Partial Tripping of DERs and Its Implications to Aggregation Modeling

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Objectives

- Investigate partial tripping of distributed energy resources (DERs)
  - Contingency-dependency
- Understand the implication of contingency-dependent partial tripping to the aggregation scheme
  - DER modeling in WECC CLM
  - Other dynamic components
- Contemplate aggregation schemes that can possibly address the issue

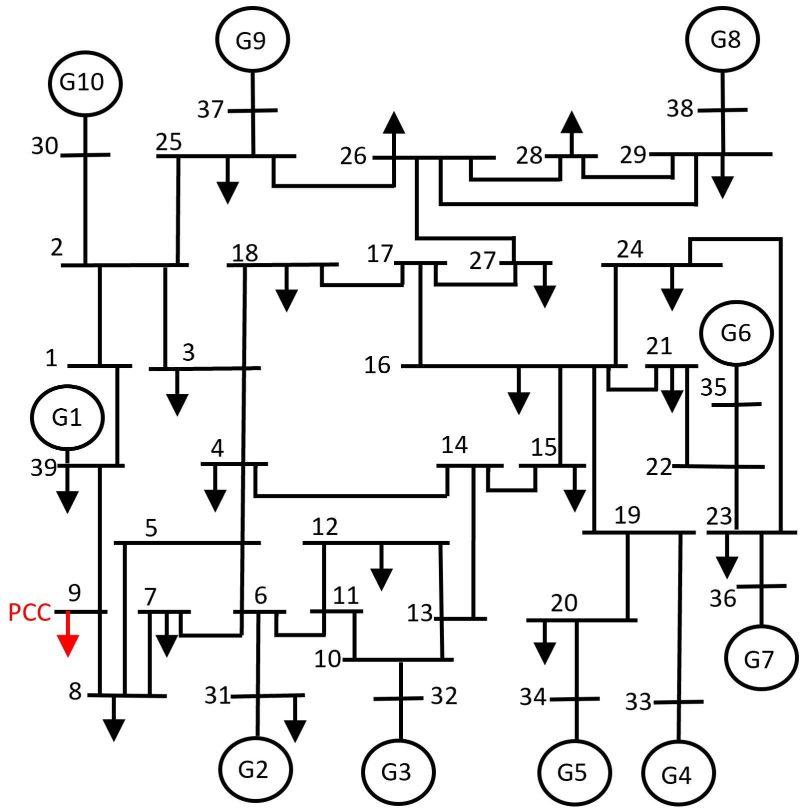
Background

- To enable a feasible dynamic contingency analysis of transmission systems, aggregated DER models are preferred
- There have been many solar PV incidents, leading to significant losses of solar generation and impacts on the transmission operation
  - All involved partial PV generation tripping
  - Deployed across a large region,
    - ✓ DERs at different locations "see" different transient conditions for a specific fault
    - ✓ A DER also "sees" different transient conditions for different fault events
  - Fault-dependent tripping phenomenon for DERs equipped with protection/control,
    - ✓ protection including voltage, current, and frequency

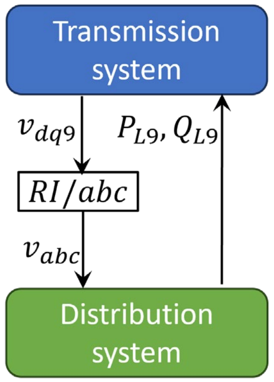
Overall Approach

- Hybrid phasor-EMT simulation of integrated T&D system
  - A distribution feeder with DERs coupled to the transmission grid at the point of common coupling (PCC)
  - Modeling of voltage/frequency protection of DERs
  - Generation of scenarios for random contingencies originated in the transmission grid
  - Types (bus fault, line outage), locations, durations, etc.
- Postulation of aggregation schemes to address partial tripping

