Modeling and Simulation of Data Center Loads in PJM System Stability Assessment

Jie Tang, Boyuan Xie, Xiaokang Xu
and Gayatri Repalle
S&C Electric Company, Chicago, IL 60026, USA

Byoungkon Choi, Lin Huang, Yiming Mao
and David Egan
PJM Interconnection LLC., Audubon, PA 19403, USA

***Abstract*— The rapid expansion of data centers has introduced new challenges for electrical grids in North America. This paper presents a study in which dynamics of large-scale data center loads (DCLs) were, for the first time, modeled and simulated in parts of the PJM system stability assessment. The paper focuses on configuring and parameterizing DCL models and dynamic load modeling in transmission system stability assessment. The paper includes a case study to demonstrate the impact of the ride-through capability and distinct tripping logics of DCLs on transmission system reliability (frequency, rotor angular or transient voltage stability).**

***Index Terms*—Data center, dynamic load modeling, composite load model, system stability, and transmission planning.**

I. Introduction

North American Transmission Systems are evolving with the rapid growth of data center loads (DCLs) which are driven by cloud computing, artificial intelligence, and digitalization. In the United States, DCL consumption reached about 176 TWh of electricity in 2023, representing 4.4% of national demand. Projections indicate consumption could continue to grow to 325–580 TWh by 2028, or 6.7%–12% of U.S. load [1]. This growth is particularly challenging in maintaining system reliability because DCLs are large and geographically clustered, such as the "Data Center Alley" in the PJM assessment areas [2], and often concentrated in regions where transmission networks are already stressed. It also may pose complexity and challenges in planning and operations of large-scale transmission systems. For transmission planning, which routinely requires system stability assessment, accurate DCL models and updated large-load integration procedures are important and necessary.

NERC has identified large emerging loads as potential risks to grid reliability. In particular, large-scale DCLs can contribute adversely to stability problems due to their high power ratings, fast controls, rapidly varying load profiles, and heavy use of active power electronics [3][4]. Oscillatory power consumption patterns associated with Artificial Intelligence (AI) training can be a source of significant forced oscillations. In [5] a dynamic load model is proposed to represent various AI load patterns as well as fault ride-through behaviors. In [6] data center demand is divided into computing, cooling, and ancillary loads to study corresponding power market integration criteria. In [7] loads of similar categories are used and specially studied how different motorized cooling infrastructures affect data center power consumptions. These data center models are not available yet in the system planning software tools being used in North American (NA) Transmission Systems. At present, most NA transmission system stability studies still rely on existing composite load (CMLD) models [8] to represent DCLs. However, the CMLD captures only part of DCL's dynamics without ramping effects considered. Recently a power electronic reconnecting and ceasing (PERC1) load model that can represent DCL's fault ride-through and ramping behaviors has been developed for large-scale system stability studies [9].

This paper presents a study in which dynamics of large-scale DCLs were, for the first time, modeled and simulated in parts of the PJM system stability assessment. The paper focuses on configuring and parameterizing the CMLD and PERC1 models to represent DCL dynamics. The paper includes a case study to show how adopting such models can influence system reliability (frequency, rotor angular or transient voltage stability) under disturbances. The main contributions include validating, tuning, and testing the CMLD and PERC1 models for DCL dynamics in the large-scale transmission system. The paper serves a useful reference for large-scale system stability analysis with large-scale DCLs.

II. Models, Critical Contingencies and Criteria

Data centers generally include four main components [3]:

- Information Technology (IT) equipment: servers, storage, and networking gear driven by power electronics, making up 60–95% of energy use.
- Power delivery systems: external power, internal distribution, Uninterrupted Power Supply (UPS), on-site emergency generation, battery and control systems.
- Cooling systems: power electronic loads such as variable speed drives and inverters, which create harmonics and reactive power demand.
- Miscellaneous loads: static loads such as lighting and security representing the smallest share of total demand.

