DYNAMIC MODEL VALIDATION LEVERAGING AMI 2.0 POINT-ON-WAVE MEASUREMENTS

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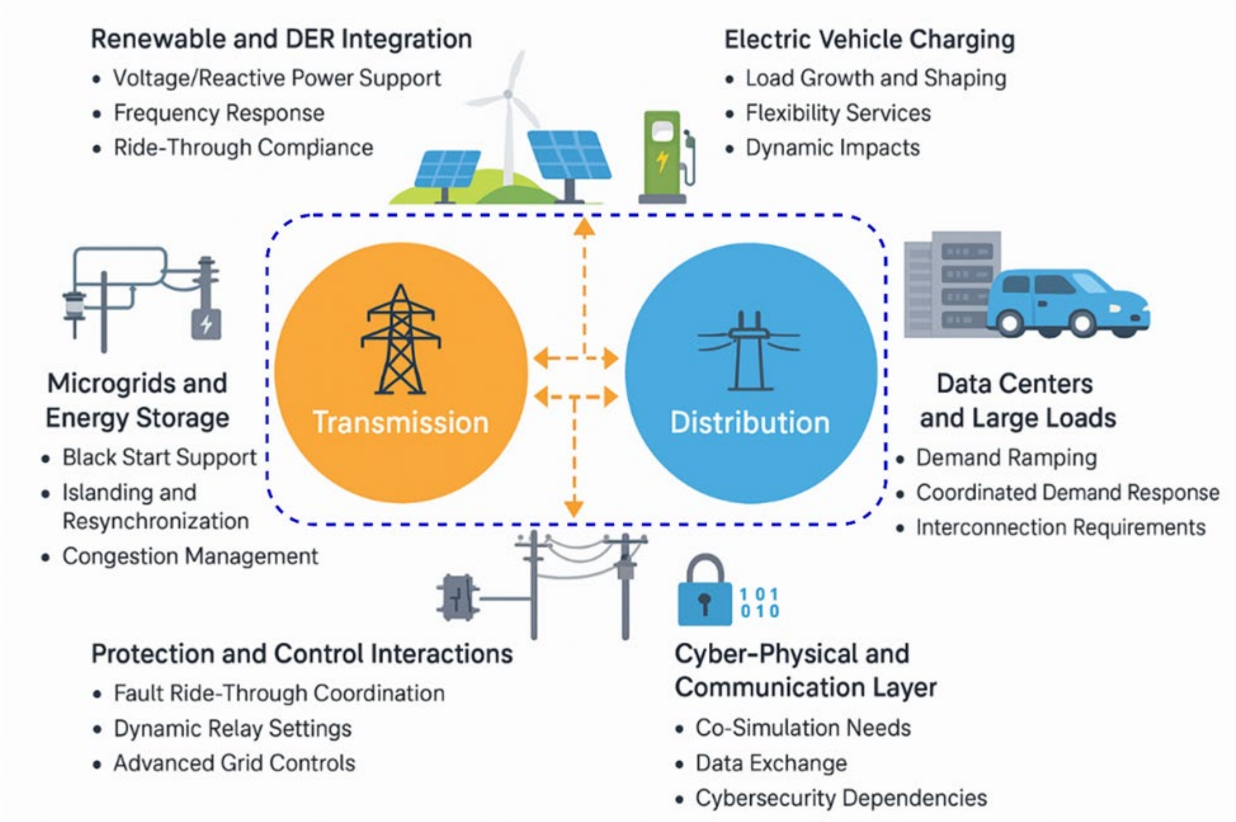
OUTLINE OF THE TALK

- Introduction
- Motivation
- Processing AMI 2.0 data for Model Identification
- Aggregation of Distribution System.
- Identification of aggregated distribution system models using AMI data.
- Conclusion.

INTRODUCTION

- Generation evolution with inverter-based resources (IBRs).
- Distribution system evolution with distributed generation (DG) like solar, battery, smarter loads that are responsive to price signals and grid disturbances.
- Development of microgrids that can operate in the islanded and interconnected modes to ensure its stable operation, etc.;
- Evolution in sensor deployment like phasor measurement units (PMUs) in T&D systems, advanced metering infrastructure, etc.;
- Evolution in data analytics and measurement-based controls; etc.



