PJM System Stability Assessment Using Composite Load and Distributed Energy Resources Models

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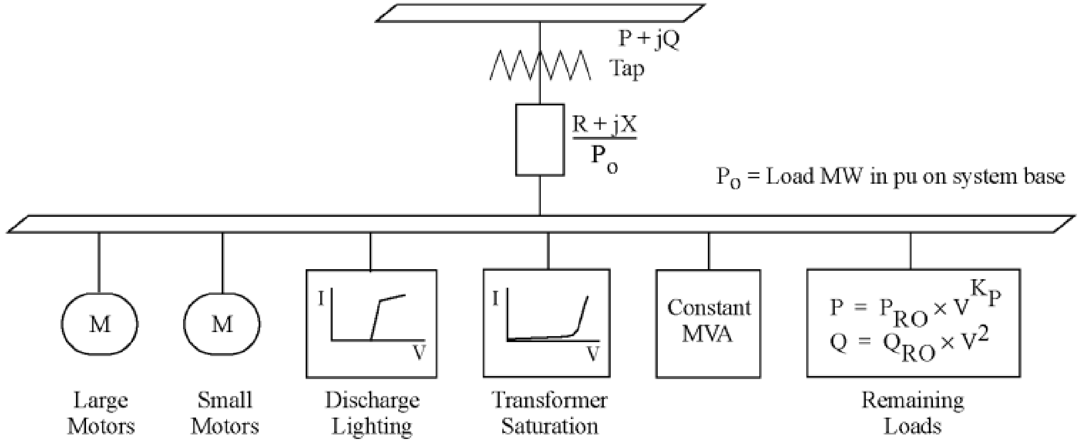
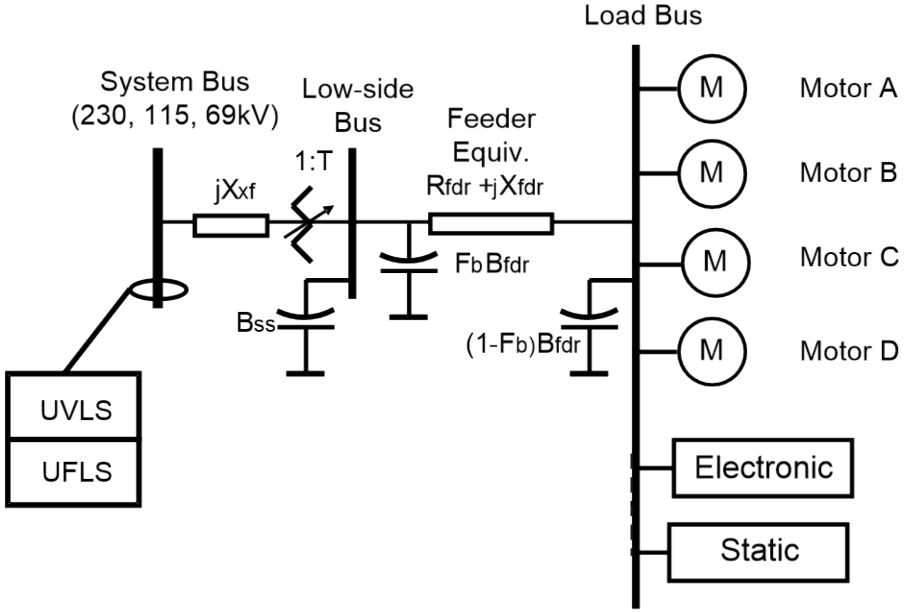
Background

- NERC has the initiatives of applying the latest Composite Load Models (CMLD) in the interconnected grids of the Eastern Interconnection.
- NERC released three CMLD datasets (Phases 1, 2 & 3) and held two rounds of testing.
- In line with the NERC initiatives, PJM is transitioning to the CMLD in system stability assessment. This transition is also in compliance with NERC TPL-001- R2.4.1 Standard which requires that system stability assessment include load models representing the expected dynamic behavior of induction motor loads.
- This presentation discusses stability studies performed with the objective of assisting PJM in transition to the CMLD.

ZIP or CLOD vs CMLD

- In the past peak load stability studies, PJM used a static load model (ZIP) or a complex load model (CLOD). The ZIP model is not able to capture induction motor load dynamics. The CLOD model accounts for large and small induction motors but has limitations regarding modeling single-phase low inertia loads such as Air Conditioners, motor stalls, protection trips or reconnections, etc.
- The CMLD model has the capability of modeling various three-phase motors (commercial or industrial) and single-phase motors (mainly residential air-conditioners) as well as motor stalling, tripping or reclosing actions, etc.

