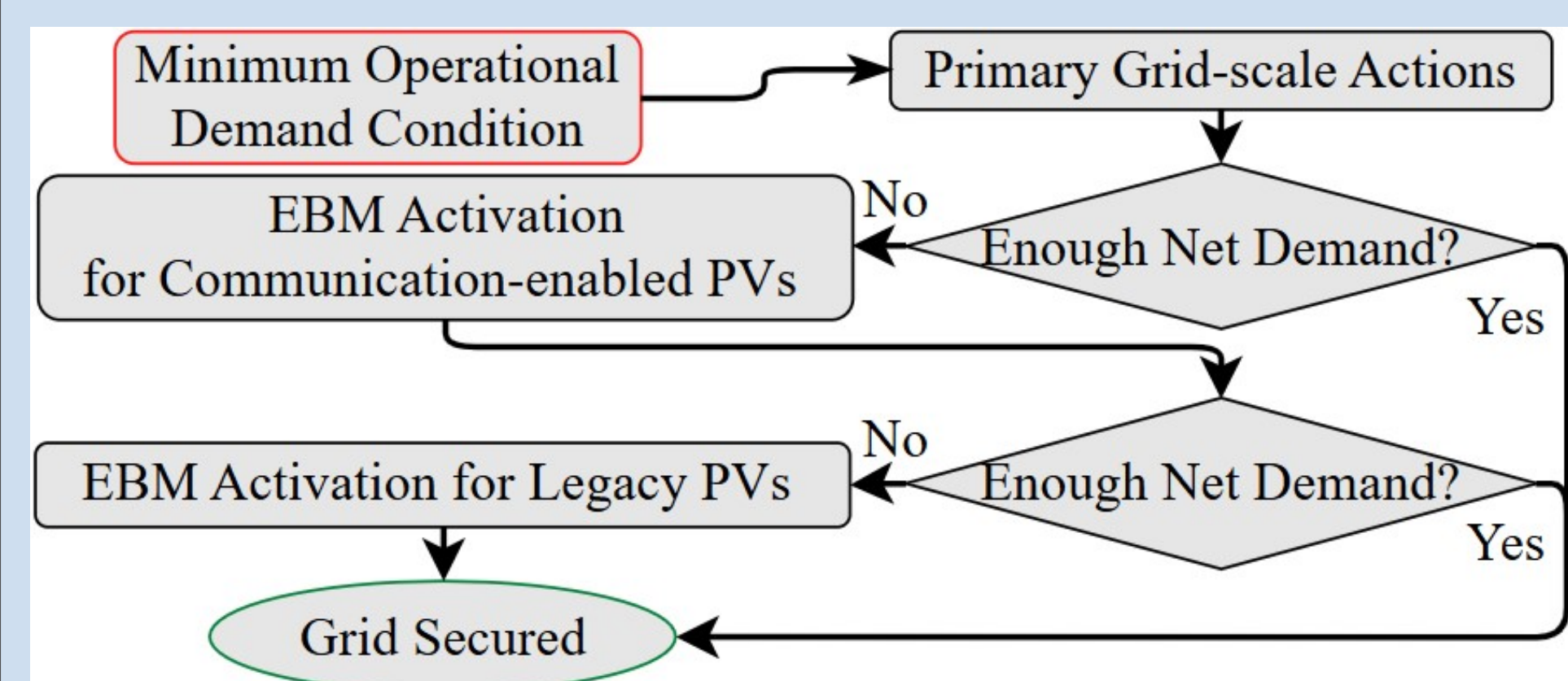


Introduction

- High rooftop PV penetration in Australia is driving periods of minimum operational demand (MOD), reducing system strength and inertia. This condition necessitates the implementation of the Emergency Backstop Mechanism (EBM) as a last-resort PV curtailment measure.
- This research develops a comprehensive distribution-level modeling framework for EBM, including analytical tools to determine required T-D transformer tap adjustments for voltage-based PV tripping, characterization of voltage propagation along feeders, and mitigation of EBM-induced active power oscillations using voltage compensation strategies.
- At the system level, this research quantifies the impact of large-scale EBM-driven PV disconnection on frequency dynamics, including RoCoF behavior and the risk of frequency-dependent cascading failures such as secondary photovoltaic tripping (SPVT).