This paper discusses modeling and simulation the impacts of IT, cooling and lighting load components on the grid. Power delivery systems mainly serve standby power sources for DCLs which are not modeled and discussed here.

A. Power Flow Modeling of DCLs

Method 1: Fig. 1 shows an example of four DCLs connected to a 230 kV bus. Each DCL combines cooling, lighting and IT load components. DCLs are modeled as constant power loads in the power flow case. In the transmission service zone under study, there is a total load of approximately 31 GW. DCLs make up for about 15 GW (about 50% of the total load).

Method 2: Referring to the example in Fig. 2, each DCL separates IT load component from cooling and lighting load components. The power factor for both components remains unchanged after splitting. They are represented as constant power loads in the power flow case.

979-8-3315-8138-1

The numbers in both Fig. 1 and Fig. 2 indicate active and reactive powers/loads in MW/MVar and voltage in kV and p.u.

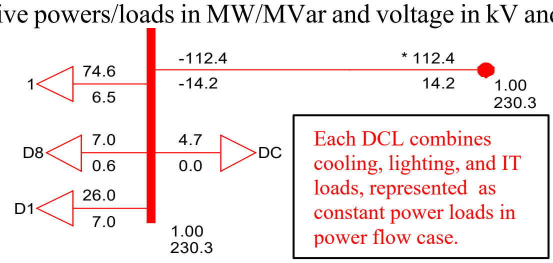

Fig. 1: Data Center Loads Modeled in Power Flow Case

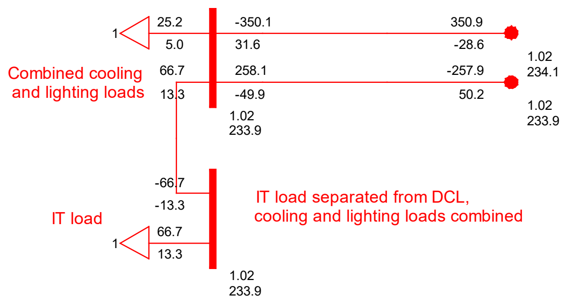

Fig. 2: Data Center Load Split as Cooling, Lighting and IT Portions

B. *Dynamic Modeling of DCLs*

Approach 1: Using the CMLD model [8] depicted in Fig. 3 to model dynamics of DCLs, this approach represents cooling and lighting loads as Motors A, B, C, D and/or static loads, and IT loads as power electronic loads.

The CMLD model captures dynamics of three-phase and single-phase motors as well as motor stalling, tripping and reclosing conditions. The CMLD model includes the following components:

- Distribution equivalent system including distribution step-down transformer and under-load tap changer control, and distribution circuit/feeder.
- Induction motors:
  - Motor A: typically representing three-phase constant-torque compressors used in commercial air conditioning and refrigeration.
  - Motor B: typically representing three-phase higher inertia motors used for driving fans whose torque is proportional to speed squared.
  - Motor C: typically representing three-phase lower inertia motors used for driving pumps whose torque is proportional to speed squared.
  - Motor D: typically representing single-phase very low inertia compressors, often used in residential air conditioners.
- Power electronic loads representing an aggregation of small electronic constant power loads (e.g., computers and loads with variable frequency drives).
- Static loads representing other unclassified aggregated loads or voltage/frequency sensitive loads (e.g., incandescent lights and resistive space and water heating).

Approach 2: For dynamics of DCLs, this approach represents cooling and lighting loads as Motors A, B, C, D and/or static loads in the CMLD model. IT loads are represented as power electronic loads using the PERC1 [9] model which is based on an electric vehicle (EV) charger model [10] since the CMLD model does not have the capability of modeling the ramping process of IT load reconnection. EV chargers have some traits in common with IT loads as both are dominated by power electronic interfaces with fault and recovery behavior. These similarities allow users to reproduce the dynamic performance of IT loads through parameter tuning. The active and reactive power controls of the IT load in PERC1 are similar, except that the reactive power control does not have a frequency-based droop for active power output of the IT load. The control logic in PERC1 models IT load ride-through, tripping (disconnection), time delay, ramping up and reconnection, voltage and frequency protections. More details of the PERC1 model can be found in [9].