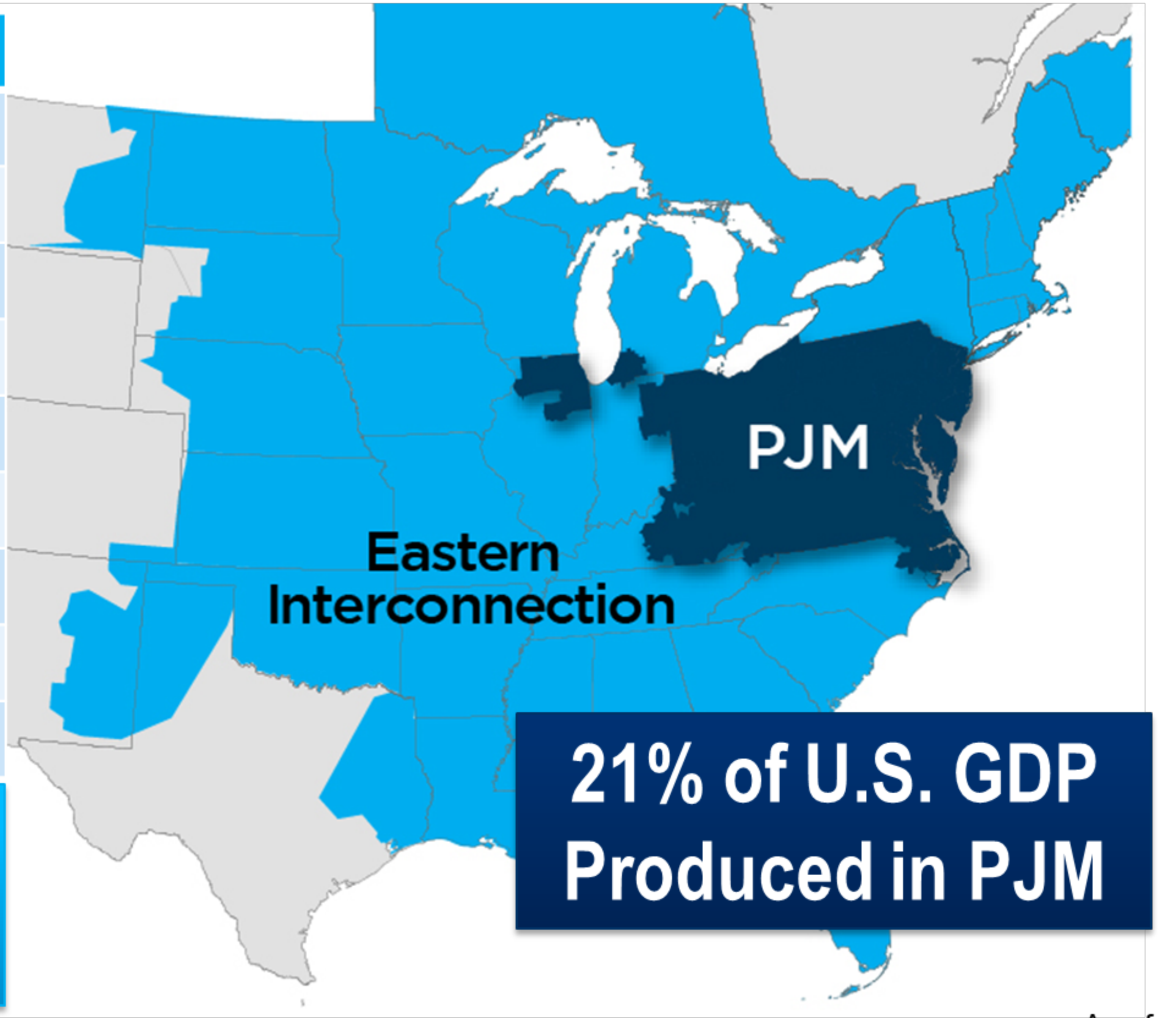




PJM as Part of the Eastern Interconnection

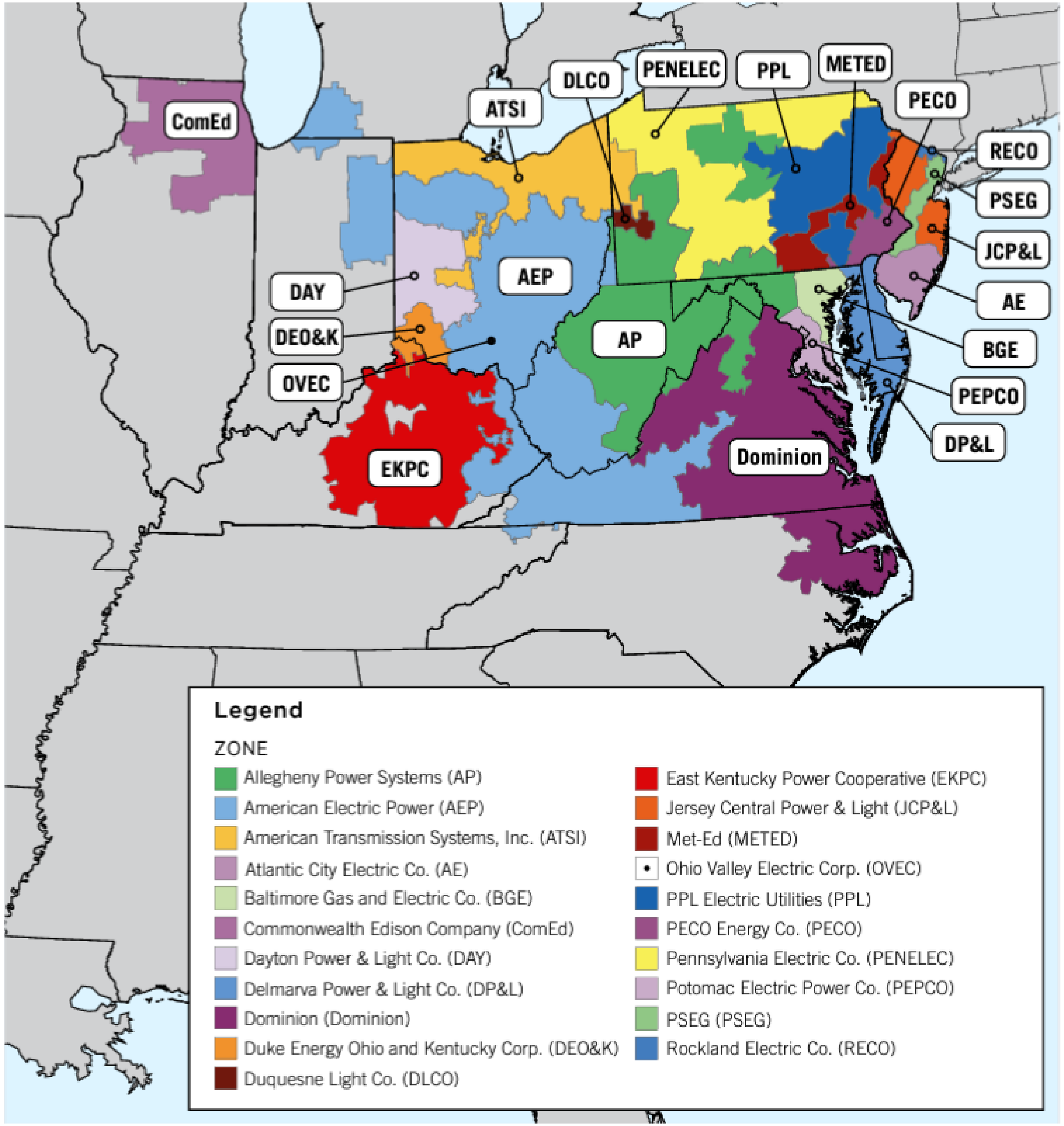
Key Statistics	
Member companies	1,090
Millions of people served	65+
Peak load in megawatts	165,563
Megawatts of generating capacity	180,785
Miles of transmission lines	88,185
Terawatt hours of annual energy	770
Generation sources	1,439
Square miles of territory	368,906
States served	13 + DC

- 26% of generation in Eastern Interconnection
- 25% of load in Eastern Interconnection
- 20% of transmission assets in Eastern Interconnection



As of 2/2024

PJM Transmission Owner (TO) Zones

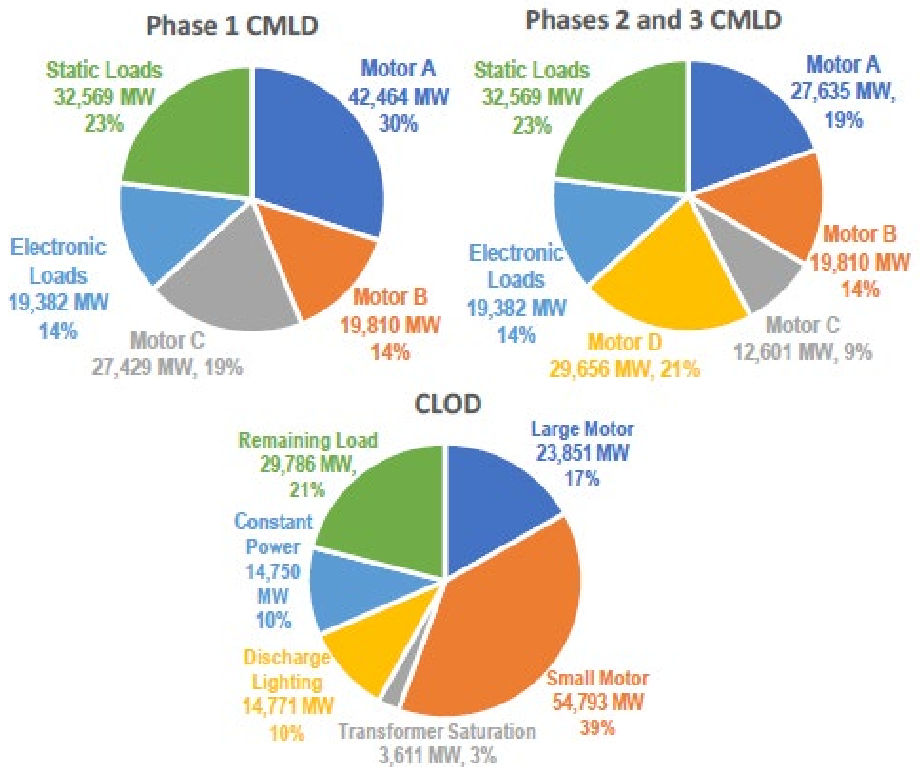


Methodology

- The following three phases of CMLD were studied:
  - Phase 1 CMLD - only Motor A, B & C included without Motor D. Percentage of Motor D was split between Motor A and Motor C.
  - Phase 2 CMLD - Motor A, B, C & D included. Motor D stalling feature was disabled.
  - Phase 3 CMLD - Motor A, B, C & D model included. Motor D stalling feature was enabled.

> - Applied to loads in the PJM system with P > 5 MW, PF ~ 0.84-0.85, V > 0.97pu
> - Approximately 6,680 loads or 141,600 MW load (89% of online loads) were modeled with CMLD.
> - For any load bus of 40 kV and under, the distribution transformer component of the CMLD model was not added to avoid potential double modeling of distribution transformer.

