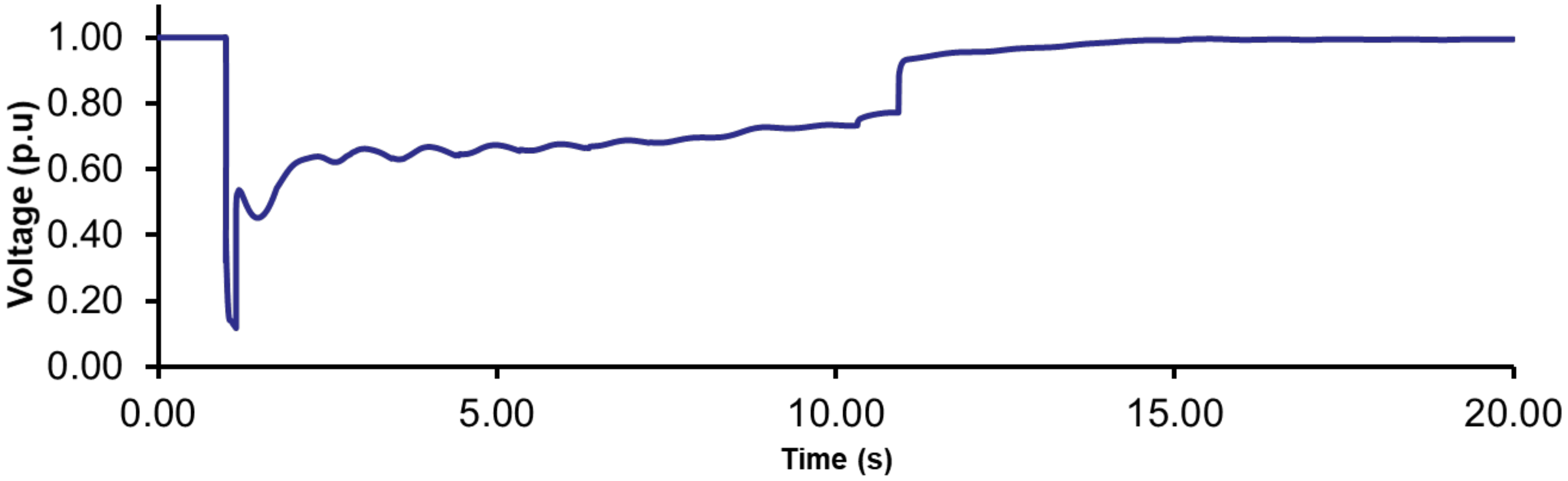
Use sensors to monitor and analyze the dynamics to quickly identify & control instability



Fast Frequency Response, Q-V control, etc.

Focus on Online Short-Term Voltage Instability Monitoring & Mitigation in Distribution System

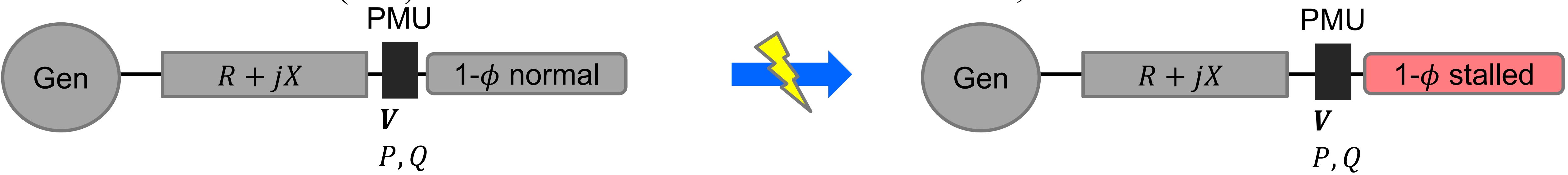
Fault Induced Delayed Voltage Recovery (FIDVR)



[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 California, 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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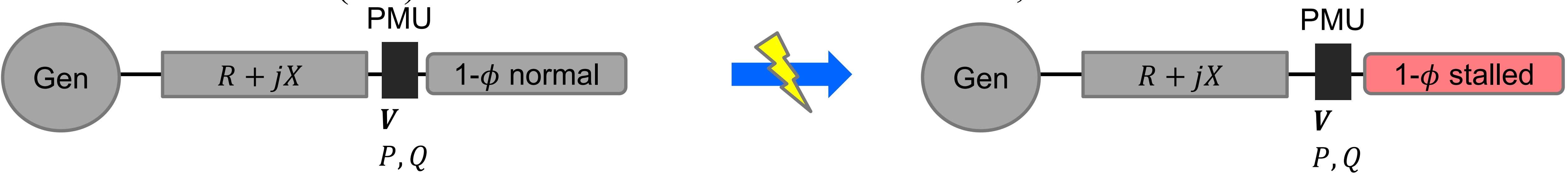

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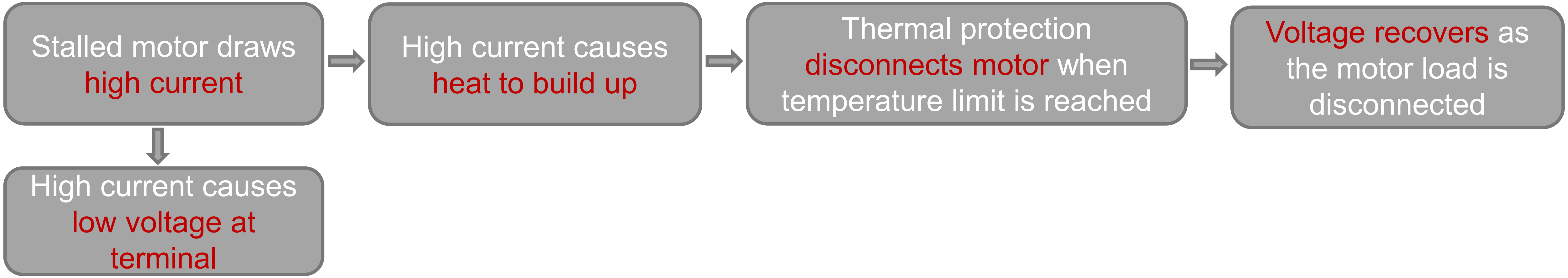

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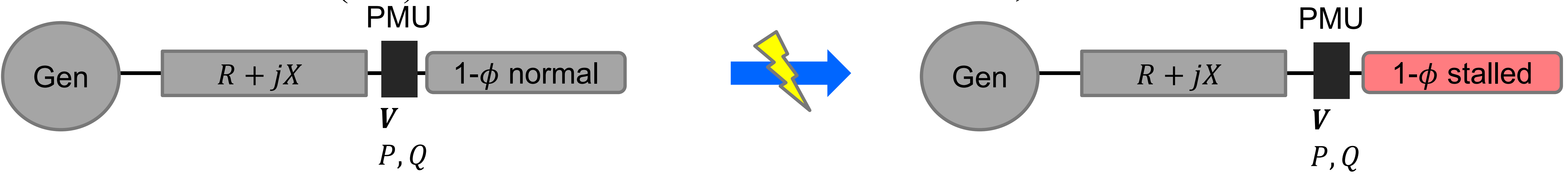