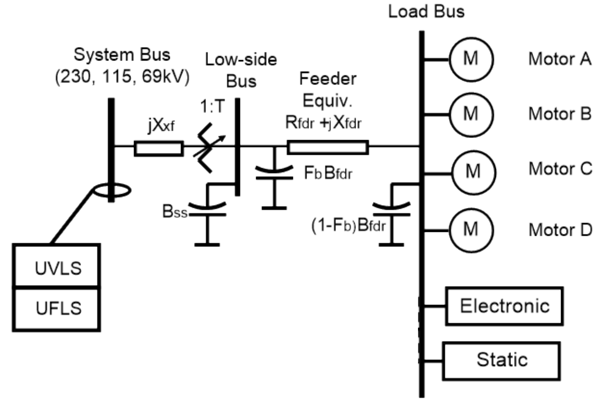

Fig. 3: Composite Load Model Structure

Both approaches configured and parameterized the CMLD and PERC1 models for DCLs such that the total IT load was about 10 GW, the total cooling and lighting load was about 5 GW in the service zone under study. IT loads may ride through, trip/disconnect or reconnect with the system depending upon system conditions (voltage and frequency performance).

C. *Dynamic Modeling of Non-DCLs*

Dynamics of other loads (non-DCLs) in the study area were represented by the CMLD model with the latest dynamic parameters [11]. Application of the latest CMLD model is in line with the NERC initiative of applying this model in the integrated grids of the Eastern Interconnection in North America of which PJM is an integral part. It follows NERC TPL-001-5.1 Standard [12] which requires that system stability assessment includes load models representing the expected dynamic behavior of induction motor loads.

Load composition fractions and motor protection settings in the CMLD model reflect substation types/region-specific feeders, seasons and climate zones, temperature and humidity of representative cities as well as system operating conditions in the PJM service zone under study.

D. *Critical Contingency Selection*

A set of critical contingencies were selected for the study which would have the most severe effects on system stability. The selection used a systematic process to screen and rank critical contingencies and considered such factors as key locations near high load centers, weak parts of the system or voltage support, heavily loaded transmission lines or transformers, and breaker configurations of the substations [13-15]. These critical contingencies represent NERC P1, P4, P6, P7 and Ex2.b contingency events [12] involving 3-phase-

979-8-3315-8138-1

to-ground and single-phase-to-ground faults with a normal clearing time of 4.5~5.5 cycles and a delayed clearing time of 10.5~11.5 cycles.

E. Criteria

Applicable stability criteria are applied in the study:

- Generators should maintain stability following a contingency.
- System voltage should not lead to voltage instability or voltage collapse following a contingency/fault. System voltage should recover above 0.7 p.u. in 2.5 seconds after the fault is cleared.
- Damping ratios for generator oscillations under a contingency should be greater than 3%.

III. Case Study

A. PJM System and Study Case

PJM Interconnection is a regional transmission organization that coordinates the movement of wholesale electricity in all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia, and the District of Columbia, as shown in Fig. 4. PJM serves more than 67 million people and covers 369,054 square miles and 88,333 miles of high-voltage lines, monitors and coordinates 1,486 generation sources with a total generating capacity of around 182,000 MW with all-time peak load of 165,563 MW.

PJM is experiencing large growth in DCLs that are in turn driving higher demand forecasts [2]. The study was performed on the entire PJM system summer peak load case in the Near-Term Transmission Planning Horizon.