Integrated T&D Test System

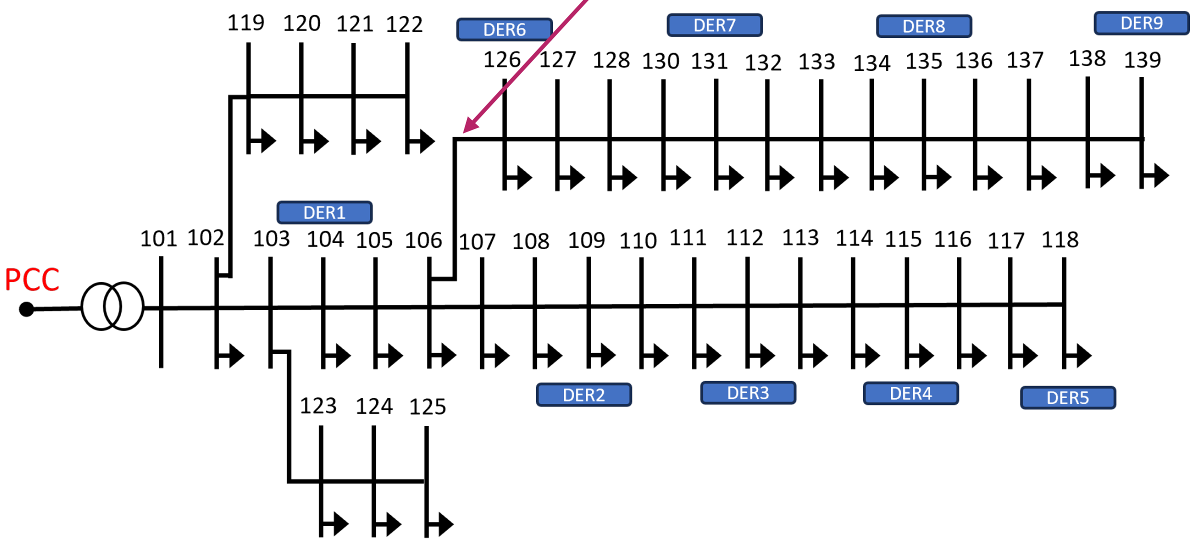


(a): IEEE 39-bus transmission system as bulk power system (Phasor model)



(b): T&D interface

Length increased such that the electrical distances from DER1 – DER 9 to the PCC increases, also added nodes 134 to 139



(c): A modified IEEE 33-node feeder with nine DERs as distribution system (EMT model)

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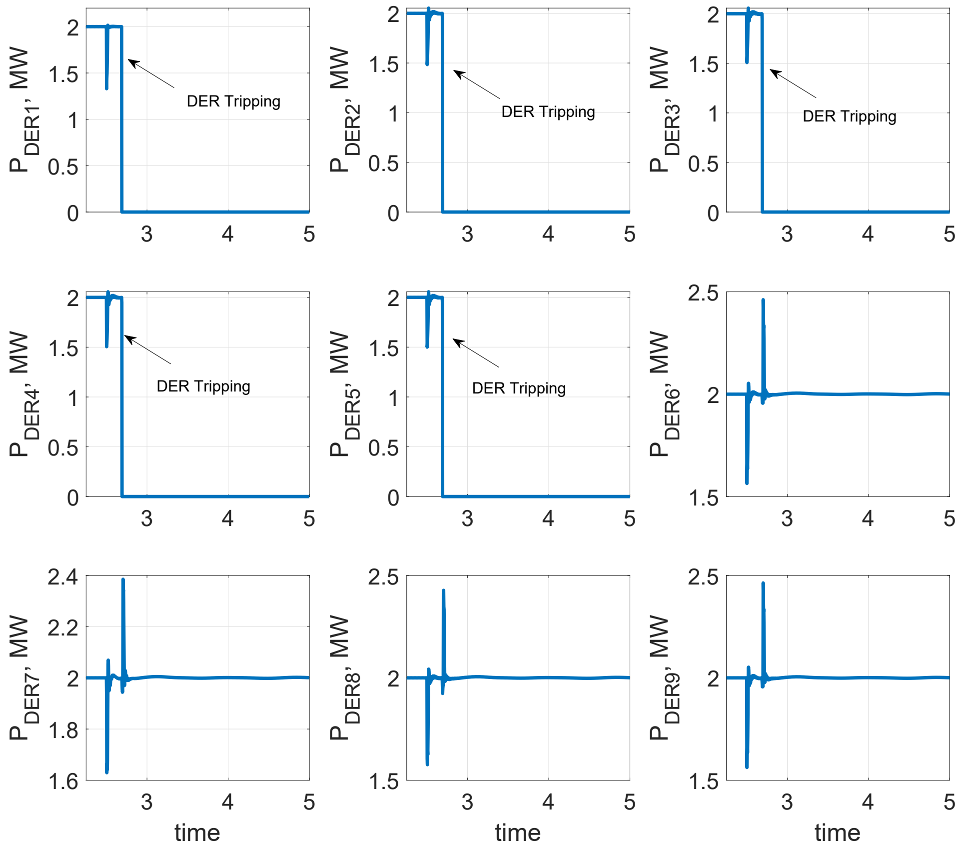
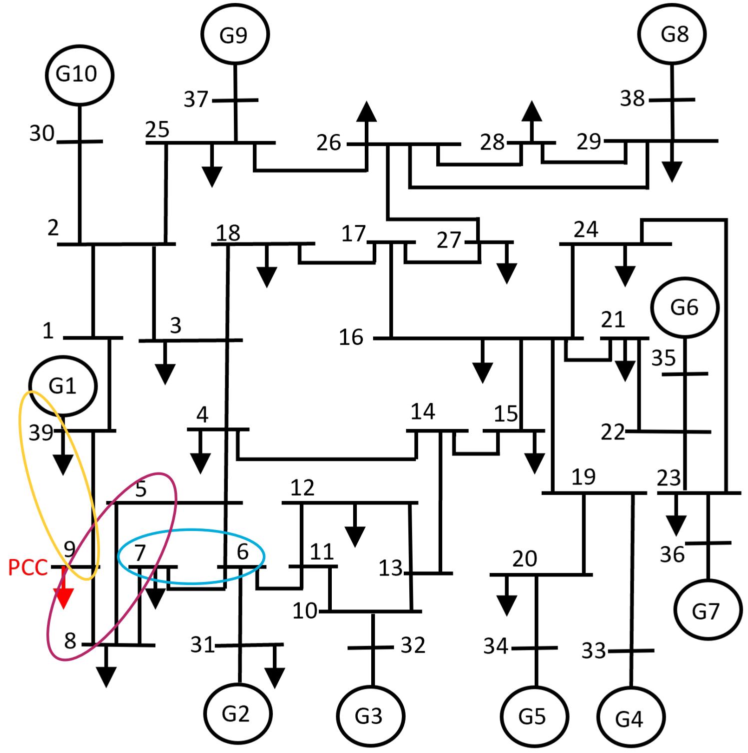
Assumptions