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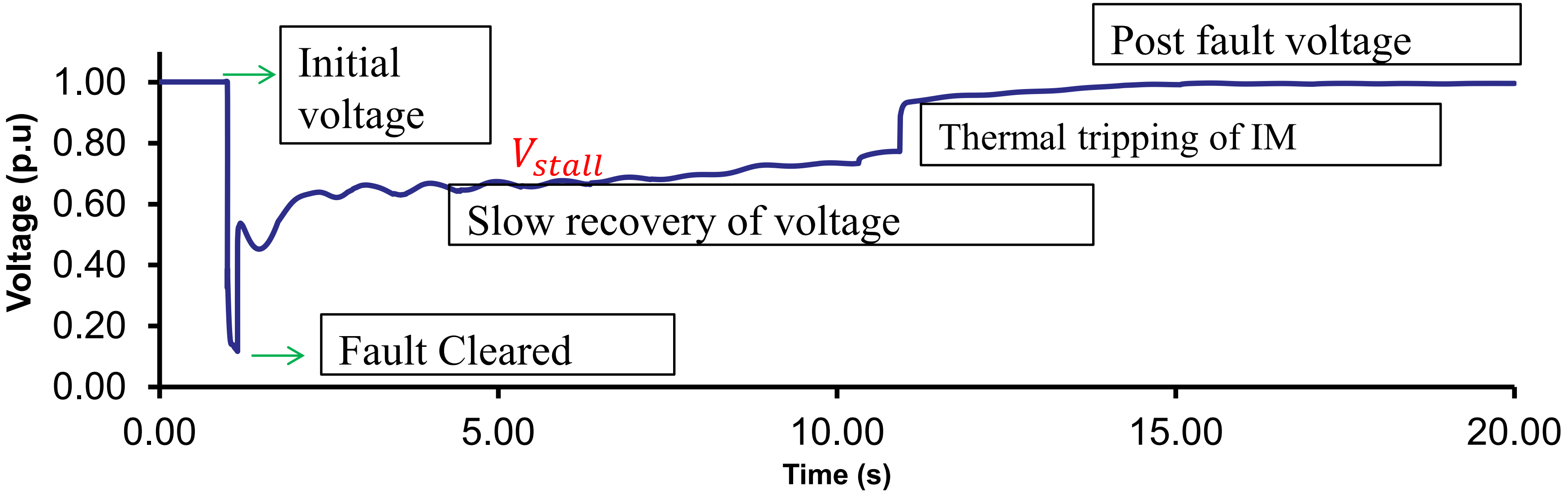

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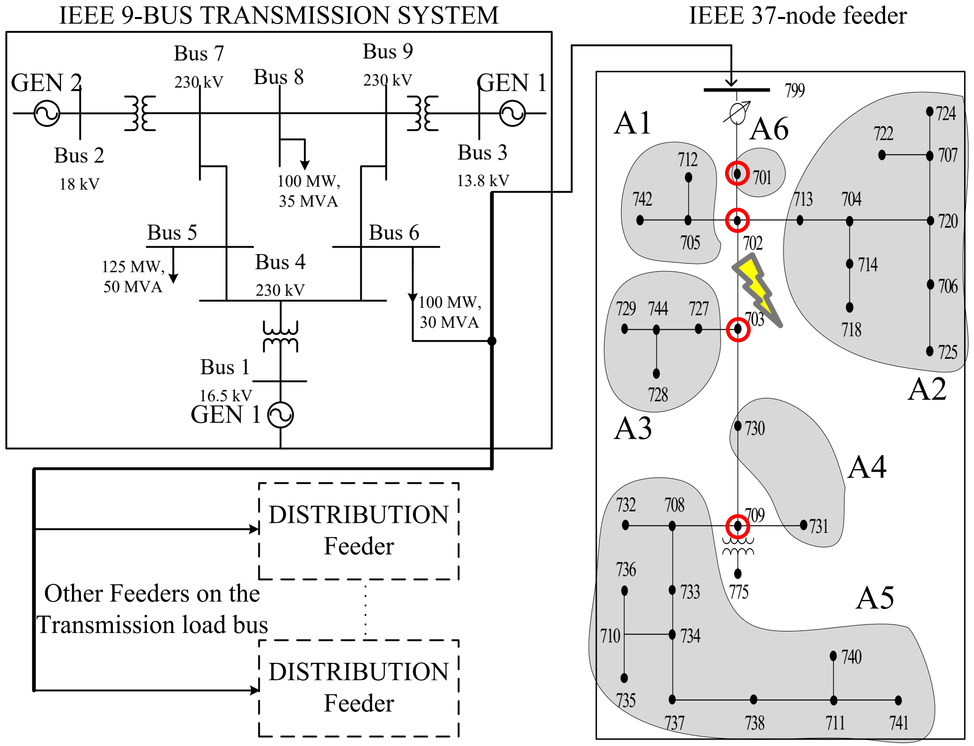
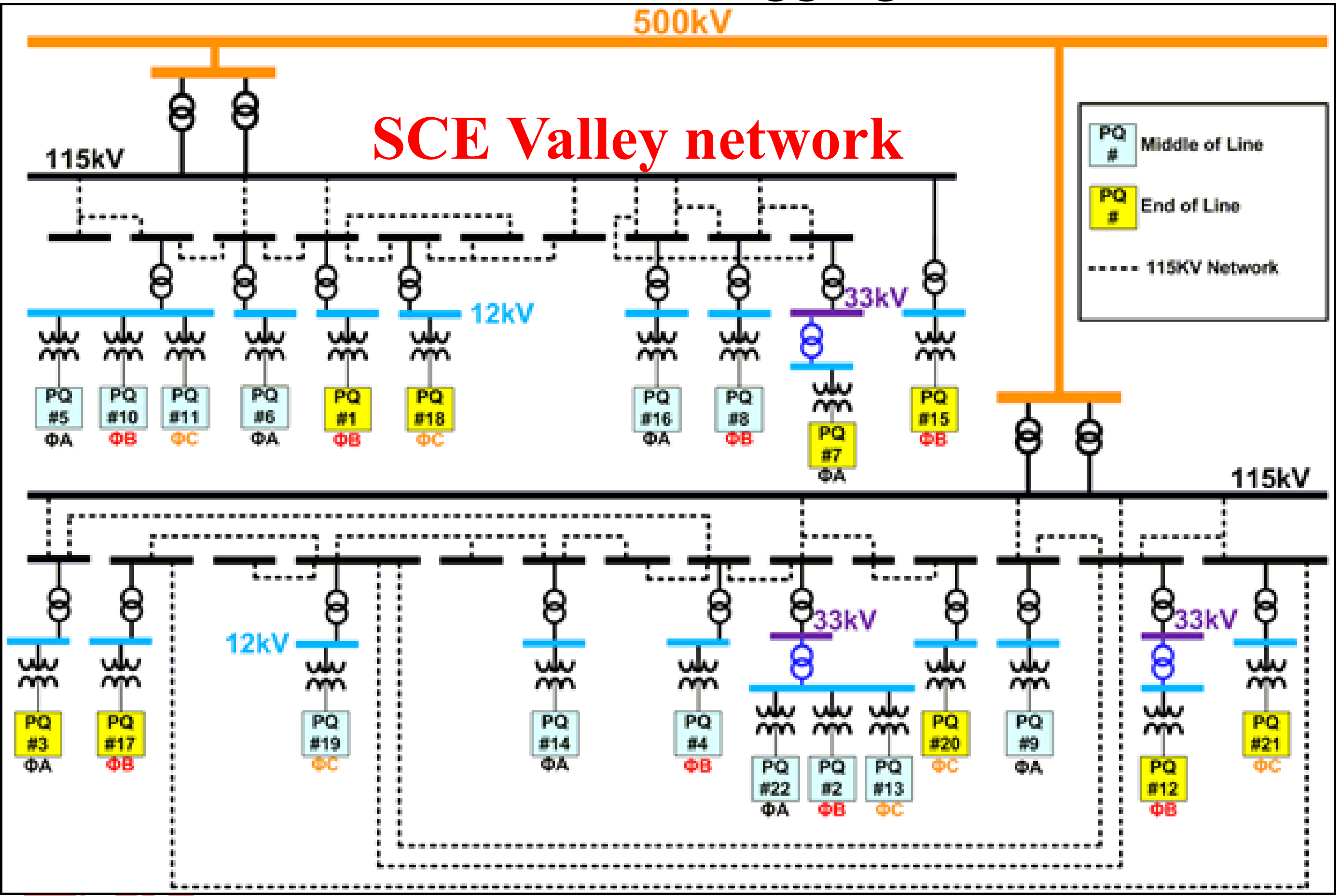
FIDVR in Distribution Feeders with DERs