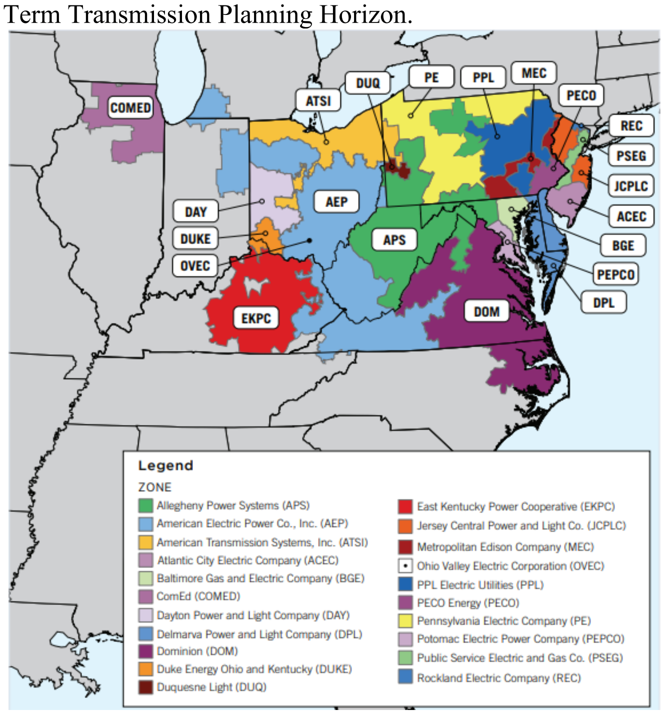

Fig. 4: Map of the PJM Footprint

B. Study Scenarios

Two scenarios were simulated in the study:

Scenario 1: This scenario simulates dynamics and tripping (disconnection) of DCLs by off-nominal voltage protection under a fault/contingency without reconnection after the fault is cleared, using modeling Method 1 and Approach 1 described in Section II. DCLs, once disconnected, do not reconnect with the system in this scenario. To simulate this behavior, power electronic (IT) loads' recovery percentage is set to 0 for all DCLs' CMLD models. The tripping voltage was set to 0.8 p.u. in the simulation. The tripping was assumed to occur instantaneously when the load bus voltage drops down to or below 0.8 p.u. This scenario is intended to evaluate the impact of the worst-case condition from the DLC ride-through perspective.

Scenario 2: This scenario simulates dynamics and voltage tripping (disconnection) of DCLs under a fault/contingency with reconnection after the fault is cleared, using Method 2 and Approach 2 described in Section II. DCLs, once disconnected, reconnect with the system after a time delay in a ramping fashion when voltage recovers. The voltage recovery parameters are tuned in the PERC1 model for IT loads, and the parameters are unchanged for the cooling and static loads. The voltage recovery threshold was set to 0.8 p.u., and the tripping voltage thresholds were set to 0.8 p.u. and 1.1 p.u. in the simulation. The tripping was assumed to be instantaneous. A delay of 4 secs was assumed for reconnection with a ramping time of 10 secs. This scenario is a more realistic scenario recognizing that most large DCLs are equipped with UPS and battery system to ride through minor transient voltage interruptions.

C. Simulation of DCLs without Reconnection (Scenario 1)

In this scenario, for the critical contingencies tested, some of them caused generator angular instability (see a representative plot in Fig. 5). The generator unstable response is due to low voltage tripping of large amounts of IT loads without reconnection. IT loads are disconnected from the grid by UPS voltage protection when the bus voltage goes below a certain level. Such an abrupt large load drop and sustained disconnections, ranging from approximately 6 GW to 10 GW, created gigawatt-scale shifts in power flows within only a few cycles resulting in the increase of system frequency and generator angle. These disturbances may exceed the capability of fast-acting generation controls to respond and restore balance between generation and load. It appears that without sufficient corrective control actions, the excess mechanical power input drove accelerating rotor dynamics, further increasing rotor angle separation and preventing the system from returning to a stable operation point. Fig. 6 shows a representative IT load disconnected at 1 sec due to low voltage (<0.8 p.u.) without reconnection. Low voltages observed following the contingency are localized near DCLs and do not propagate to the rest of the system.