A. K. Bharati, V. Ajjarapu, K. K. Challa, M. Hong and C. Loutan, "T&D Interactions and Future-Grid Stability: Role of IBR-DER-Driven T&D Interactions in Future-Grid Stability," in *IEEE Power and Energy Magazine*, vol. 24, no. 1, pp. 82-92, Jan.-Feb. 2026

INTRODUCTION

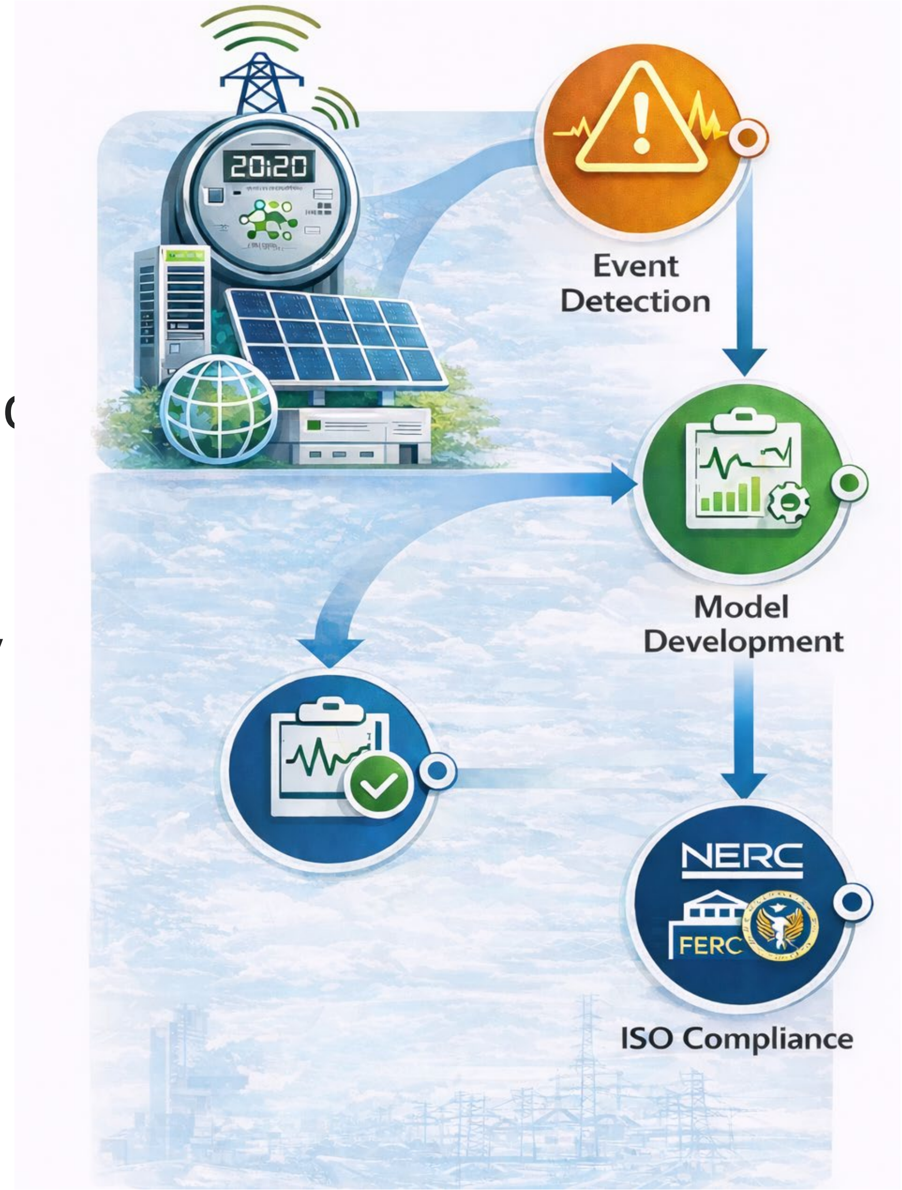
- **Market Access for DG Aggregations**: Enables aggregated DGs to participate in wholesale energy, capacity, and ancillary services markets
- **Aggregation Framework:** Allows multiple small distributed generation to be combined as a single market resource
- **Coordination with Distribution Utilities:** Requires coordination between: RTO/ISO ↔ Distribution Utility (DSO)
- **Performance & Visibility Requirements:** DER aggregations must meet same performance requirements as traditional resources

ISOs must have **sufficient visibility and data** to Model, dispatch and maintain reliability

Federal Energy Regulatory Commission, *Participation of Distributed Energy Resource Aggregations in Markets Operated by Regional Transmission Organizations and Independent System Operators*, Order No. 2222, Docket No. RM18-9-000, Sep. 17, 2020.