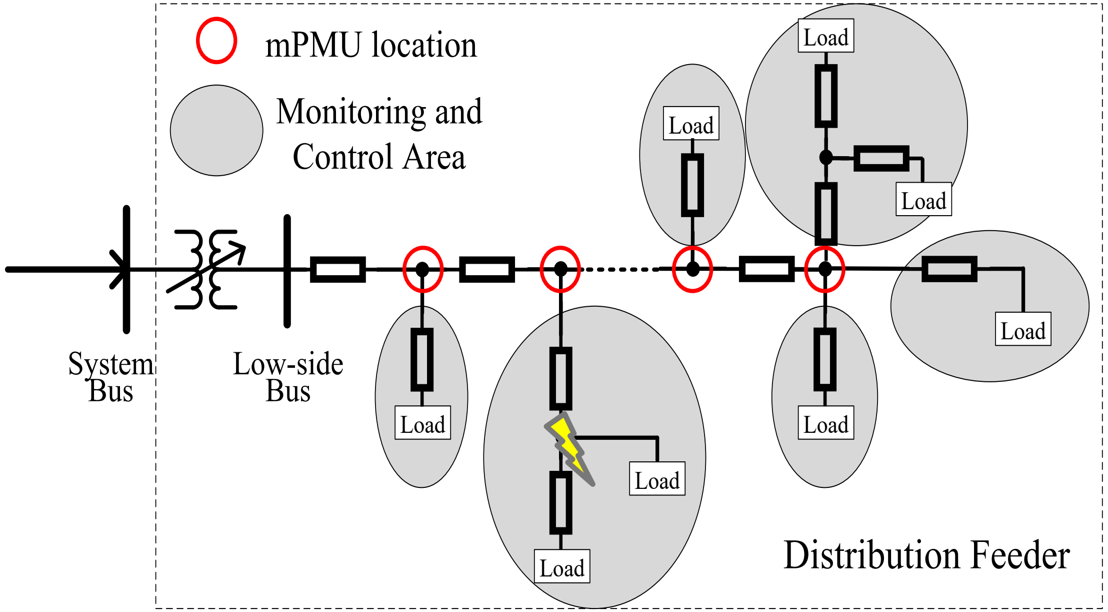


[C1] **Ramapuram Matavalam A.R.;** R. Venkatraman; V. Ajjarapu, "Mitigating Delayed Voltage Recovery Using DER & Load Control in Distribution Systems", IEEE PES General Meeting, 2022.

Features of the Distribution Networks

- Transmission voltage is mostly unaffected – distribution voltage is impacted.
- Voltage measurements *cannot* localize FIDVR due to radial topology.
- Radial nature allows aggregation of devices for monitoring with less μPMUs