  - CLOD - for comparison with Phase 1 CMLD.
  - ZIP - for comparison with Phase 1 CMLD.



Study Cases and Contingency Events

- The study was performed on the following planning cases:
  - Summer peak load case
  - Heavy transfer cases for two transmission zones

- Approximately 270 contingencies were simulated:
  - NERC P1, P4, P6 and P7 contingency events & Extreme contingency events (Ex 2.b)
    - 3-phase fault with normal clearing (P1)
    - 3-phase fault with a prior outage and normal clearing (P6)
    - Single line to ground (SLG) fault with breaker failure and subsequent delayed clearing (P4)
    - SLG fault with common tower circuit outages and normal clearing (P7)
    - 3-phase fault with breaker failure and subsequent delayed clearing (Ex 2.b)

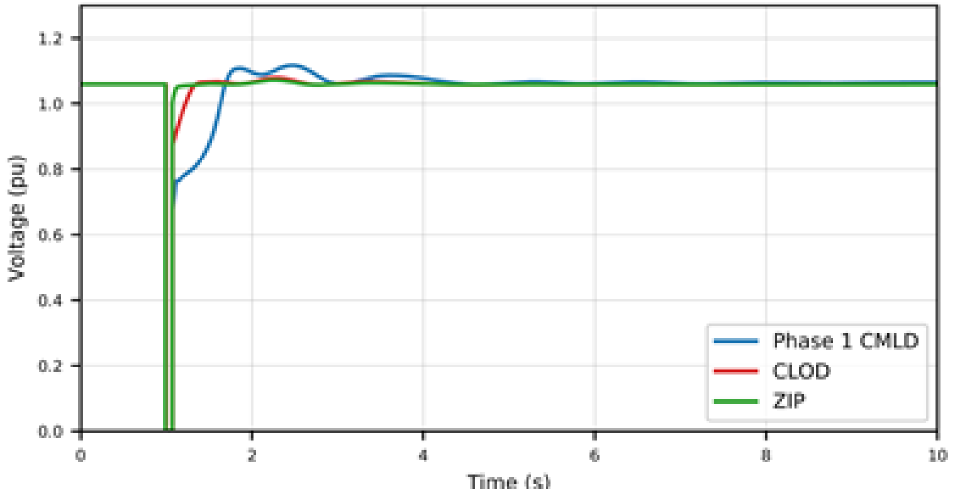
Contingency Location and Selection Criteria

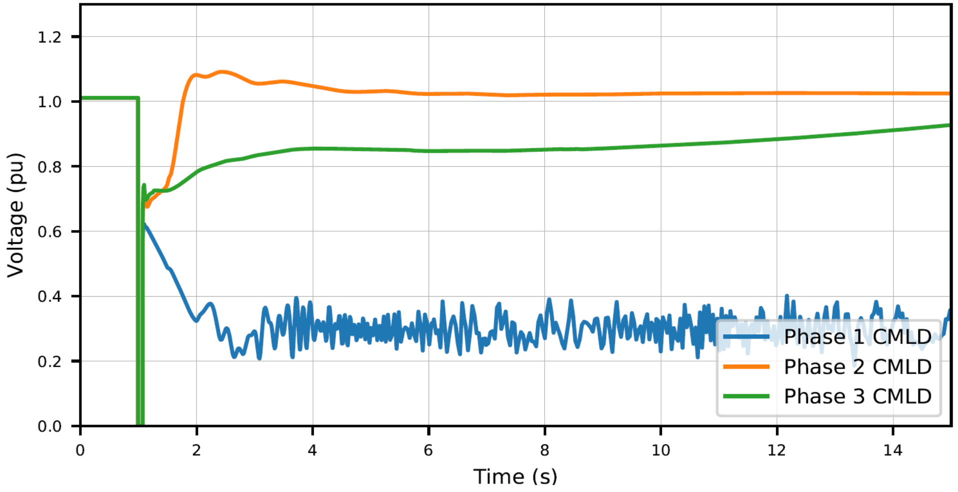
- Contingencies were selected based on:
  - Substations located near high load centers (focusing on more severe impacts on load bus voltages)
  - Substations with low short circuit currents and low generation level in the close proximity (indicating weak parts of the system)
  - Substations, transmission lines or transformers with heavy power flows (Prior outages or faults on these facilities would significantly impact on system transient and voltage stability.)
  - Voltage contingency ranking (ordering the impacts of contingencies on system voltage from the highest to the lowest)
  - Key geographic locations based on transmission system maps (from voltage support perspectives)
  - Breaker configurations of the substations and transmission circuits (based on the severity of loss of a facility)

- Studies were automated using Python scripts for
  - Contingency selection, simulation execution, and results post-processing.

Summary of Results

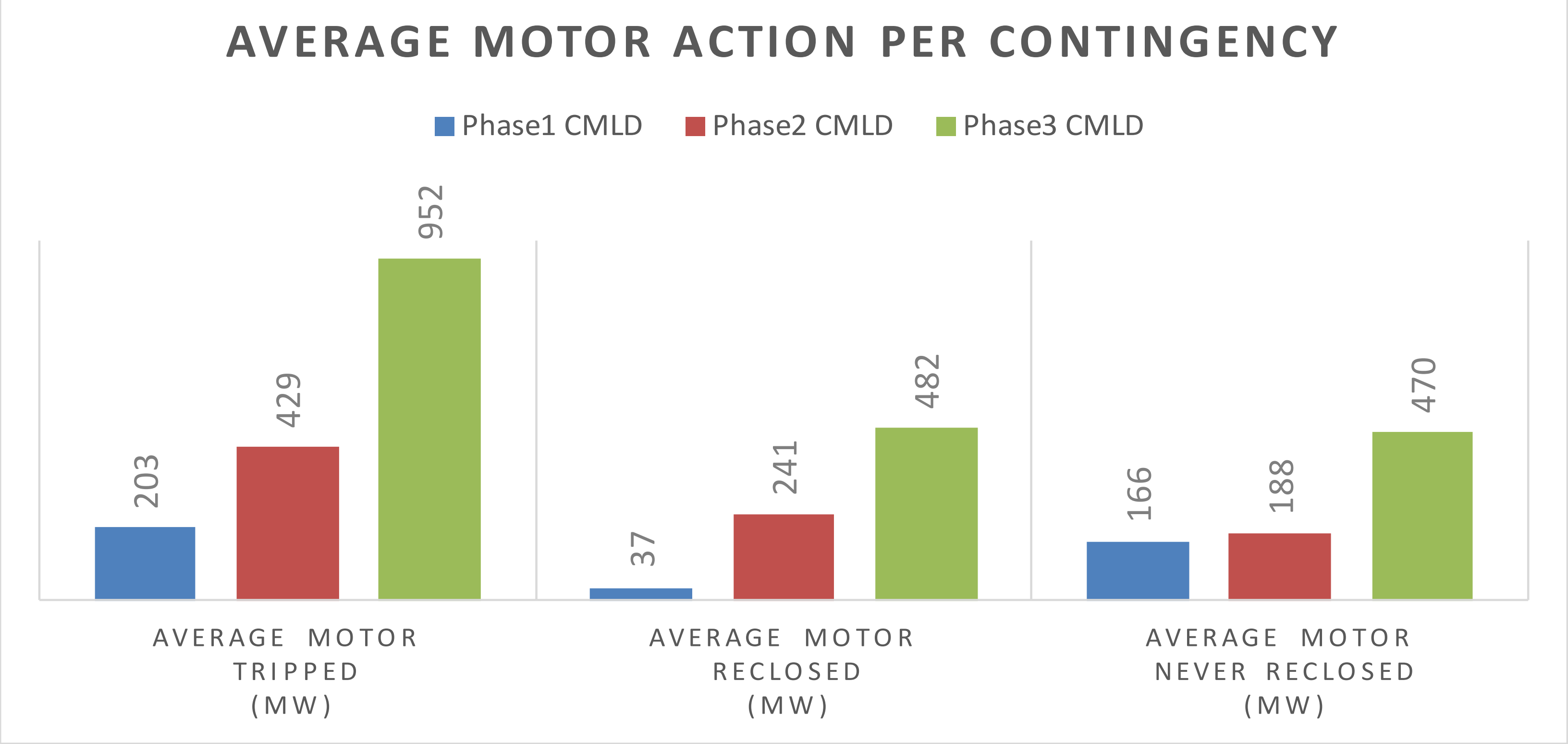
- The CMLD has more severe impact on the system voltage and/or angular stability performance than ZIP loads since it includes a large amount of induction motor loads. In some cases, the system with the CMLD shows different responses from one with the CLOD. This is due to the modeling differences in both models such as distribution feeder and transformer, motor fractions, protection settings and load components and parameters.
- The system with Phase 1 CMLD presents more transient voltage and/or angular stability issues than one with Phase 2 or 3 CMLD due to a higher fraction percentage of Motor A and more conservative protection settings in Phase 1 CMLD.
- The system with Phase 3 CMLD presents more potential voltage recovery violations than one with Phases 1 or 2 CMLD due to Motor D stalling in Phase 3 CMLD that resulted in a higher reactive consumption and worse voltage performance. Below are representative plots under P6 contingencies.