Disconnection of gigawatt-scale DCLs also causes system frequency to deviate from nominal (high frequency in this case), as shown in the representative plot in Fig. 7. In North America, the initial frequency deviation is measured by the rate of the change of frequency (*RoCoF*) over the first 0.5-second window after a contingency [16][17]:

$$RoCoF_{0.5} = \frac{f(t = t_0 + 0.5) - f(t = t_0)}{0.5} \left[\frac{Hz}{s}\right]$$

The estimated $RoCoF_{0.5}$ for the plot in Fig. 7 is approximately 240 mHz/s. Currently there is no *RoCoF* limit

979-8-3315-8138-1

requirement in the Eastern Interconnection in North America of which PJM is an integral part.

D. Simulation of DCLs with Reconnection (Scenario 2)

The simulation results of this scenario show that a slow ramp rate can fail the DCLs reconnection process

Fig. 8 shows representative voltage and IT load responses with a failed reconnection. For this IT load, it initially tripped at 1 sec due to low voltage (<0.8 p.u.). After the fault is cleared, load starts reconnecting and bus voltage drifts upward. However, the slow reconnection raised voltage too high (>1.1 p.u.) at 8 secs, then the load tripped (disconnected) again by high voltage protection which failed the reconnection process.

Fig. 9 shows representative voltage and IT load responses with a slow but successful reconnection, in which the IT load is reconnecting with a ramping time of 10 secs.

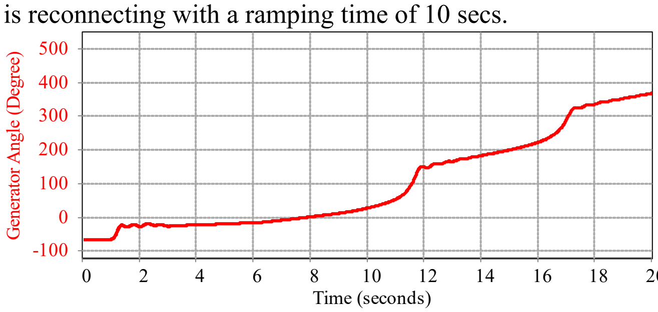

Fig. 5: Generator Angle Responses under Contingency (Scenario 1, Red Line for Generator Angular Instability with IT Load Disconnection)

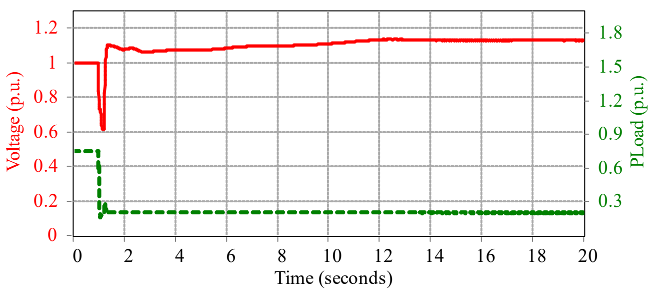

Fig. 6: Voltage & IT Load Responses under Contingency (Scenario 1, Red Line for Voltage, Green Line for IT Load Disconnection)

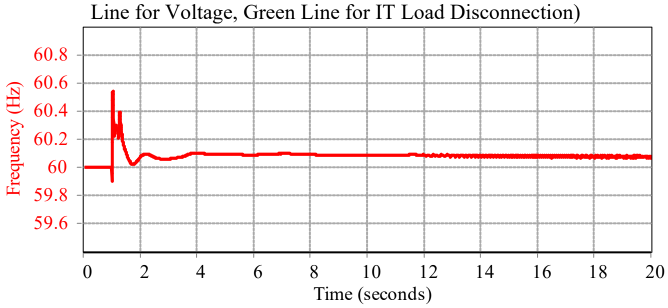

Fig. 7: Frequency Response under Contingency (Scenario 1, Red Line for Frequency Response with IT Load Disconnection)