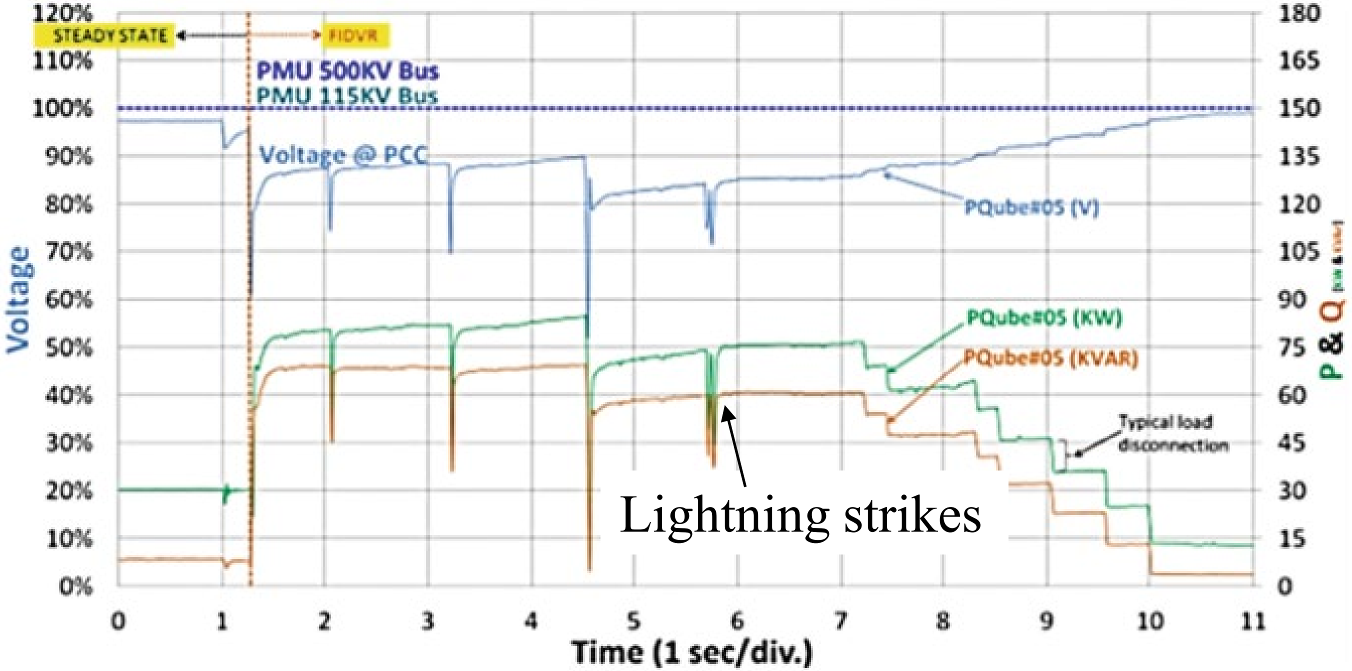


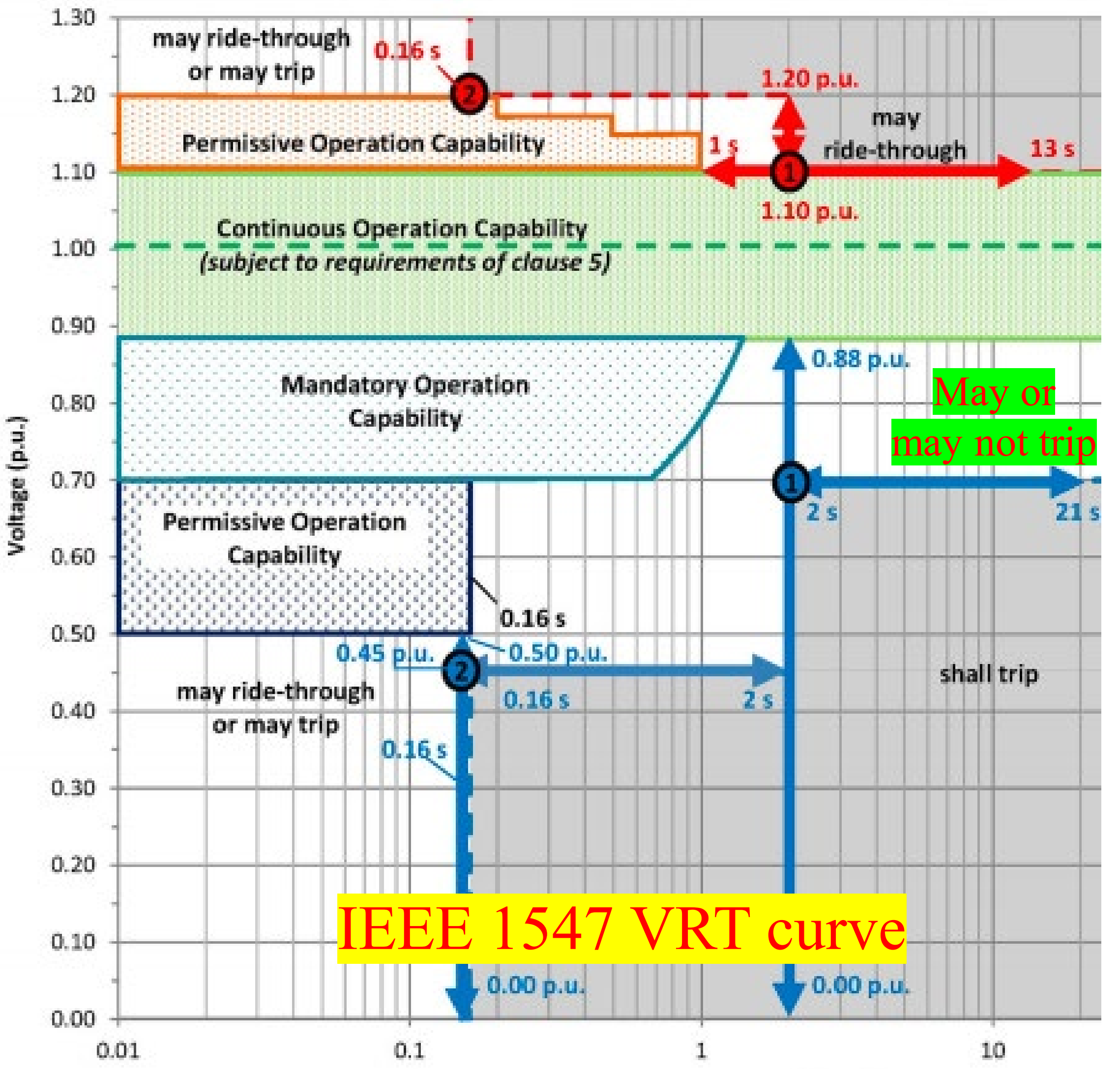


[A] S. Robles, "2012 FIDVR Events Analysis on Valley Distribution Circuits". Prepared for LBNL by Southern California Edison, 2013

FIDVR Event in Southern California Edison

- D-PMU (#5) in distribution and PMU at upstream Transmission substation
- DERs can disconnect due to low voltage based on settings– low voltage may spread to other feeders in the distribution system

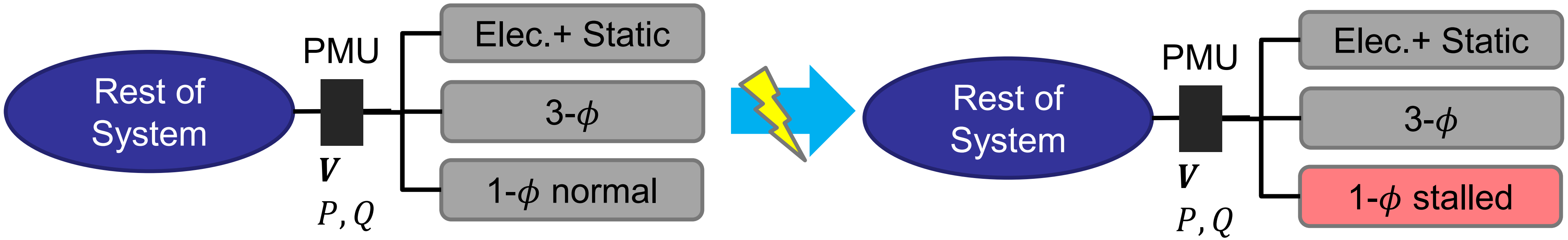




How to characterize and localize FIDVR Reliably?