Summary of Results (Cont’d)

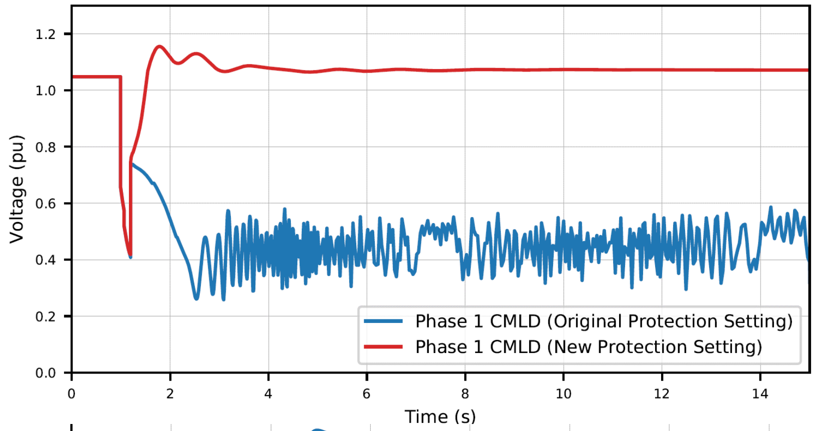
- The system shows more load trips, reconnections and non-reconnections with Phase 3 CMLD than with Phase 1 or 2 CMLD. This is likely due to less conservative Motor A protection settings and the suppressed voltage condition caused by Motor D stalling in Phase 3 CMLD. The below figure summarizes the statistics of load trips, reconnections and non-reconnections seen in the system with each phase of CMLD under the stable contingencies.

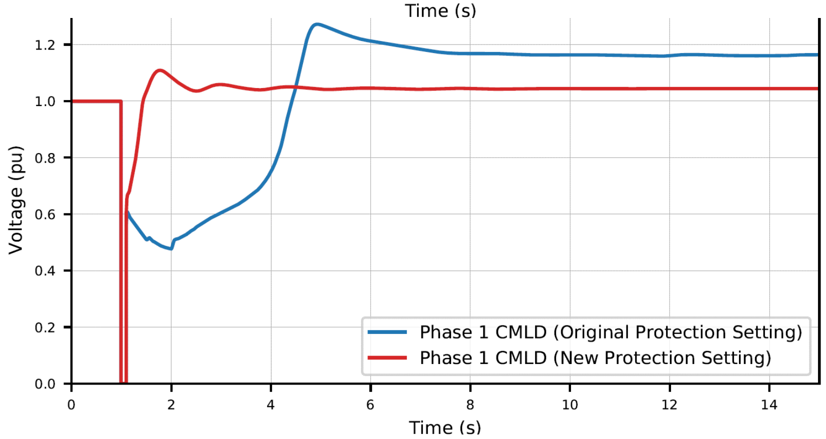


Sensitivity Analysis

- The voltage stability performance improvement with the updated settings is likely due to the higher tripping fraction and faster tripping time. The below plots show the improved voltage recovery response with the updated settings following P1 and P4 contingencies. The initial settings are more conservative settings and hence result in a slower Motor A load tripping or no reclosing following the contingency event.

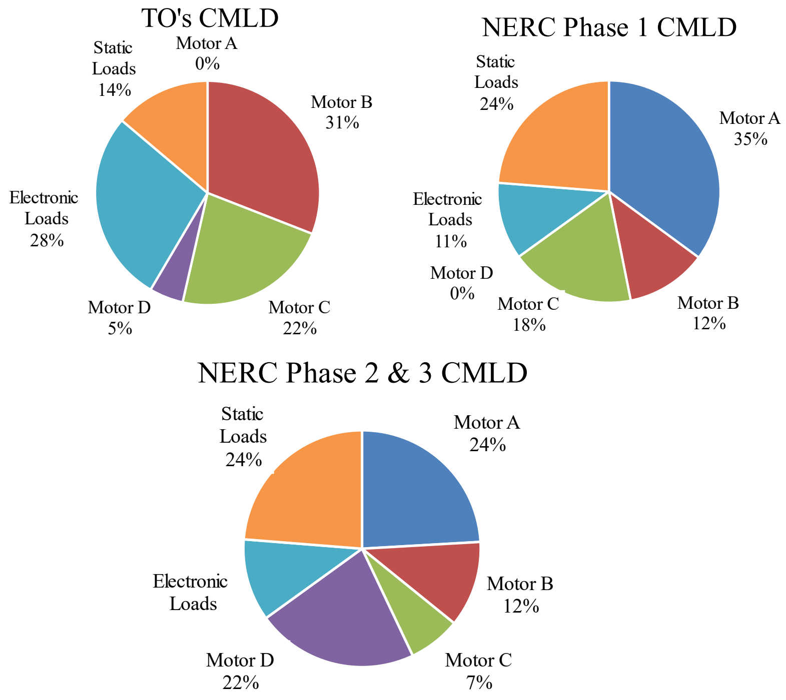
Motor A Parameter	Initial	New
Vtr1 - 1st undervoltage trip voltage, p.u.	0.5	0.5
Ttr1 - 1st undervoltage trip delay, s	0.5	0.033
Ftr1 - 1st undervoltage trip fraction	0.33	0.5
Vrc1 - 1st undervoltage reclose voltage, p.u.	1	0.8
Trc1 - 1st undervoltage reclose delay, s	9999	0.1
Vtr2 - 2nd undervoltage trip voltage, p.u.	0.55	0.6
Ttr2 - 2nd undervoltage trip delay, s	1	0.15
Ftr2 - 2nd undervoltage trip fraction	0.33	0.25
Vrc2 - 2nd undervoltage reclose voltage, p.u.	1	1
Trc2 - 2nd undervoltage reclose delay, s	9999	9999