- All loads in the test feeder are constant impedance
- DER Modeling:
  - All nine DERs and their protection/controls are identical
  - Constant P-Q control mode
  - IEEE Standard 1547-2018 frequency and voltage ride-through
- Fault characteristics:
  - Bus or line faults
  - Single- or three-phase faults
  - Different clearing times

Case Study for Three-phase Bus Faults



Power output of nine DERs following the 3-phase fault at bus 8.



Bus faults vs. DER tripping status

Fault Locations (Bus No.)	Tripped DER(s)	DER(s) Remained Online
All other buses	None	1 to 9
6, 7	1	2 to 9
5, 8	1 to 5	6 to 9
9, 39	1 to 9	None

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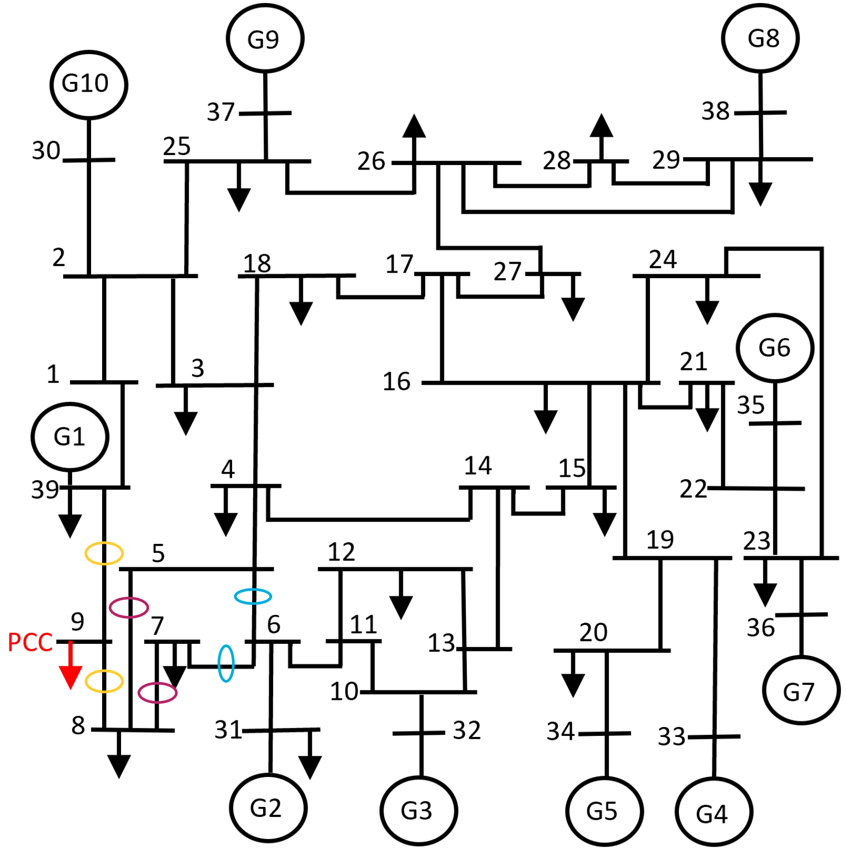
Case Study for Line Faults