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

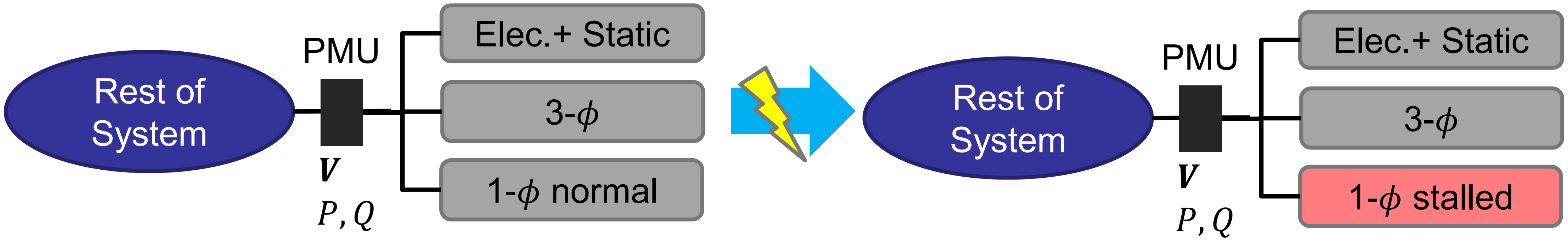
FIDVR Modelling – Composite load model



- The composite load model is the state-of-the-art model for FIDVR as it aggregates the behavior of several loads
- Challenge: The voltage is the symptom and NOT the cause of the phenomenon. The voltage behavior is a result of multiple system level phenomenon. How do we localize the cause of FIDVR?

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. How do we localize the cause of FIDVR?
- Solution: The stalled 1ϕ IM is an admittance, so estimate it from measurements & model.

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

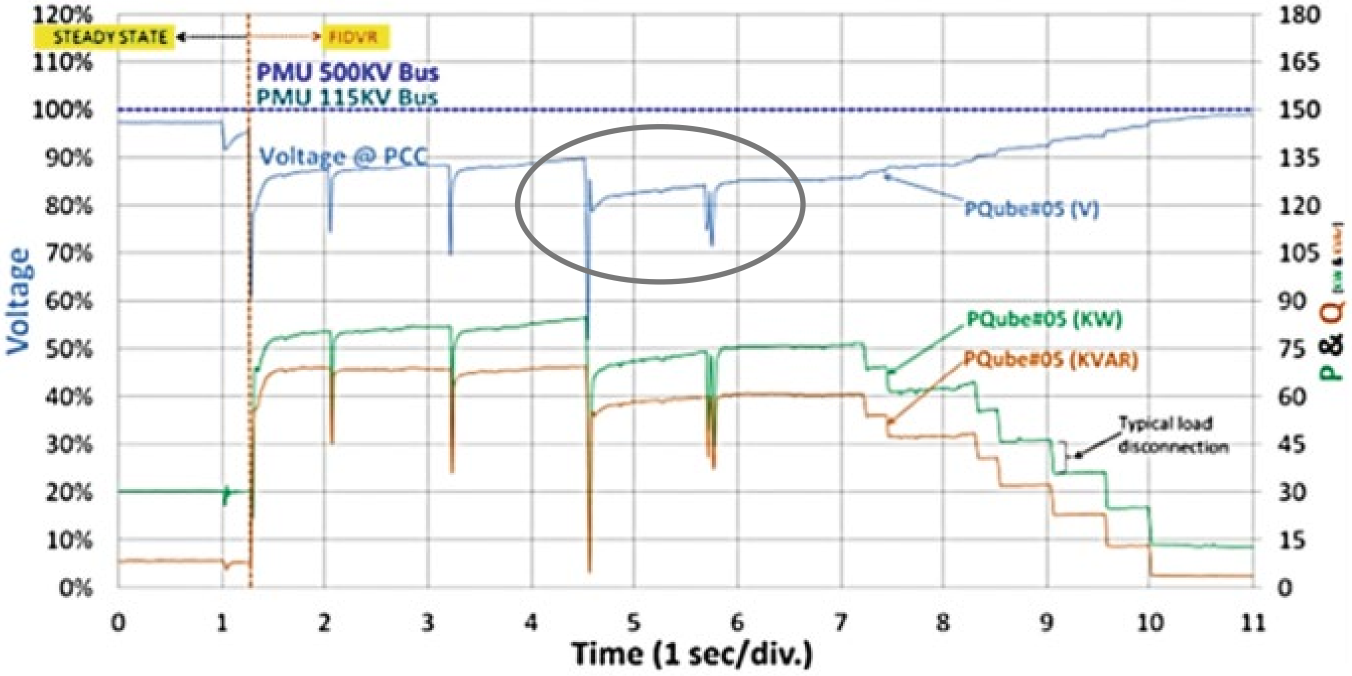
$Y_{PMU} = \dfrac{P + jQ}{|\boldsymbol{V}|^2}$

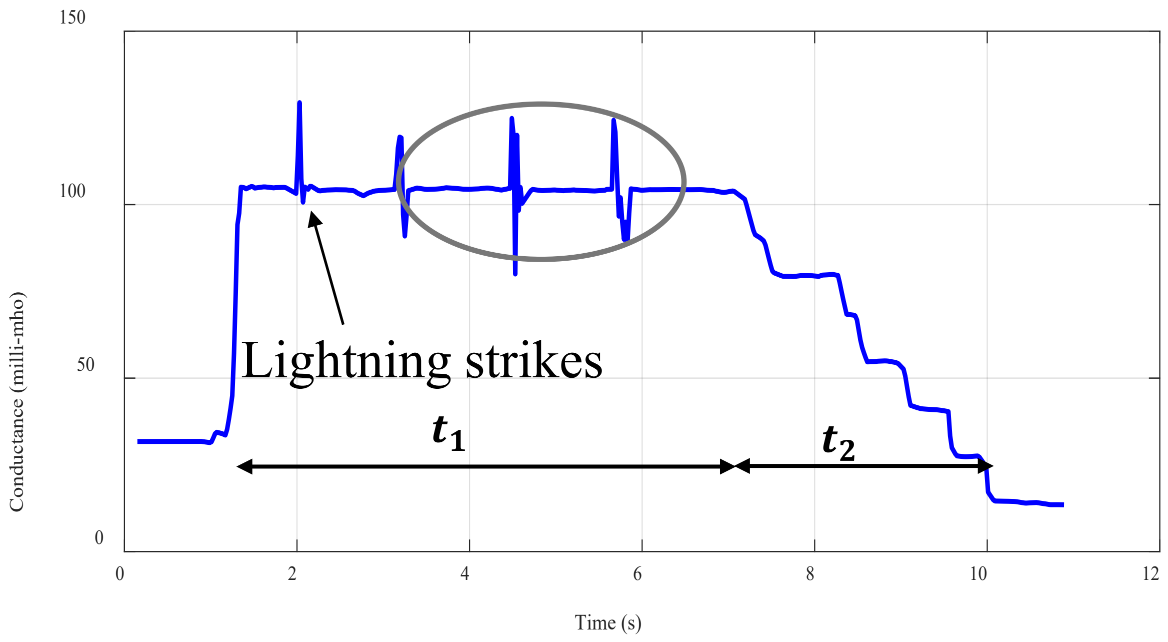
$(Y_{elec} + Y_{stat} + Y_{3\phi})$: Function of Voltage and Model