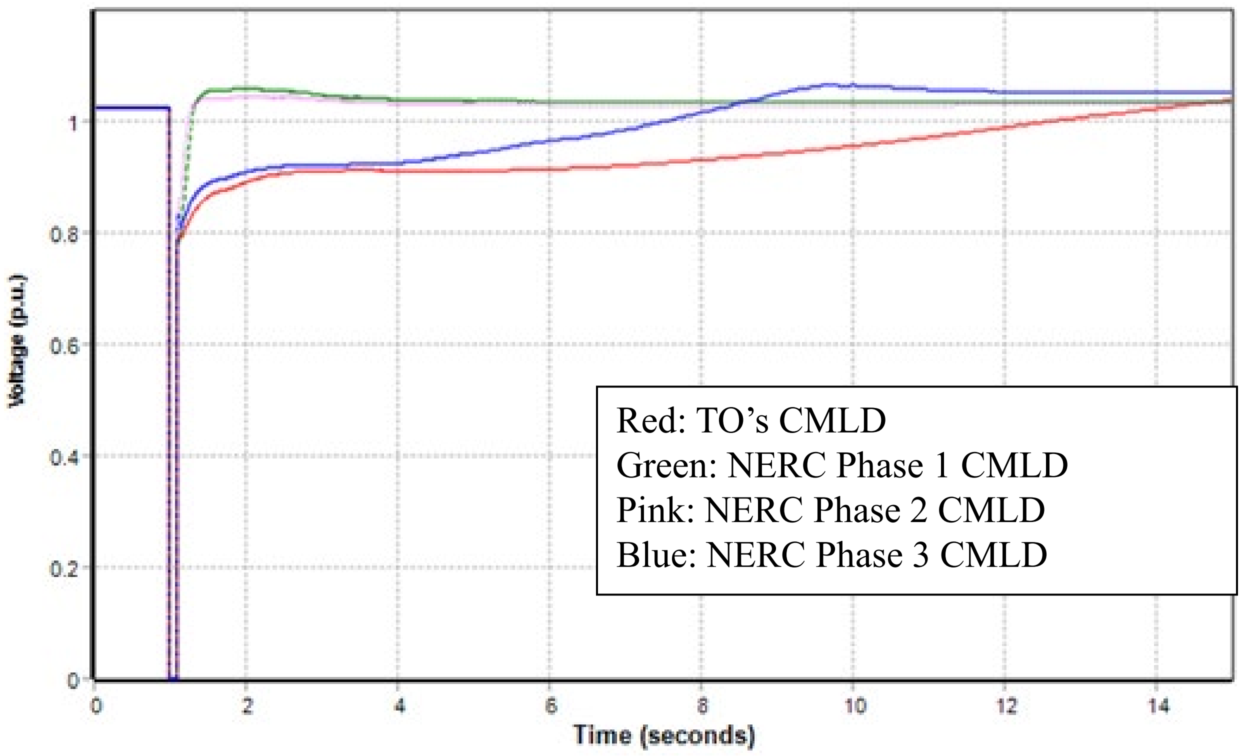




Sensitivity Analysis (Cont'd)

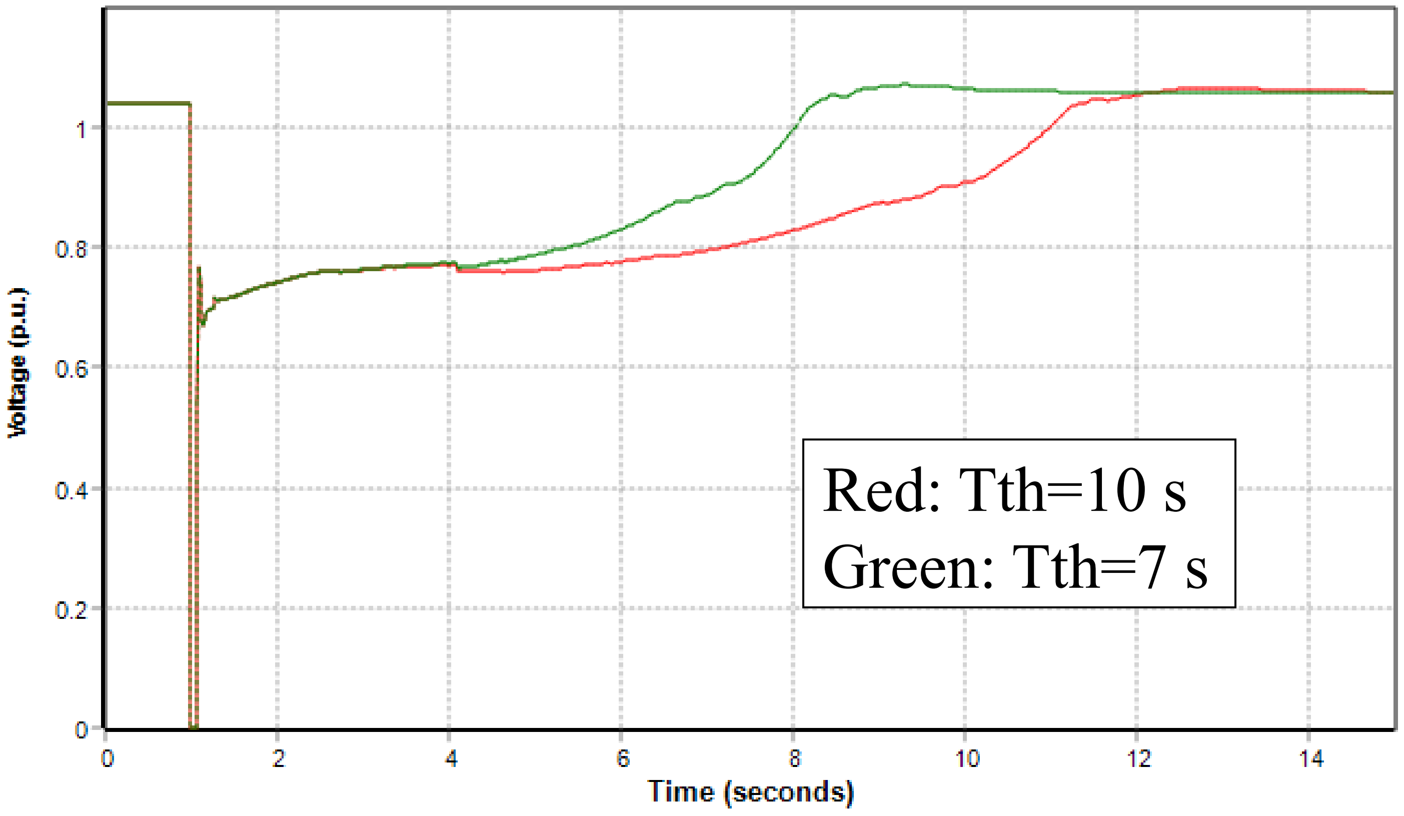
- Motor fractions and protection in the CMLD determine the amount of load tripped or re-connected under various voltage conditions and hence significantly influence system voltage performance. For example, a fraction of Motor A load (commercial three-phase constant-torque compressors), when tripped after fault clearing, does not automatically reconnect since this type of motor loads requires manual reconnection. The below simulation plot shows voltage responses with the CMLD parameterized by TO and the NERC Phases 1-3 CMLD following a P6 contingency. The plot indicates that the voltage from the NERC Phase 3 CMLD recovers faster than that from the TO's CMLD since the TO's CMLD uses more conservative motor protection settings.





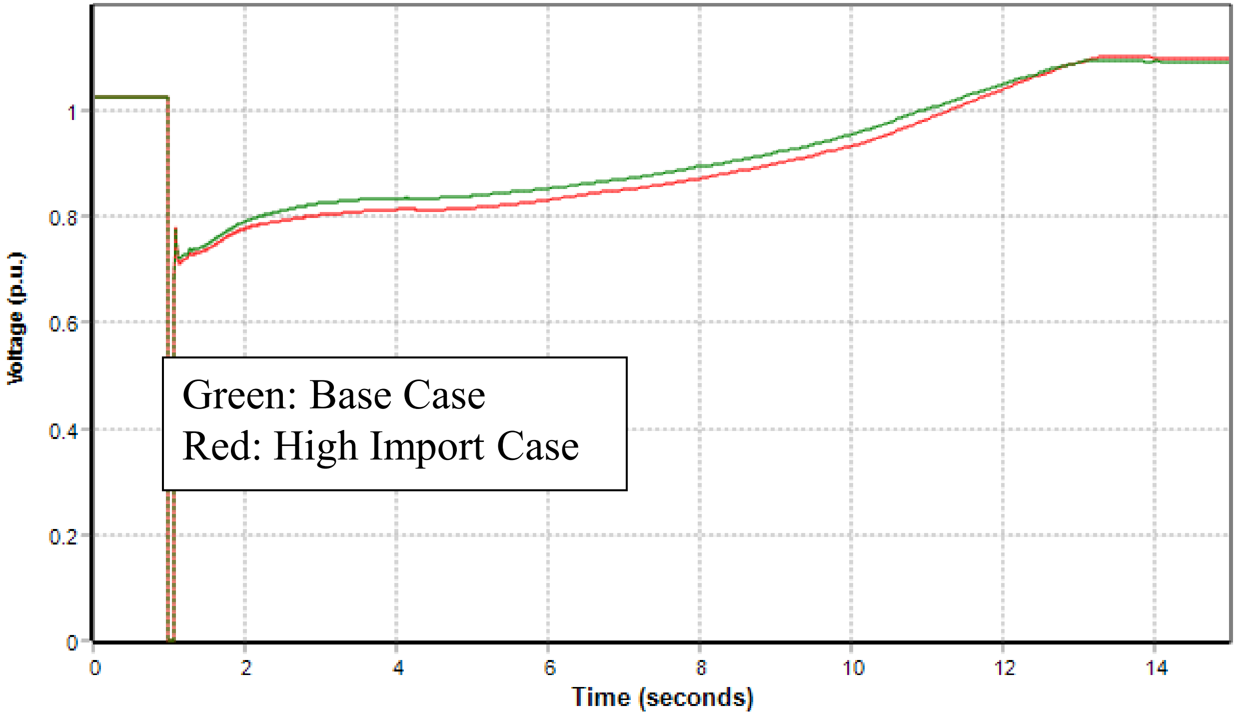
Sensitivity Analysis (Cont'd)