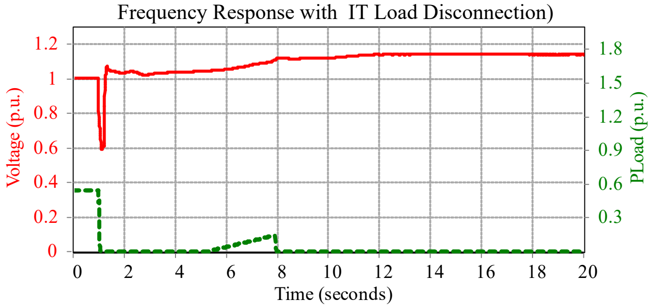

Fig. 8 Voltage & IT Load Responses under Contingency (Scenario 2, Red Line for Voltage, Green Line for IT Load Failed Reconnection)

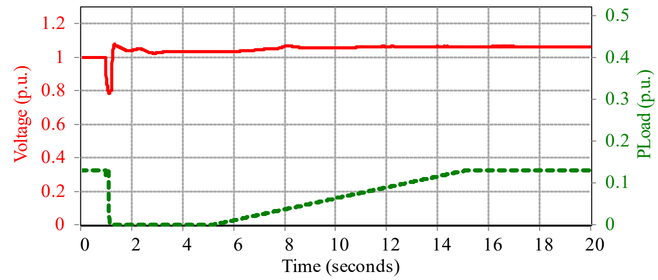

Fig. 9 Voltage & IT Load Responses under Contingency (Scenario 2, Red Line for Voltage, Green Line for IT Load Slow Reconnection)

E. Sensitivity Analysis with Faster DCLs Reconnection Speed

A sensitivity case with a ramping time of 5 secs for Scenario 2 was tested, and the results show improvement on system stability and voltage recovery performance. This is due to faster ramping and successful reconnection of the tripped IT loads. Fig. 10 shows representative voltage and IT load responses with a faster reconnection, in which the IT load is reconnecting with a ramping time of 5 secs. Compared to Fig. 8, a faster ramping makes the reactive surplus period shorter, thus preventing the voltage rising above the high voltage protection threshold to fail the reconnection process.

Fig. 11 shows representative generator angle responses with 5-sec and 10-sec ramping times for IT loads. As seen in the figure, the generator with faster IT load reconnection is stable, while it is unstable with slow IT load reconnection. With faster ramping, the difference between mechanical and electrical power is smaller hence the accelerating power is reduced to help the generator angles settle down quicker.

Fig. 12 and Fig. 13 show representative frequency and voltage responses, respectively, with 5-sec and 10-sec ramping times for IT loads. It is seen in the figures that the fast reconnection brings frequency back to normal and improves voltage recovery as compared to the failed or slow reconnection.

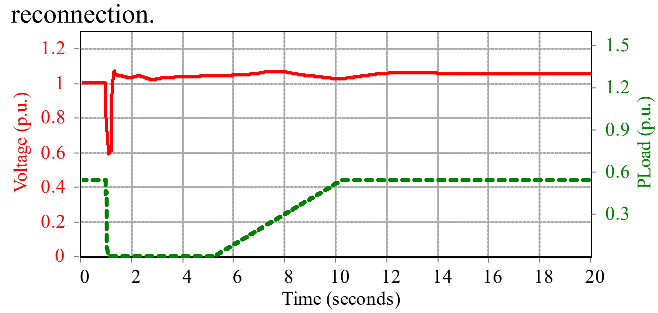

Fig. 10 Voltage & IT Load Responses under Contingency (Scenario 2, Red Line for Voltage, Green Line for IT Load Fast Reconnection)