Line faults vs. DER tripping status

FAULT SEVERITY ↓

Fault Locations (Lines)	Tripped DER(s)	DER(s) Remained Online
All other lines	None	1 to 9
5-6, 6-7	1	2 to 9
5-8, 7-8	1 to 5	6 to 9
8-9, 9-39	1 to 9	None

Observation of Cast Study Results

- DERs trip due to voltage ride-through during the transients
  - As a fault is closer to the PCC, more DERs trip
  - DERs that are electrically closer to the PCC trip first
- A phenomenon of contingency-dependent partial DER tripping
  - Different faults may cause different numbers of DERs to trip
  - DERs that remain online may be determined by fault conditions, DER locations, and even DER characteristics (e.g., control/protection setting)
- A single DER aggregation model is unlikely sufficient

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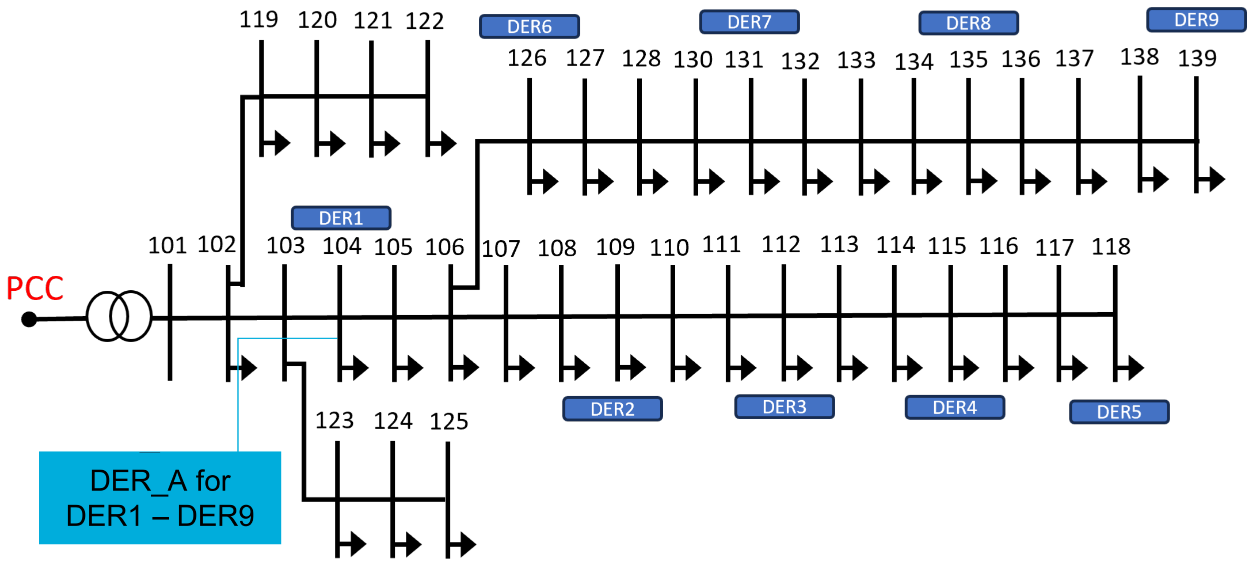
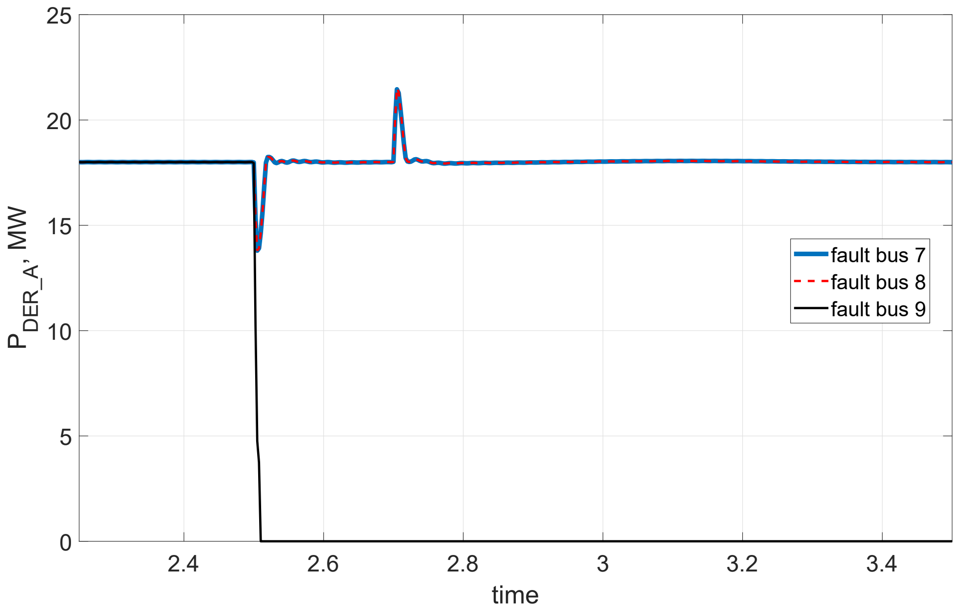
Existing DER Aggregation Scheme