Modeling Foundation



Communication-based PV curtailment model:

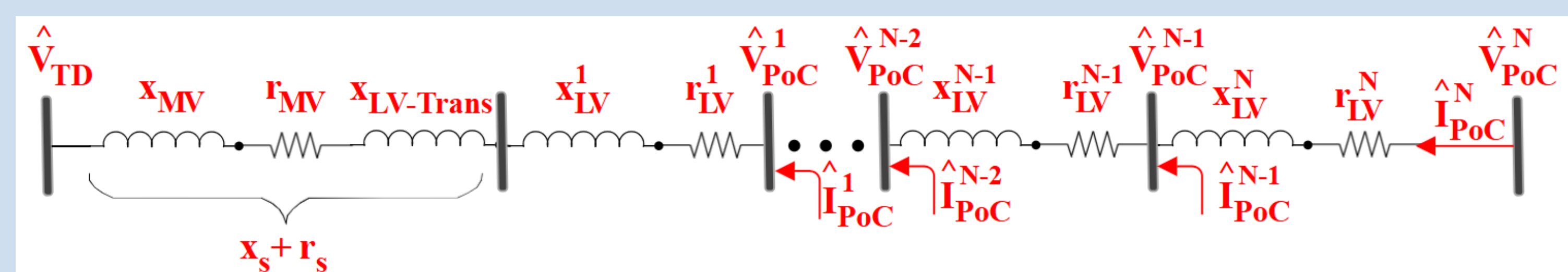
$$P_{\text{out}} = \begin{cases} P_{\text{set}}, & S = 1 \\ S \cdot P_{\text{set}}, & S \in [0, 1] \\ 0, & S = 0 \end{cases}$$

Voltage-based PV tripping (legacy inverters): PV disconnects when PoC voltage exceeds grid-code limits and reconnects only when voltage returns below the reconnection threshold.

Condition	Description
A / B	Instantaneous over-voltage trip
C	10-min average over-voltage trip
D	Reconnection when voltage is safe

Distribution-level Analysis

Distribution feeder with multiple DERs



For a feeder with N PV units, the voltage at the i -th PoC is approximated as:

$$|\hat{V}_{\text{PoC}}^i| = \tau_{TD} + \sum_{k=1}^N \left(\hat{P}_{\text{PoC}}^k \frac{\hat{r}_s \sqrt{a_s^2 + 1}}{\tau_{TD} a_s} \right) + \sum_{k=1}^i \sum_{h=k}^N \left(\hat{P}_{\text{PoC}}^h \frac{\hat{r}_{LV}^k \sqrt{(a^k)^2 + 1}}{\tau_{TD} a^k} \right)$$

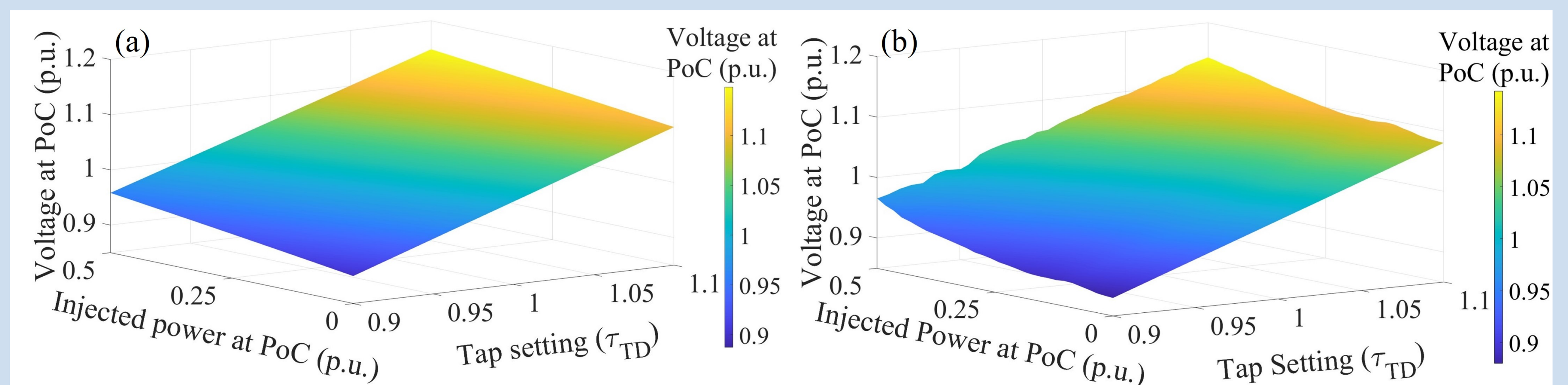
Required tap for tripping:

$$\tau_{TD}^{\text{Trip}, i} = \frac{|\hat{V}_{\text{PoC}}^{\text{Trip}}| \pm \sqrt{(|\hat{V}_{\text{PoC}}^{\text{Trip}}|)^2 - 4C_i}}{2}$$

where

$$C_i = \sum_{k=1}^N \hat{P}_{\text{PoC}}^k \frac{\hat{r}_s \sqrt{a_s^2 + 1}}{a_s} + \sum_{k=1}^i \sum_{h=k}^N \hat{P}_{\text{PoC}}^h \frac{\hat{r}_{LV}^k \sqrt{(a^k)^2 + 1}}{a^k}$$

Analytical vs simulation results comparison

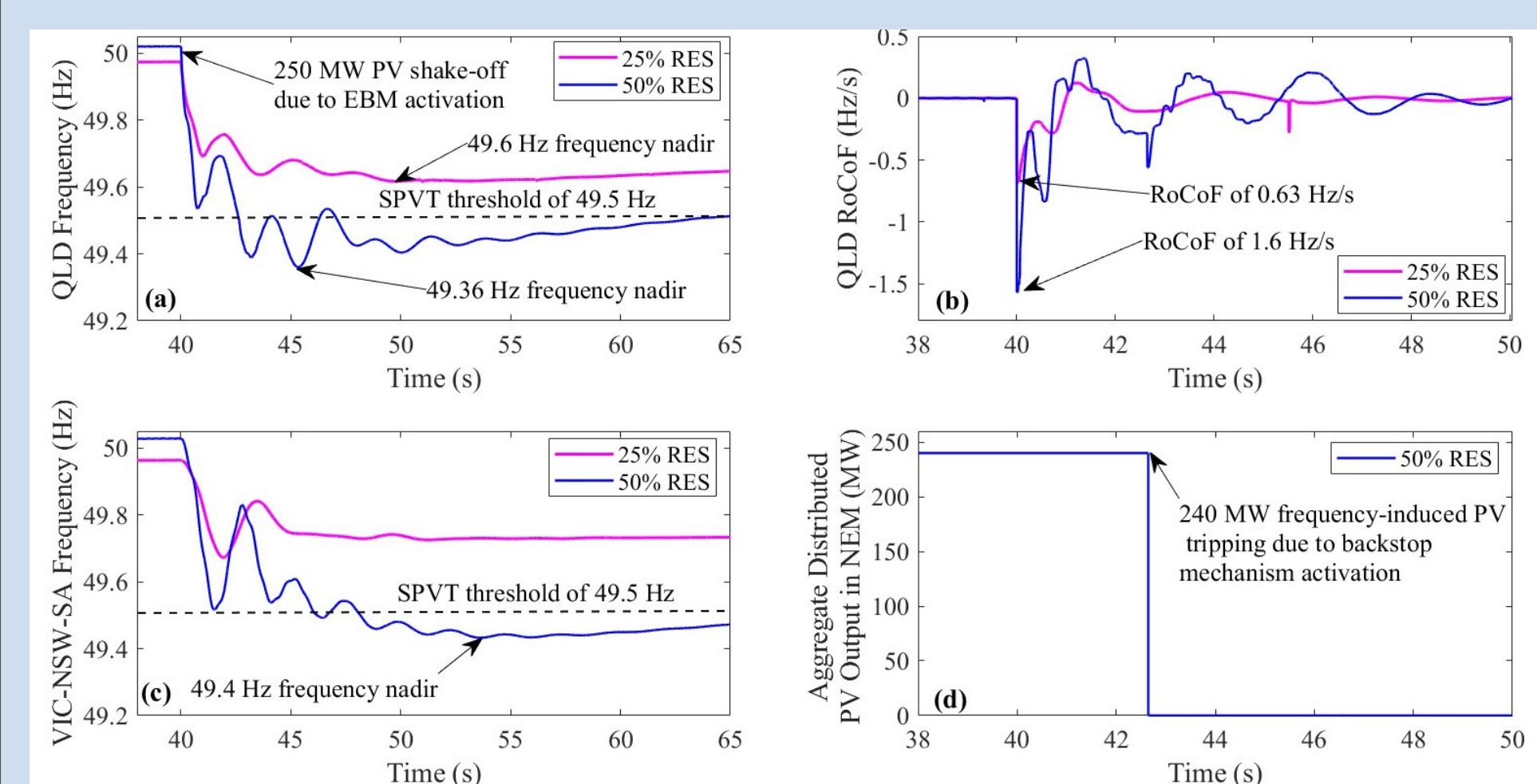


System-level Analysis

Large-scale voltage-based EBM activation can result in in-mass disconnection of distributed PV units, imposing a sudden active power imbalance on the transmission system and driving system-wide frequency dynamics.