- Motor D fractions and settings have a significant impact on system voltage recovery following a contingency. Voltage recovery with Motor D heating time constant Tth=7s is faster than that with Tth=10s, as shown in the figure below, since a smaller Tth means a faster tripping of Motor D load, thus resulting in voltage to recover faster.



Sensitivity Analysis (Cont'd)

- Heavy transfer cases were created such that power transfer levels for transmission zones reached at a higher level than the normal level. For example, in a transmission zone, the net power interchange (import) was increased by approximate 1500 MW from approximate 3600 MW in the base case to approximate 5100 MW in the heavy transfer case. The below simulation plot compares the voltage responses with the NERC latest Phase 3 CMLD following a contingency for both the base case and the high import case, indicating that voltage responses are similar in both cases with a slightly slower voltage recovery in the high import case.

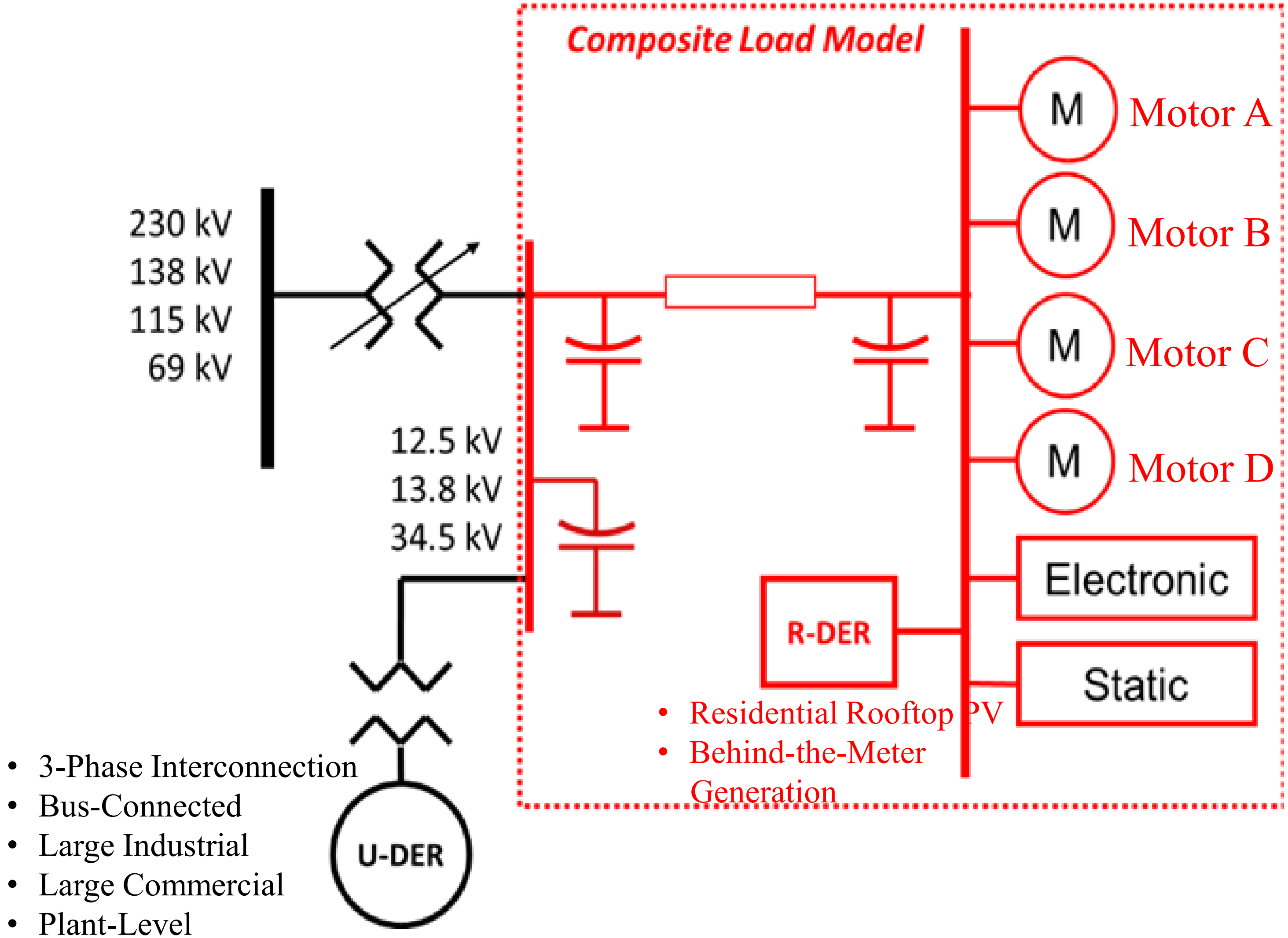


Impacts of DERs

- The impact of Distributed Energy Resources (DERs) were evaluated since transmission grids are being integrated with more and more DERs, which has an impact on system reliability including stability and voltage recovery. DERs are generally categorized as:
  - Utility-Scale DERs (U-DERs): These are DERs directly or closely connected to the distribution bus or connected to the distribution bus through a dedicated, non-load serving feeder. These resources are typically three-phase interconnections and can range in capacity (e.g., 0.5 to 20 MW).
  - Retail-Scale DERs (R-DERs): These are DERs that offset customer load, including residential, commercial, and industrial customers. Typically, the residential units are single-phase while the commercial and industrial units can be single- or three-phase facilities.

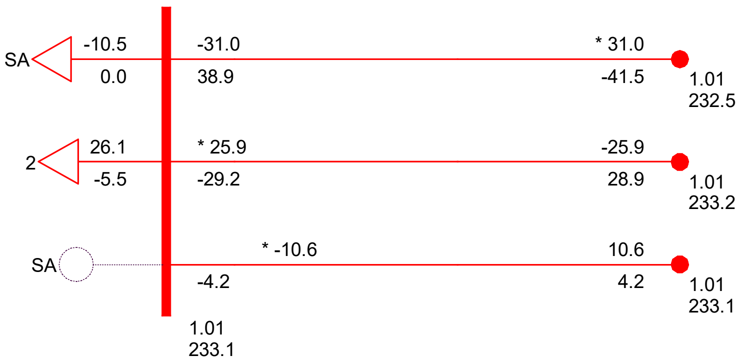
Modeling and Simulation of DERs

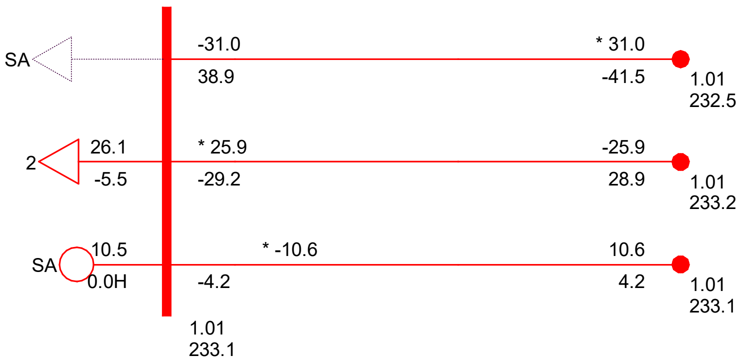
- DER models are typically representative of either one or more larger U-DERs or aggregate amounts of smaller R-DERs spread across a distribution feeder, e.g., Behind-the-Meter solar Photovoltaic (PV) generation.