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

FIDVR Event in SCE Analyzed by Admittances

- Reconstructed total conductance plots for real FIDVR events in distribution & transmission systems – from P, Q and V data [A]
- Admittance *can* localize FIDVR & Admittance identifies no more stalling after the first lightning strike – Recovery time is a good indicator of FIDVR severity
- Similar behavior seen on transmission data [B]



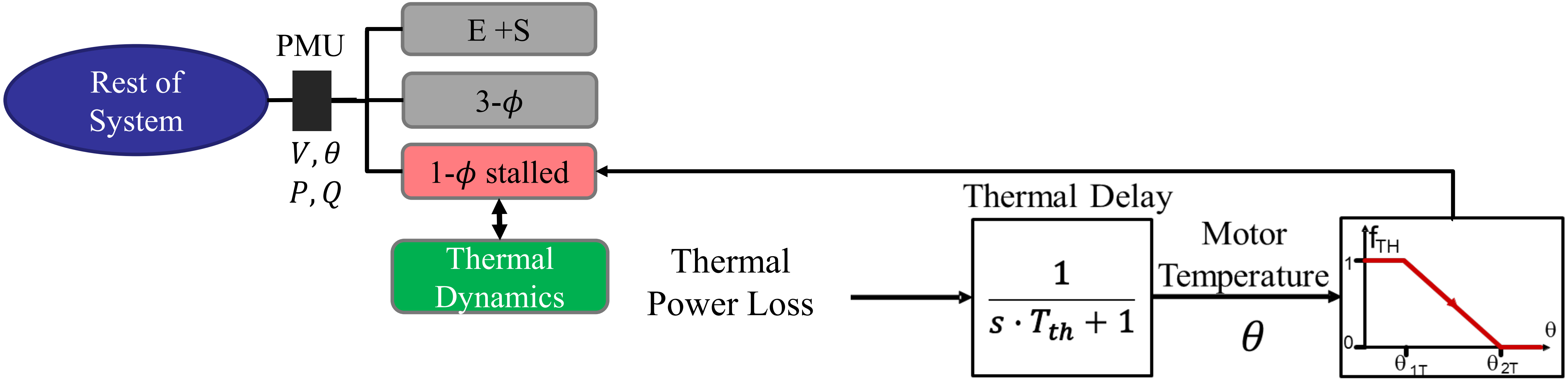


[A] S. Robles, "2012 FIDVR Events Analysis on Valley Distribution Circuits". Prepared for LBNL by Southern California Edison, 2013

[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

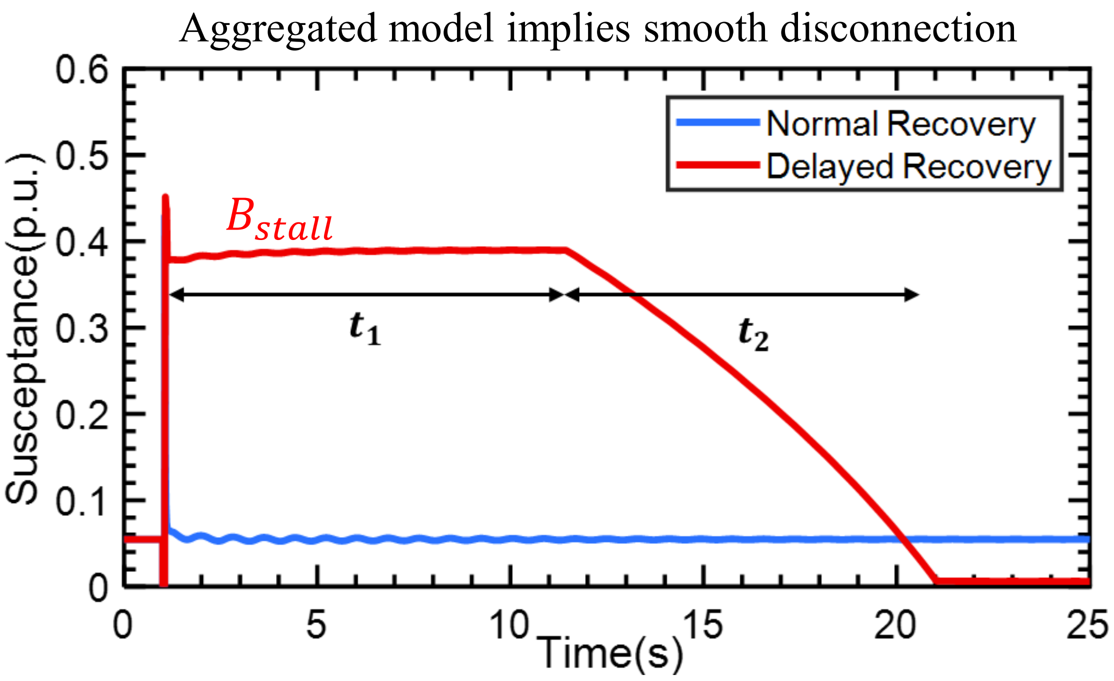
- The stalled admittance of the 1ϕ IM varies with time due to thermal protection.



- 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



Solving the non-linear differential equations leads to:

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

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

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

Total recovery time = $t_1 + t_2$

Use t_1 & t_2 expressions with B_{stall}, V_{stall} to capture total recovery time for characterizing FIDVR severity

[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

Recovery Time Prediction for 37 Node System

- Simulated in OpenDSS + MATLAB
- Coefficients trained on few 1$\boldsymbol{\phi}$ IM % and tested