- DER_A model is used
  - Existing scheme
    - ✓aggregate all DERs into a single model



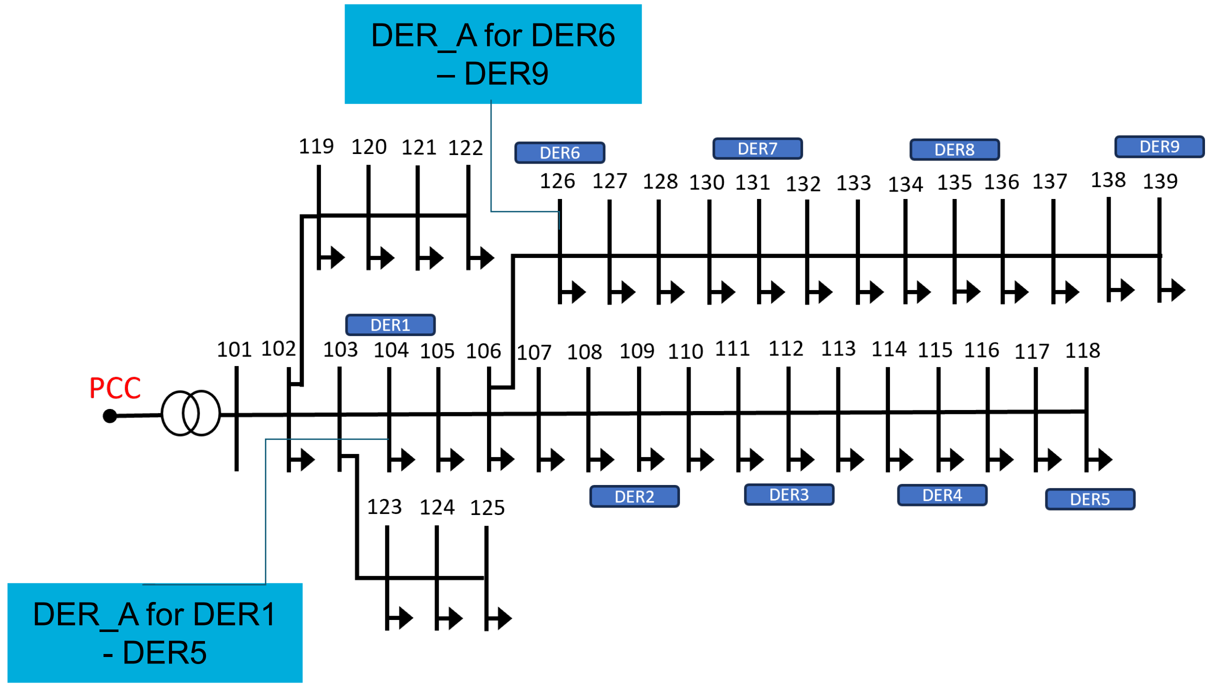


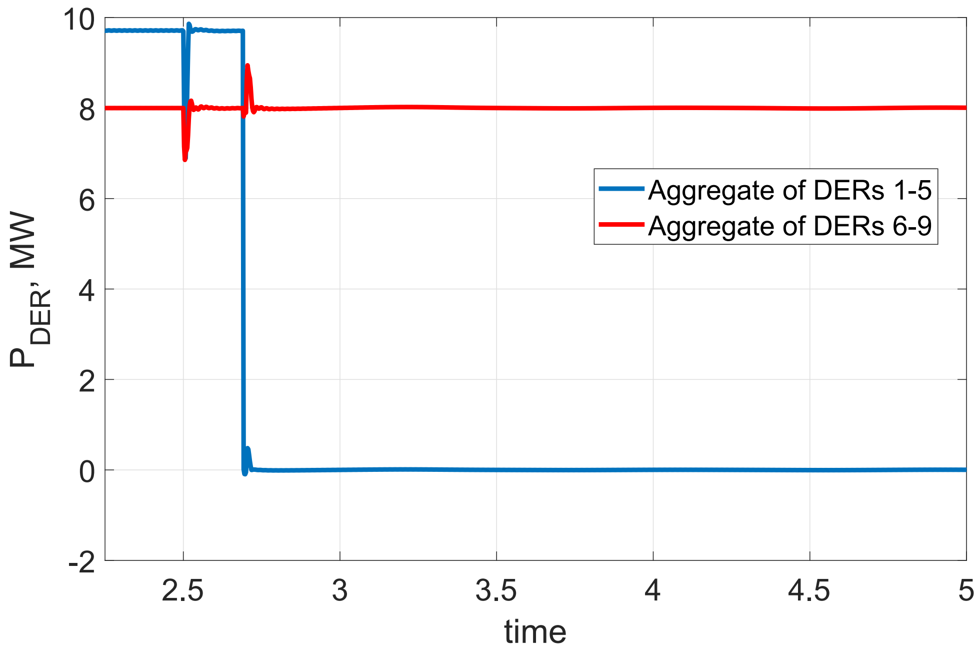
Fails to match the total DER output for any partial tripping (Faults at buses 7 and 8).

Can replicate the total DER output if all DERs are tripped or no DER trips (fault at bus 9).

A Preliminary Enhanced DER Aggregation

- Enhanced scheme