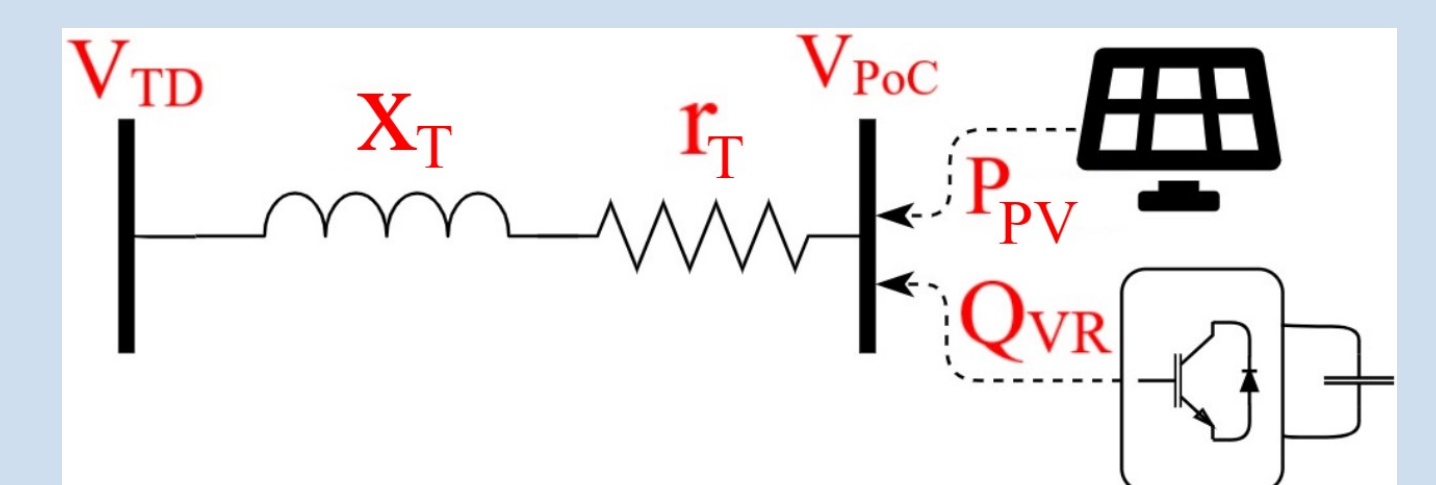
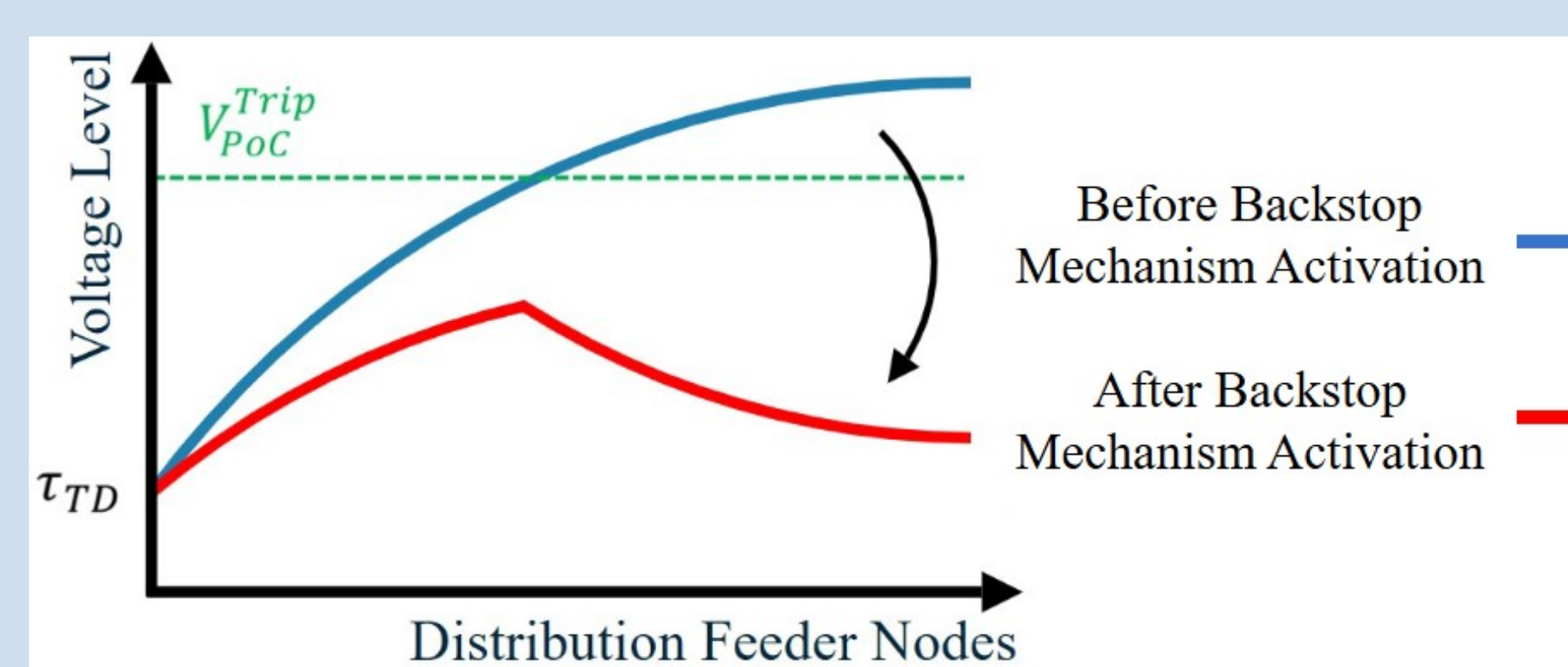
$$|\Delta P_{\text{net}}| < 2H \cdot \dot{\omega}_{\text{critical}}$$