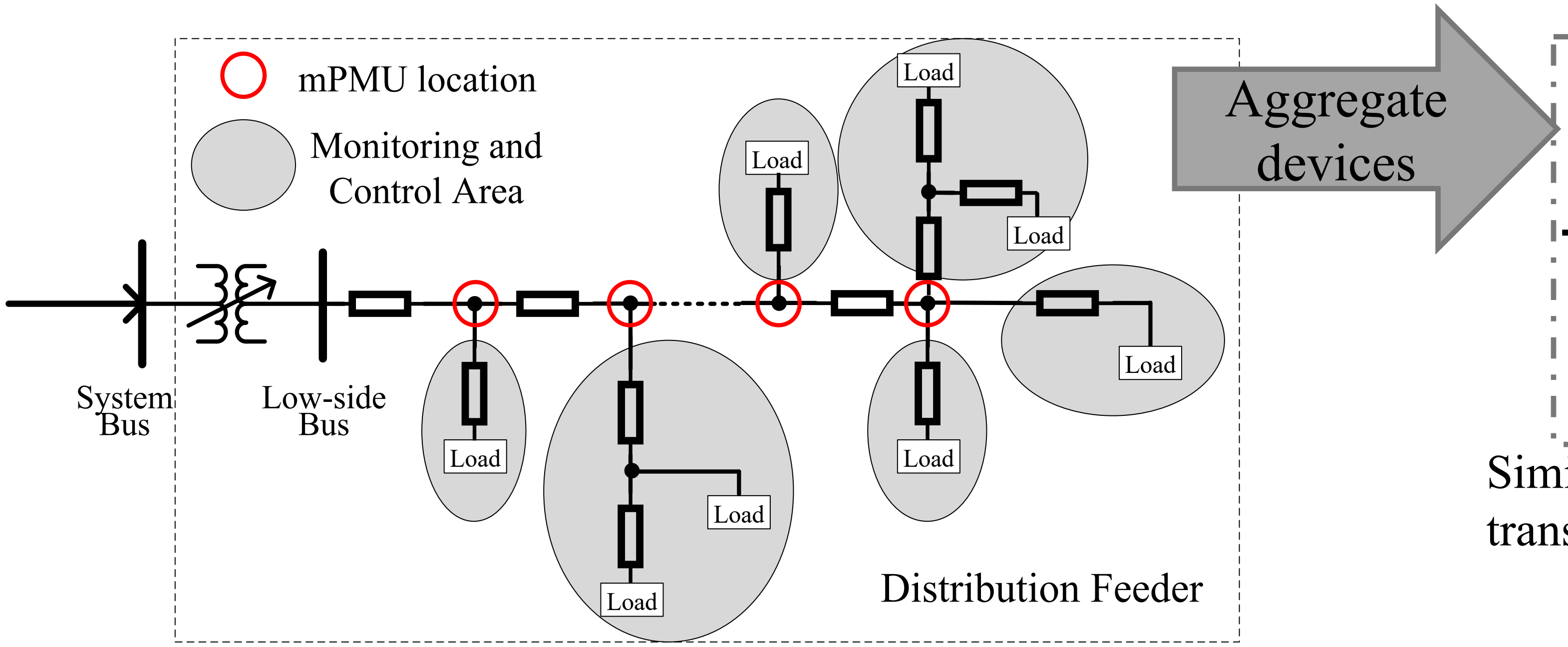
Fault location	Fault duration	Actual t_{total}	Estimated t_{total}	Abs. Error (%)
701 (near substation)	80 ms	15.7 s	14.9 s	5 %
	65 ms	11.4 s	12.1 s	6 %
720 (in A2)	75 ms	14.7 s	14.1 s	4 %
	50 ms	9.2 s	10.2 s	11 %
740 (in A5)	80 ms	13.6 s	13.4 s	1.5 %
	50 ms	7.9 s	9.0 s	13.5%

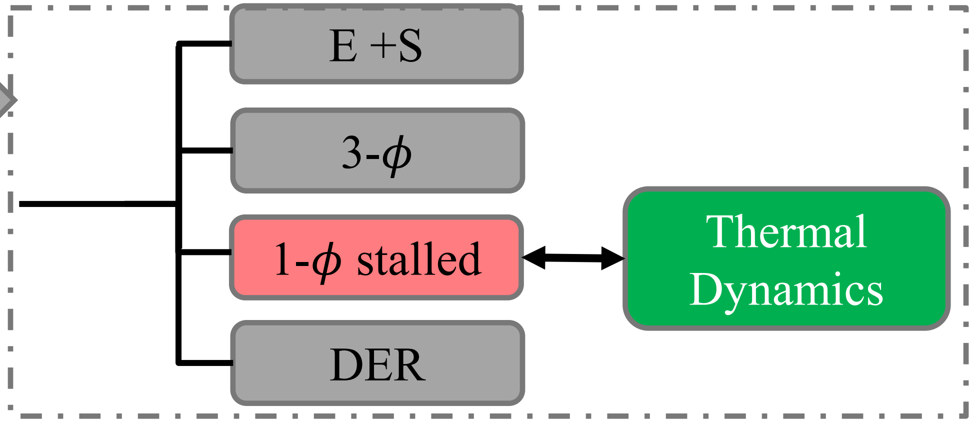
- The values of B_{stall} 1 second after fault are used – quick identification of severity

Admittance works for Monitoring. Mitigation ?

Online Control on Distribution Networks

- Load & DER control at any node will indirectly change voltage at all nodes which changes recovery time - Small geographic footprint makes control feasible
- Analytical expressions of $t_1 + t_2$ should be used along with system topology information – use parameters of aggregated model





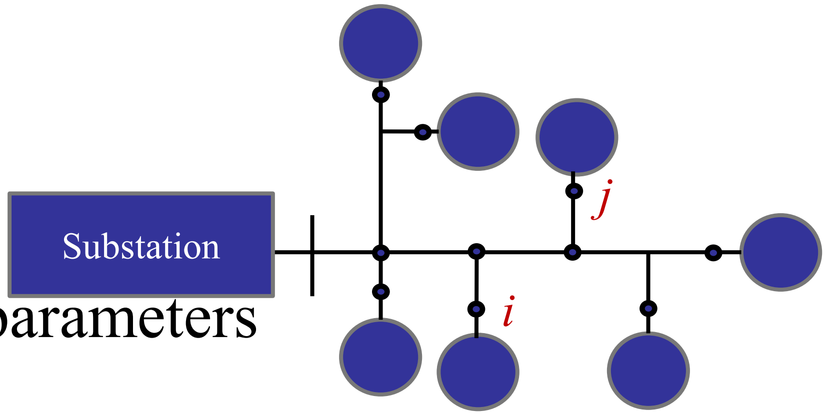
Similar structure as the load model used in transmission

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 Optimization Formulation for DER + Load control

- Linear approximation for change in recovery time at cluster *j* due to control (u) at cluster *i*

$$\Delta t_{rec,j} = \left(\frac{dt_{rec,j}}{du_i}\right)\Delta u_i = \left(\frac{\partial t_{1,j} + \partial t_{2,j}}{\partial u_i}\right)\Delta u_i$$



- $\partial t_{1,j}/\partial u_i$ and $\partial t_{2,j}/\partial u_i$ are function of topology, model parameters
- More generally, $\boldsymbol{\Delta t_{rec}} = A \cdot \boldsymbol{u}$

$$\min c^T \cdot |\boldsymbol{u}|$$

s.t.