  - knowing the status of individual DERs under a specific fault, separately aggregate the DERs that tripped and remained online





For the 3-phase fault at Bus 8:

- Aggregated models for DER1 to DER 5 and for DER6 to DER 9.
- Can replicate the total DER output correctly.

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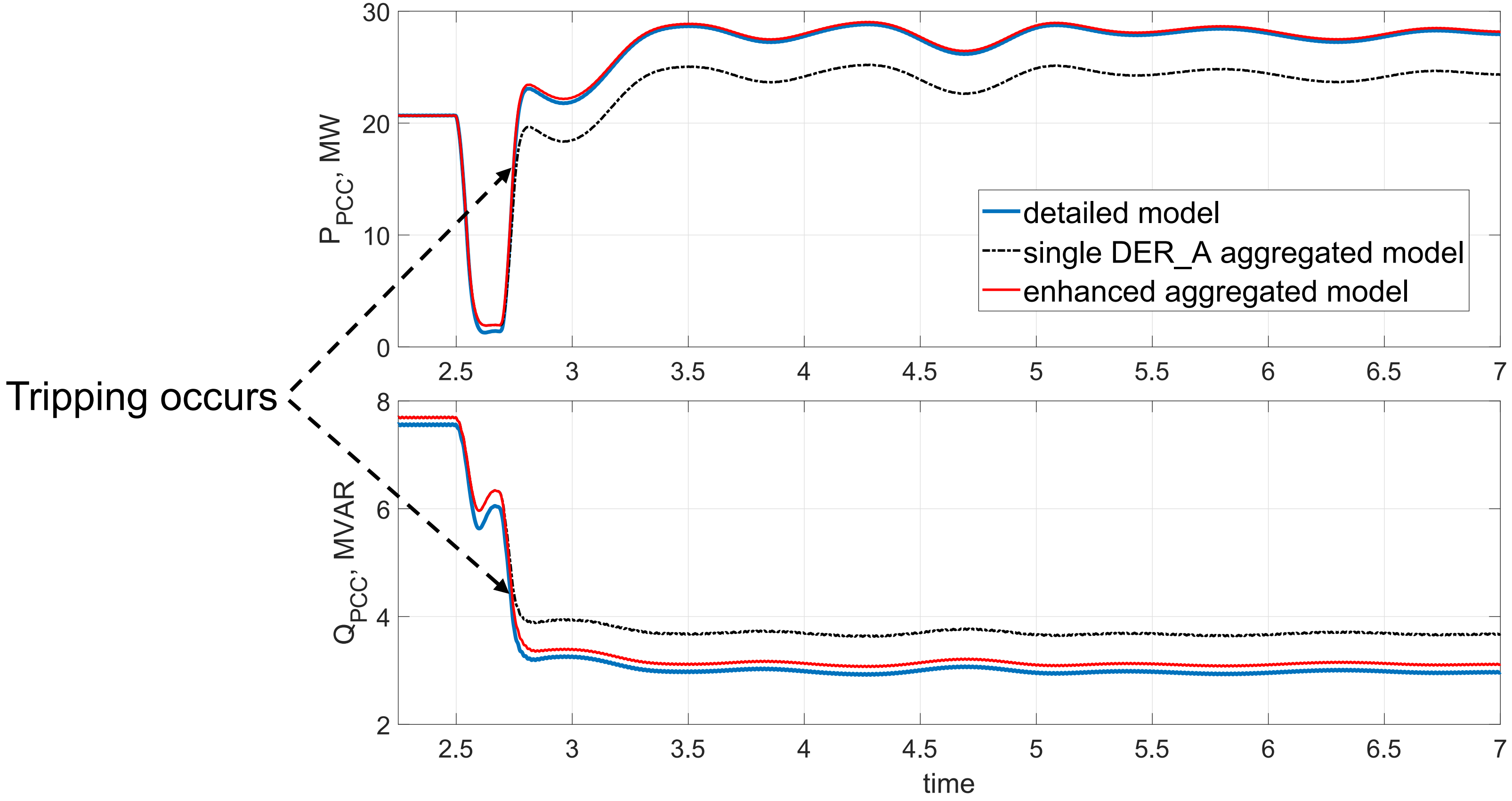
Performances of Aggregation Schemes