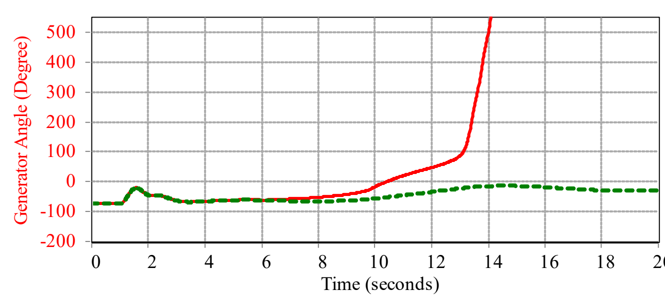

Fig. 11: Generator Angle Responses under Contingency (Scenario 2, Red Line for IT Load Reconnection with 10-sec Ramping, Green Line for IT Load Reconnection with 5-sec Ramping)

979-8-3315-8138-1

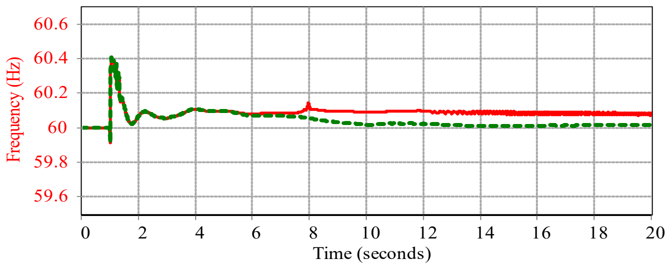

Fig. 12: Frequency Responses under Contingency (Scenario 2, Red Line for 10-sec Ramping, Green Line for 5-sec Ramping)

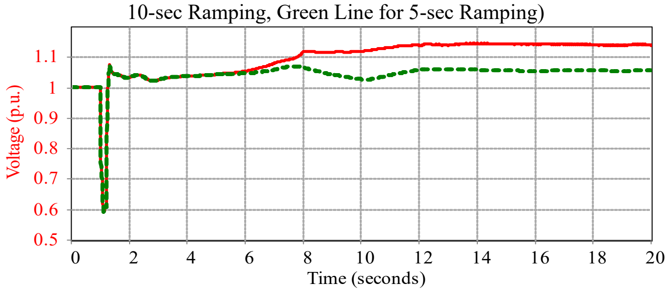

Fig. 13: Voltage Responses under Contingency (Scenario 2, Red Line for 10-sec Ramping, Green Line for 5-sec Ramping)

IV. Conclusion

The study presented in this paper shows that the inability of DCLs to ride through faults or their slow reconnection can cause generators to lose angular stability (synchronism) for critical contingencies. The study also shows the adverse impact of the tripping of large-scale IT loads on system frequency and voltage performance. Thus, accurate modeling of voltage and frequency ride-through behaviors and speedy reconnection of DCLs during disturbances play an important role in system stability performance (angular, frequency or voltage stability).

In addition to modeling, contingencies are also important to DCLs. Because of the size and clustering of data centers, a small number of contingencies/faults can dominate system risk. A structured method discussed in [13-15] may be used to identify critical contingencies that can best reveal their impact on system reliability.

DCL's impact on system frequency depends upon system operating conditions, contingency/fault types, and dynamic model parameters and settings for data center loads, etc. Further studies on this impact and *RoCoF* are being planned for the future.

Accuracy of DCL models is crucial for dynamic simulations. New generic DCL models are still being developed. It is recommended that DCL models be validated with PMU data near data centers or recorded system events whenever possible. The next steps involve enhancing the DCL model's accuracy with actual field data and defining effective DCL ride requirements to ensure system security.

V. Acknowledgments

The authors gratefully acknowledge Dr. Kannan Sreenivasachar of ISO New England for implementing and sharing the user-defined model version of the PERC1 in PSS®E [18], the software tool used in this study. The authors also thank Dr. Zhenyu (Henry) Huang, Argonne Distinguished Fellow, for providing useful discussions and comments on DCLs.