MOTIVATION

- AMI 2.0 provides high-resolution **point-on-wave data** for accurate dynamic model development.
- Event-based measurements enable real disturbanc
validation of distributed generation and load
models.
- Wide deployment offers **node-level observability** across distribution systems.
- AMI data helps characterize **aggregated DG** dynamic behavior and variability.
- Supports compliance with **NERC MOD-032** and **FERC 2222** model visibility requirements.



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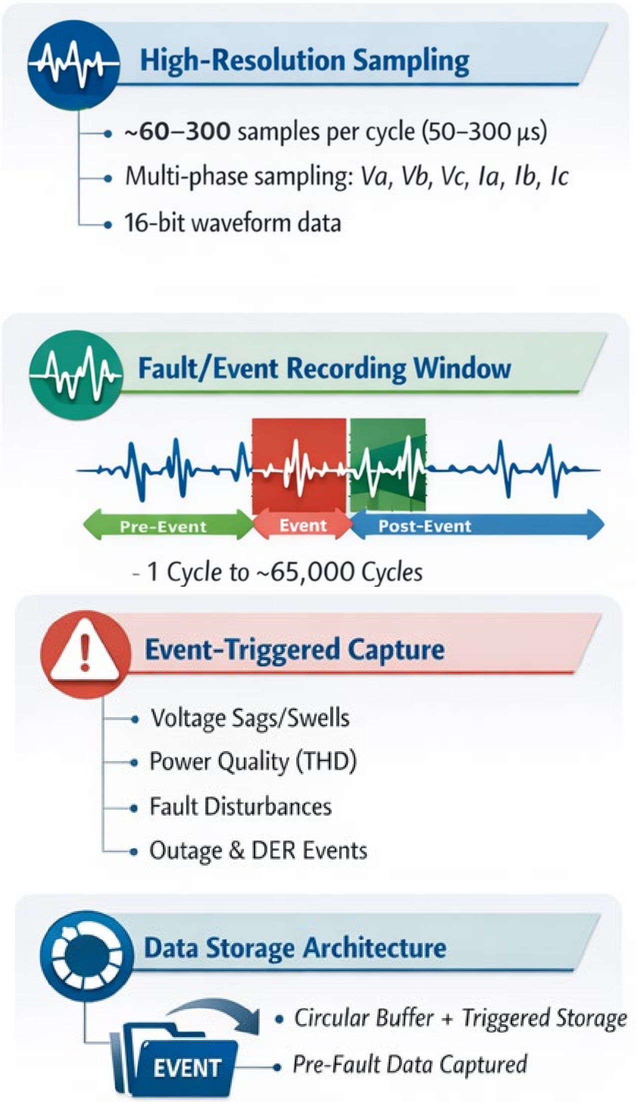
AMI 2.0 MEASUREMENTS AND EVENT RECORDS

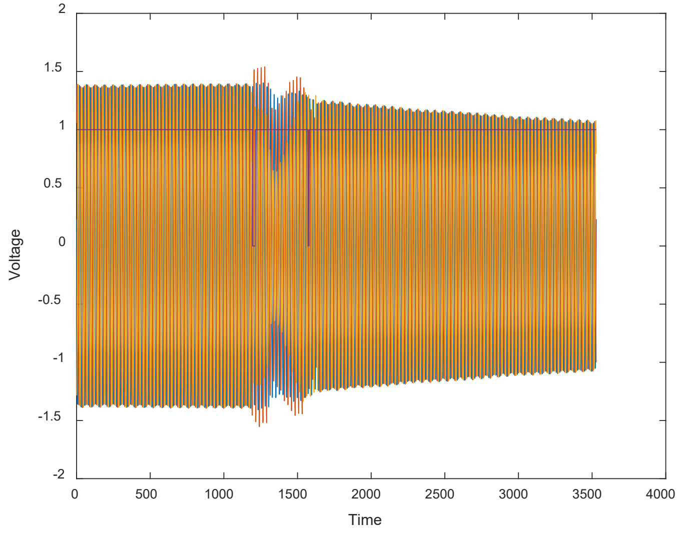
- Enables **continuous monitoring** of distribution system dynamics beyond traditional interval metering.
- Provides **localized insights** into feeder-level behavior and phase conditions.
- Supports **data-driven identification** of abnormal grid conditions and emerging issues.
- Enhances **visibility of DG** interactions with the distribution network.
- Improves **situational awareness** for operators through near real-time data streams.
- Serves as a foundation for **advanced analytics and grid digitalization** initiatives.