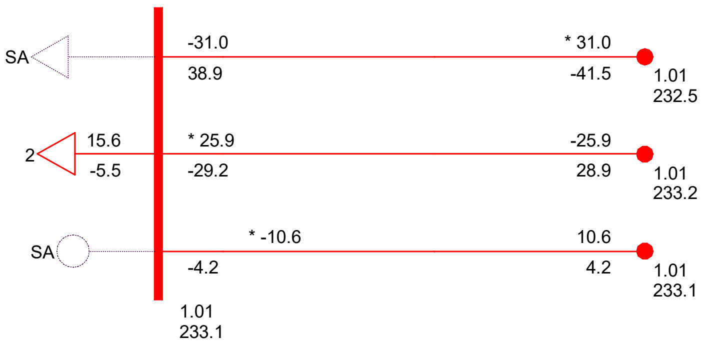


Modeling of DERs

- In most previous system stability studies, DER generators are netted with negative loads and DER dynamics are not captured.
- In the study, U-DERs are represented as online renewable generators and R-DERS are represented as distributed generation (DG) embedded in load. DG would offset load and thus the net load would decrease. In the case setup, both DER reactive outputs are set to close to zero with no voltage control in steady state condition so that DER reactive reserves are maximized for voltage support during dynamics.

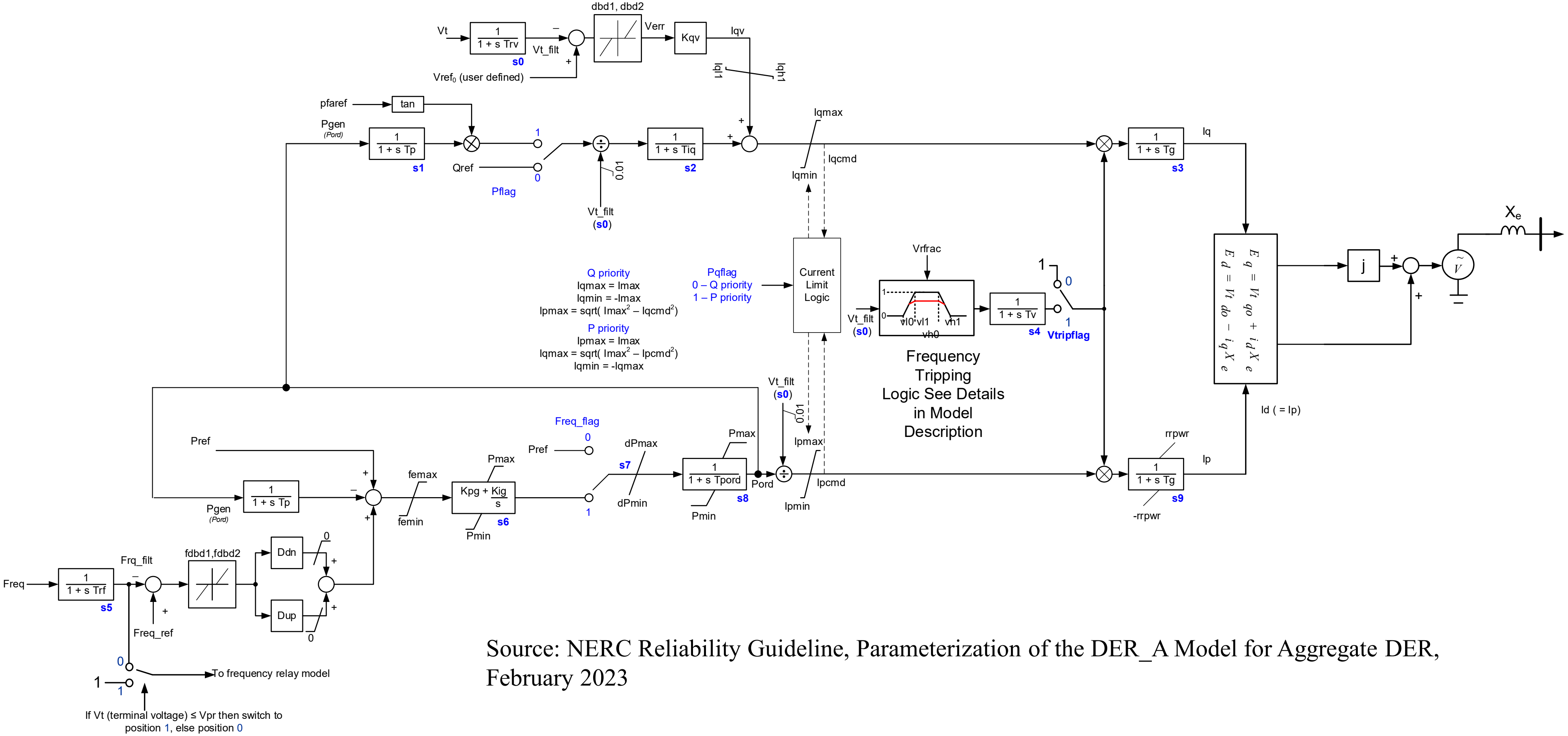






Modeling of DERs (Cont'd)

- Dynamics of DER generators are modeled using the DER_A model.
- Dynamics of DG are modeled as part of the composite load (CMLD) model, i.e., "CMLDDG" model.



Source: NERC Reliability Guideline, Parameterization of the DER_A Model for Aggregate DER, February 2023

Modeling of DERs (Cont’d)

- Both the DER_A model and the DG part of the CMLDDG model are parameterized based on the NERC Reliability Guideline[1]. The following controls were set in the study:
  - Voltage and reactive control (pfFlag=0, Kqv=5).
  - Active power-frequency control with droop (FreqFlag=1 and Ddn=20, downward control only, assuming that DERs are dispatched at the maximum capacity and thus cannot provide frequency response for underfrequency conditions.)
  - Fraction of DER tripping or entering momentary cessation on voltage enabled (VtripFlag=1).
  - No fraction of DER restoring output after tripping (Vrfrac=0, assuming a conservative condition).
  - Reactive current priority for dynamic voltage support (PQFlag=0, Q priority).
- Dynamic parameters for the CMLD part of the CMLDDG model are set by PJM respective TOs

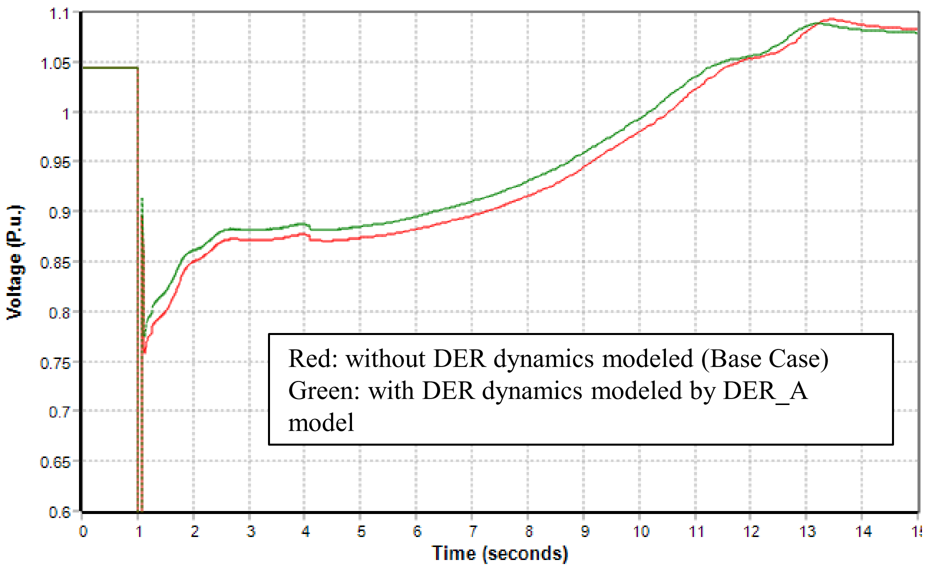
1. NERC Reliability Guideline, Parameterization of the DER_A Model for Aggregate DER, February 2023