Responses at the PCC for different DER modeling for a fault at Bus 8.

Implications of Contingency-dependent Partial Tripping

- Further complicates the aggregated modeling
  - DER model in WECC CLM
  - Other dynamic components, e.g., electronic load (EL) tripping and motor stalling?
    - Voltage "seen" by individual load devices at different locations along the feeder varies, causing different EL devices to trip or different motors to stall
    - An EL load device or motor may or may not trip/stall for different fault events
- To accurately capture this phenomenon, there is a need to know whether, what, and when DERs, ELs, or motors would trip/stall for a specific transmission fault

Determining DER Tripping Status

- Analytical Approach:
  - Analysis based on physics-based dynamic models for the integrated T&D
    - ✓ The challenge is to analytically derive the transients of individual DERs under a transmission level fault
- Data-driven Approach
  - Simulation-based data generation:
    - ✓ The challenge is the difficulty in developing detailed models for individual DER models and computational effort to run the simulation
  - Real event data collection:
    - ✓ Assuming that utilities know the loss of DER generation during the event
    - ✓ Challenge is the infrequent fault events

Machine Learning Approach to Determining Partial Tripping

- Generate datasets under different contingencies
- Based on the simulated data, we developed an ML-based approach to derive the status of individual DERs for unseen faults
  - Input: types, locations, and clearing times of faults
  - Output: DER status
- Challenges:
  - Whether the approach is feasible with a small dataset
  - Mixed types of input:
    - ✓ Fault types in "texts" or integers
    - ✓ Fault locations in integers
    - ✓ Fault duration in continuous values

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A BERT Model for Tripping Status

- BERT is powered by a multilayer bidirectional transformer encoder consisting of multiple encoder layers stacked sequentially
- BERT processes input by tokenizing the given text, converting tokens to embeddings, encoding the embeddings to capture the context and relationships, and further processing the output of transformer encoders.
  - A prompt engineering approach for BERT: DER-Prompt-BERT
  - An example input to the DER-Prompt-BERT model:

	Textual Input
Our Prompt	A bus fault is detected at the bus location one for 0.12 seconds of fault duration time.
Naïve Prompt	Fault Type: Bus Fault; Location: Bus One; Duration: 0.12s