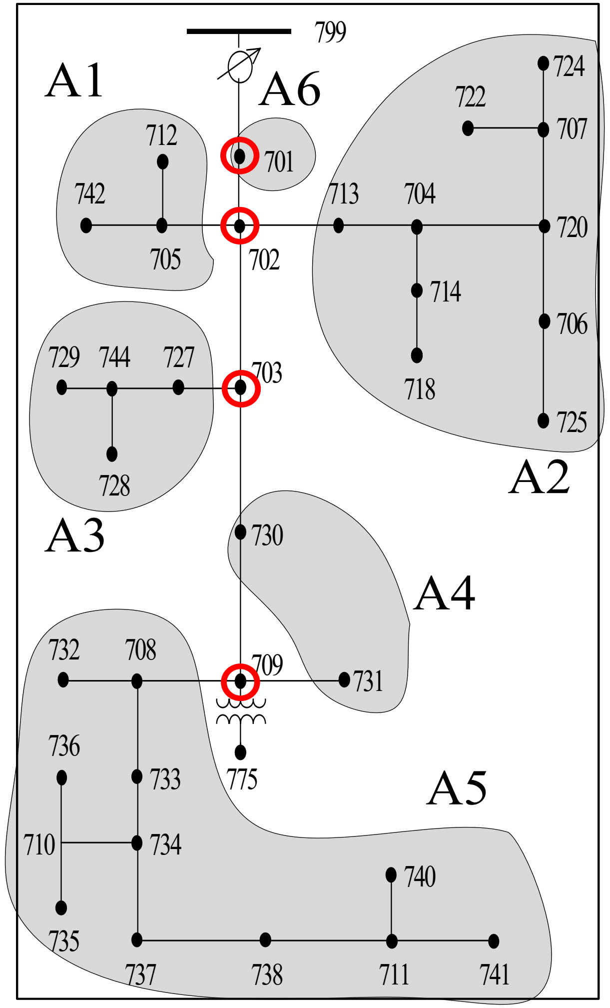
$$A \cdot \boldsymbol{u} \geq t_{spec} - t_{rec}$$

$$\boldsymbol{u}_{min} \leq \boldsymbol{u} \leq \boldsymbol{u}_{max}$$

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

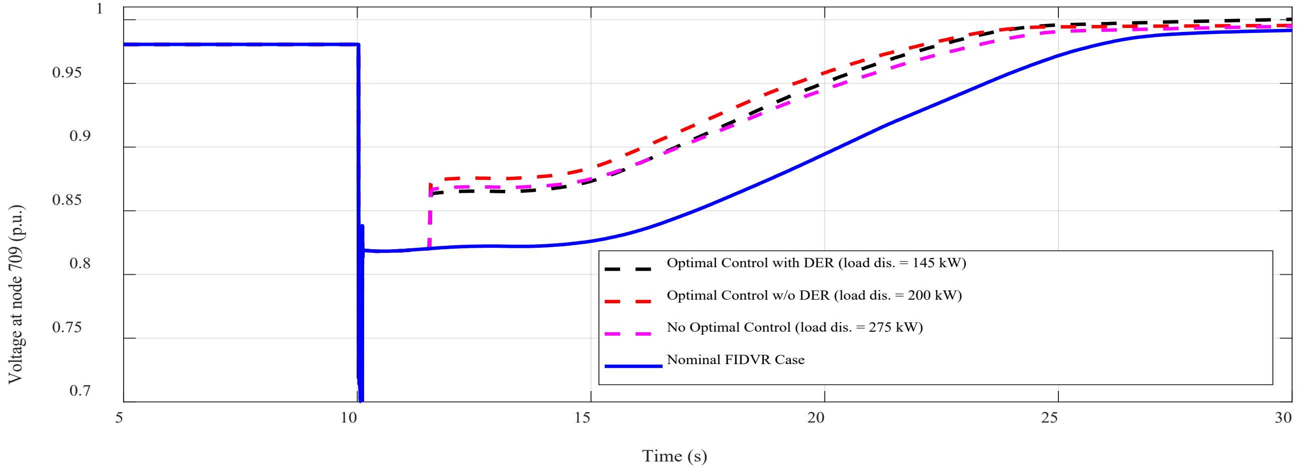
[C1] **Ramapuram Matavalam A.R.;** R. Venkatraman; V. Ajjarapu, "Mitigating Delayed Voltage Recovery Using DER & Load Control in Distribution Systems", IEEE PESGM, 2022.

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



- Control triggered 2s after FIDVR detected,
- Reduce recovery time from 13.5s to 10s.

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



Optimal Control leads to Load control reduction of 40%

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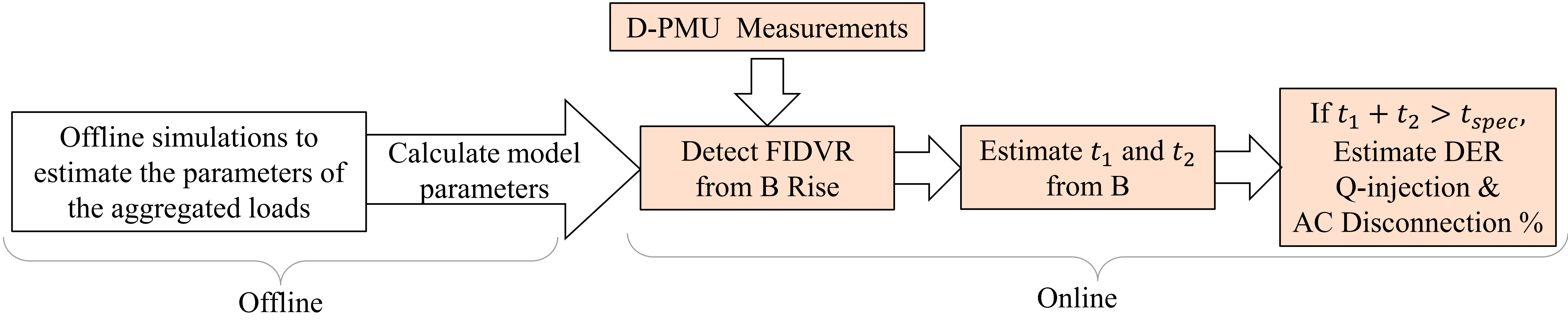
Summary of Overall Approach



- 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
- Similar admittance-based approach can also be used for Transmission systems

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Key Takeaways

- The admittances can accurately *localize regions of motor stalling* and quantify the severity of FIDVR from D-PMU measurements
- The physics inspired reduced model based on admittances & thermal dynamics *simplifies FIDVR* analysis – analytical recovery times
- The *linear* optimization formulation based on recovery time sensitivities utilizing DER Q-injection and can *reduce the load disconnection* by 40%
- **Potential Impact:** Enables utilities to localize the reason for voltage instability in real time and identify real-time controls to ensure that sustained low voltages are mitigated

Questions ?

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