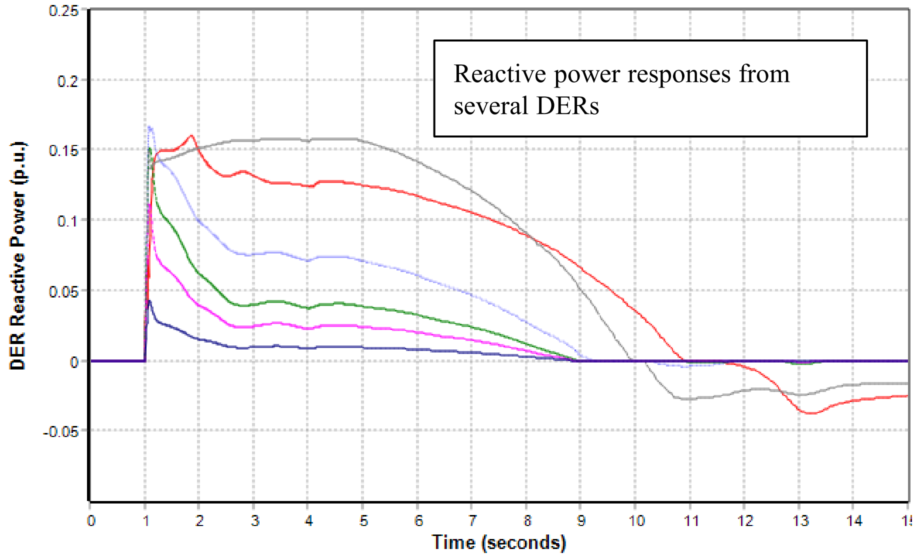
Simulation of DERs

- Two transmission zones with relatively high levels of DERs were selected for evaluation of DER impacts. DERs in these two zones were dispatched at the capacity factor of 40%~60%, resulting in approximately 480~620 MW of DERs in service in each zone, representing about 2~5% of the zone total generation.
- These DERs represents either U-DERs or R-DERs or the mix of the two types of DERs.

Simulation of DERs with DER_A Model

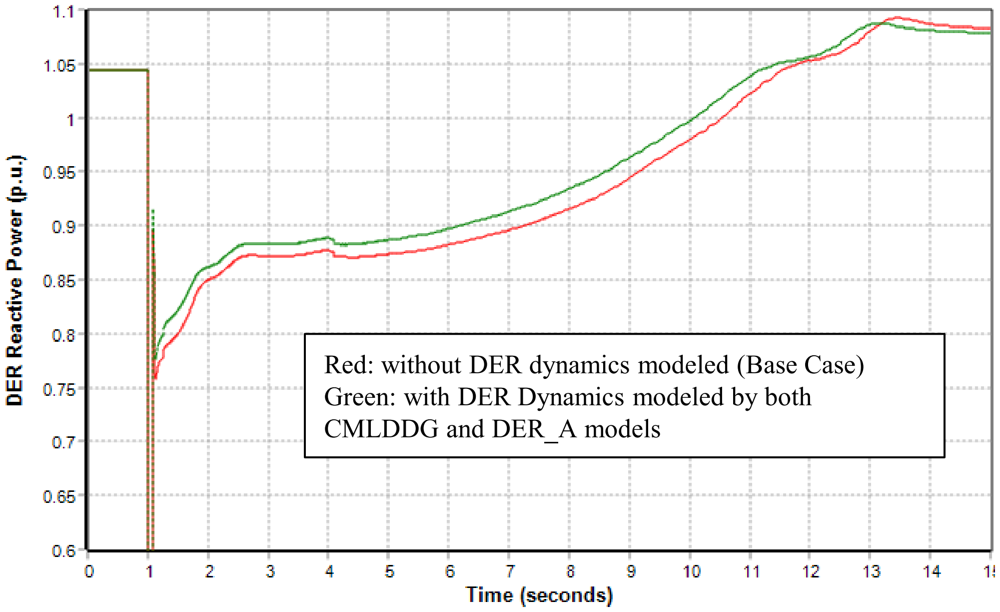
- In the simulation, in addition to the CMLD model applied, the DER_A model was applied to all DERs (about 620 MW) to capture DER dynamics in one transmission zone. The system is transiently stable and voltage is dynamically recovered with the selected normal planning P1 and P4 contingencies tested. The DER_A model performs as expected. The impact of DERs on angular stability of the system is insignificant. With DERs in voltage/reactive control mode, a noticeable improvement in voltage recovery is observed following contingency events. This voltage recovery improvement would help avoid motor stalling conditions during dynamics.





Simulation of DERs with CMLDDG Model

- In this simulation, in addition to the CMLD model applied, the mix of DER_A and CMLDDG models were applied to all DERs to capture DER dynamics in the service zone (DER_A model for 320 MW and CMLDDG model for 300 MW). The system is transiently stable, and voltage is dynamically recovered with the selected normal planning P1 and P4 contingencies tested. The CMLDDG model performs as expected. The results in this case are similar to those with the DER_A model only. This is expected since the DG part embedded in load is modeled and parameterized in the CMLDDG model in the same way as in the DER_A model.



Recommendations on CMLD

- Validate and update TOs stability model databases to fully adopt NERC Phase 3 CMLD.
- Avoid using the CLOD in combination with the CMLD and expedite the replacement of the CLOD with Phase 3 CMLD.
- Benchmark NERC Phase 3 CMLD against available load field measurements or recorded events.

Future Work on DER

- The following conditions are considered for future DER analysis and testing:
  - Higher penetrations of DERs in transmission zones.
  - Reverse power flow conditions due to DERs.
  - Faults close to DER and/or load locations.
  - More severe faults leading to DER or load tripping. Different ramp limits for DER output restoration.
  - Disturbance events for frequency control by DERs.

References

1. Xiaokang Xu, Jie Tang, Boyuan Xie, Byoungkon Choi, Lin Huang and Yiming Mao, “Modeling and Simulation of Distributed Energy Resources in PJM System,” presented at and in Proc. of the 2024 IEEE PES General Meeting, 21–25 July, 2024 in Seattle, Washington.
2. Xiaokang Xu, Reza Yousefian, Jie Tang, Byoungkon Choi, Lin Huang and Yiming Mao, “Sensitivity Studies on Composite Load Models in PJM System Stability Assessment,” presented at and in Proc. of the 2023 IEEE PES General Meeting, 16–20 July, 2023, Orlando, Florida.
3. Xiaokang Xu, Reza Yousefian, Jie Tang, Mohamed Elkhatib, Byoungkon Choi, Lin Huang, Yiming Mao and Aaron Berner, “PJM System Stability Assessment Using Dynamic Load Models,” presented at and in Proc. of the IEEE PES General Meeting, 25-29 July, 2021, Washington, DC.
4. Xiaokang Xu, Mohamed Elkhatib and Ming Wu, “Application of A New Composite Load Model in Dynamic Voltage Assessment,” presented at and in Proc. of the IEEE PES General Meeting, August 2-6, 2020, Montreal, Quebec, Canada.