System-wide frequency response following EBM activation



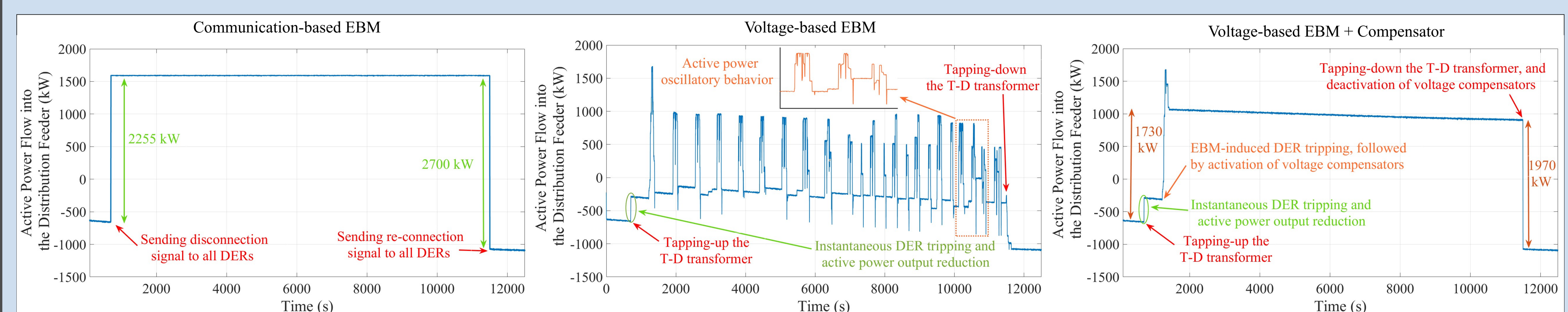
EBM-induced Active Power Oscillations

Observed oscillatory behavior:



$$Q_{VR} \approx \frac{\sum_{i=1}^N P_{\text{PoC}}^i r_{MV}}{x_{MV}}$$

Simulation case studies for different EBM scenarios



Conclusion

- An analytical tap-voltage formulation enables predictable PV tripping and improves certainty in voltage-based EBM implementation.
- Voltage-based EBM may induce PV disconnection-reconnection oscillations, which are effectively mitigated using voltage compensation.
- Large-scale EBM-driven PV disconnection can cause severe frequency excursions and cascading PV tripping.
- Secure EBM operation requires coordination with system inertia and fast frequency response to maintain whole-system stability.