  - Output: Status of every single DER, i.e., DER1 to DER9

Case Study Using BERT Model

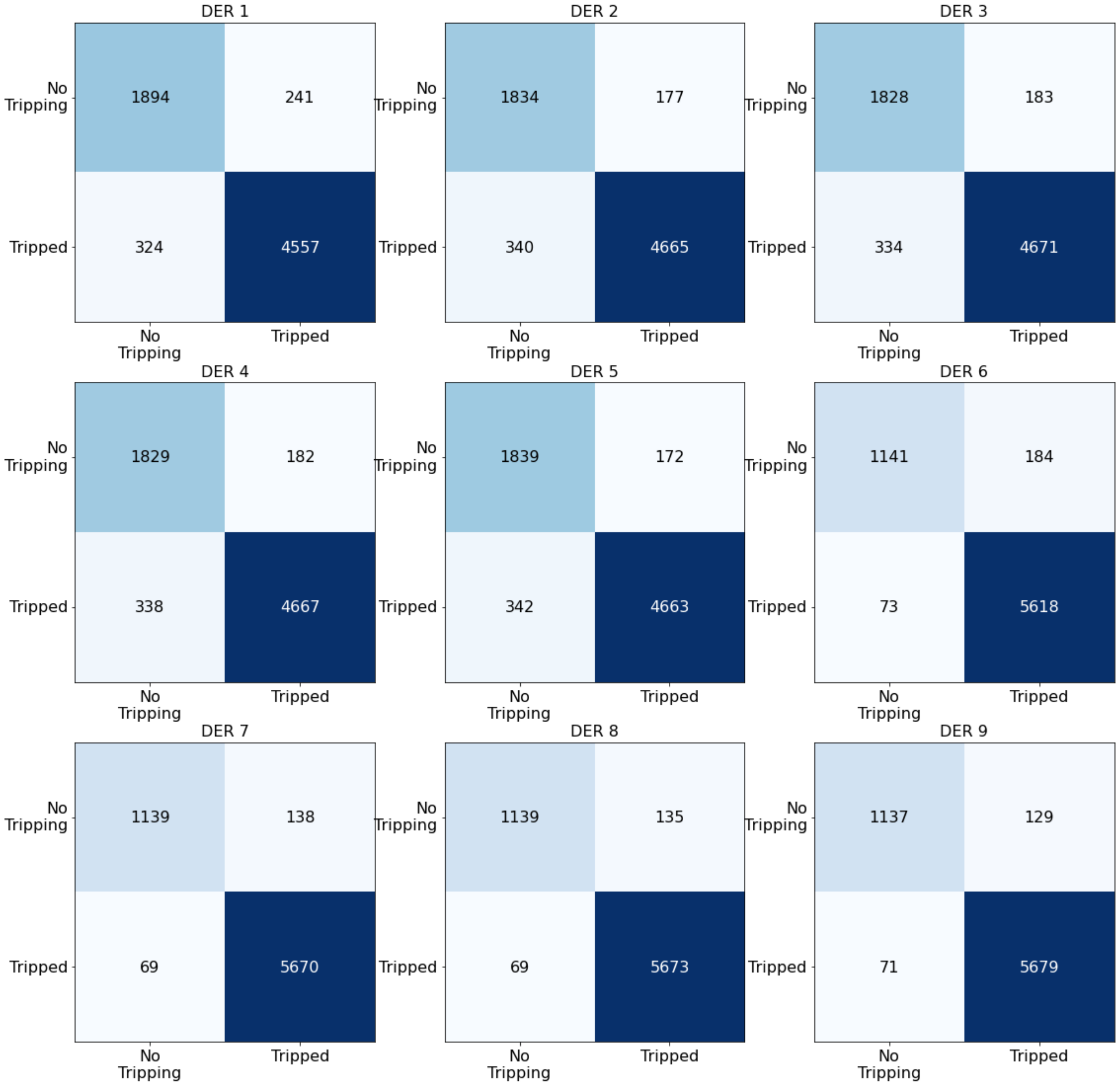
- Assuming faults at different buses and lines with a clearing time uniformly distributed between 0.1s and 0.2s.
  - A total number of 7,765 datasets was generated
  - Other ML models were used for comparison

Comparative performance using different ML models

	Precision	Recall	F1-score
DER-Prompt-BERT	0.98	0.99	0.99
XGBoost	0.91	0.92	0.91
MLPClassifier	0.90	0.86	0.88

Case Study Using BERT Model and Reduced Dataset

- 10% of the generated dataset was used in training the DER-Prompt-BERT model
  - Can be particularly advantageous in practical applications



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Summary and Conclusions

- Investigated the partial DER tripping using a hybrid simulation approach for integrated T&D systems by
  - Modeling of protection and control functions of DERs in a distribution feeder
  - Postulating different fault scenarios originated in the transmission grid
- Identified the phenomenon of contingency-dependent partial tripping and its implication to aggregation of dynamic components
  - A single aggregated model can be insufficient for dynamic contingency study
- Proposed a preliminary enhanced aggregation scheme for DERs
- Developed an ML-based approach for determining individual DER status during fault events
  - Can be possibly used to implement the enhanced aggregation scheme

[1] Yogarathnam, N. R. Chaudhuri, and M. Yue, "Need for Enhanced Contingency-Dependent DER Aggregation Scheme for Transient Analysis in Modern Power Grid: A Case Study," accepted by IEEE PES GM 2024.
[2] T. Zhao, A. Yogarathnam, and M. Yue, "A Large Language Model for Determining Partial Tripping of Distributed Energy Resources," first revision submitted to IEEE Power Engineering Letters, under review.

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