VI. References

[1] Lawrence Berkeley National Laboratory, "U.S. Department of Energy, "2024 United States Data Center Energy Usage Report," December 2024. https://escholarship.org/uc/item/32d6m0d1

[2] North American Electric Reliability Corporation (NERC), "Long-Term Reliability Assessment 2024," 2024. www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_Long%20Term%20Reliability%20Assessment_2024.pdf

[3] NERC Large Loads Task Force White Paper: "Characteristics and Risks of Emerging Large Loads," July 2025. www.nerc.com/comm/RSTCReviewItems/3_Doc_White%20Paper%20Characteristics%20and%20Risks%20of%20Emerging%20Large%20Loads.pdf

[4] NERC Incident Review, "Considering Simultaneous Voltage-Sensitive Load Reductions," January 8, 2025. https://www.nerc.com/pa/rrm/ea/Documents/Incident_Review_Large_Load_Loss.pdf

[5] Jimenez-Ruiz, A., & Milano, F. (2025), "Data Center Model for Transient Stability Analysis of Power Systems," arXiv preprint arXiv: 2505.16575, May 2025. https://arxiv.org/pdf/2505.16575

[6] C. Guo, F. Luo, Z. Cai, and Z. Dong, "Integrated energy systems of data centers and smart grids: State-of-the-art and future opportunities," Applied Energy, vol. 301, 117474, 2021. https://doi.org/10.1016/j.apenergy.2021.117474

[7] J. Sun, M. Mihret, M. Cespedes, D. Wong and M. Kauffman, "Data Center Power System Stability — Part II: System Modeling and Analysis," in CSEE Journal of Power and Energy Systems, vol. 8, no. 2, pp. 420-438, March 2022. https://ieeexplore.ieee.org/document/9713964

[8] NERC Reliability Guideline, "Developing Load Model Composition Data," March 2017. www.nerc.com/comm/RSTC_Reliability_Guidelines/Reliability_Guideline_-_Load_Model_Composition_-_2017-02-28.pdf

[9] Jamie Weber, Power Electronic Reconnecting and Ceasing (PERC1) Load Model, November 18, 2025. https://www.powerworld.com/files/Power-Electronic-Reconnecting-and-Ceasing-PERC1-Load-Model.pdf

[10] NERC EV Modeling and Parameterization: "Electric Vehicle Technical Reference Report," November 2023. www.nerc.com/comm/RSTC_Reliability_Guidelines/EV_Modeling_Technical_Reference_Report.pdf

[11] NERC Load Modeling Working Group, Load Model Data Tool, 2023. https://dev.azure.com/nerc/_git/LMWG_Resources

[12] NERC Planning Standard TPL-001-5.1, July 1, 2023. https://www.nerc.com/pa/Stand/Reliability%20Standards/TPL-001-5.1.pdf

[13] 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," Proc. of the IEEE PES General Meeting, 25-29 July 2021,Washington, DC. https://ieeexplore.ieee.org/document/9638099

[14] 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. https://ieeexplore.ieee.org/document/10252582

[15] 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, Seattle, Washington. https://ieeexplore.ieee.org/document/10689217

[16] Reza Yousefian, Xiaokang Xu, et al, "Benchmarking and Simulation of Frequency Events in the Eastern Interconnection," presented at and in Proc. of the IEEE PES General Meeting, 17-21 July 2022 in Denver, Colorado. https://ieeexplore.ieee.org/document/9916748

[17] NERC Essential Reliability Services Working Group, Measures Framework Report, November 2015. https://www.nerc.com/globalassets/programs/rapa/ra/erstf-framework-report---final.pdf

[18] PSS®E Rev 35.3 Manuals, Siemens PTI, Schenectady, NY, July 2021. https://www.siemens.com/us/en/products/energy/grid-software/planning/pss-software/pss-e.html

979-8-3315-8138-1