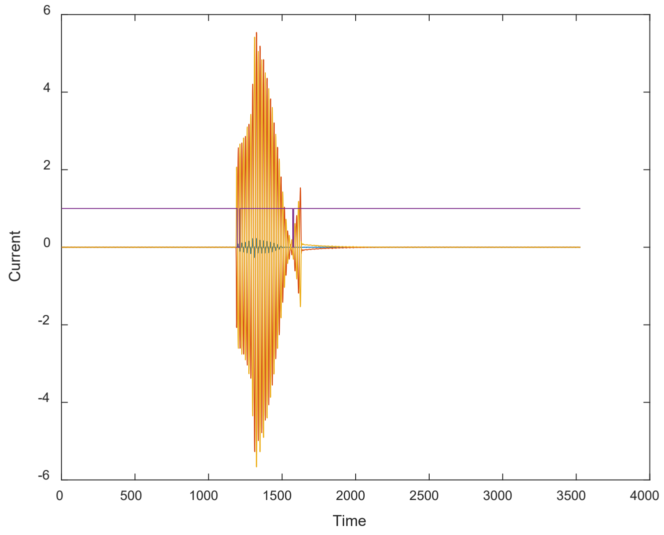


IEC 61000-4-30, IEEE 1159, IEEE C37.111, NERC PRC-002, and commercial AMI meter datasheets (e.g., GE kV2c, Itron OpenWay)

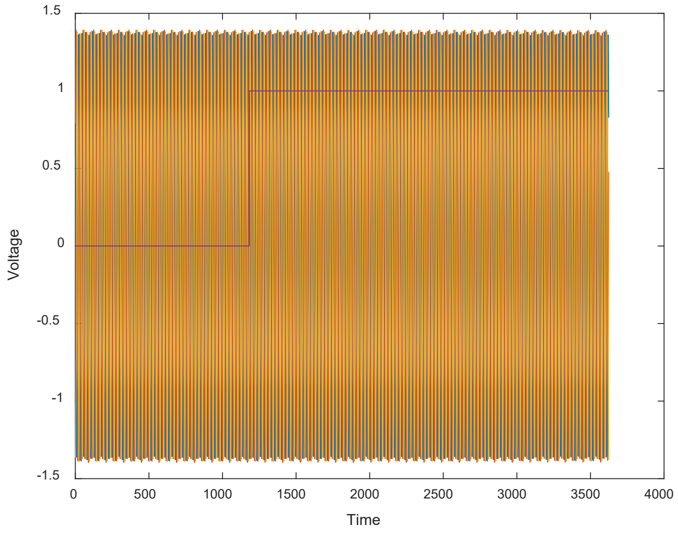
SAMPLE RAW DATA

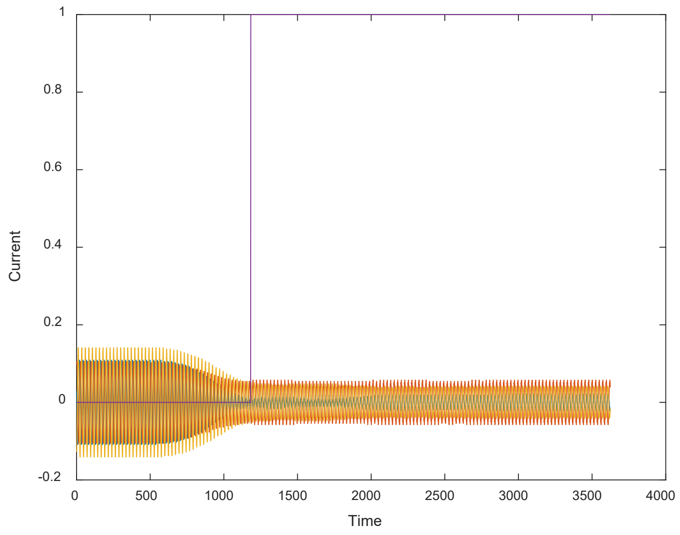
Sample 1



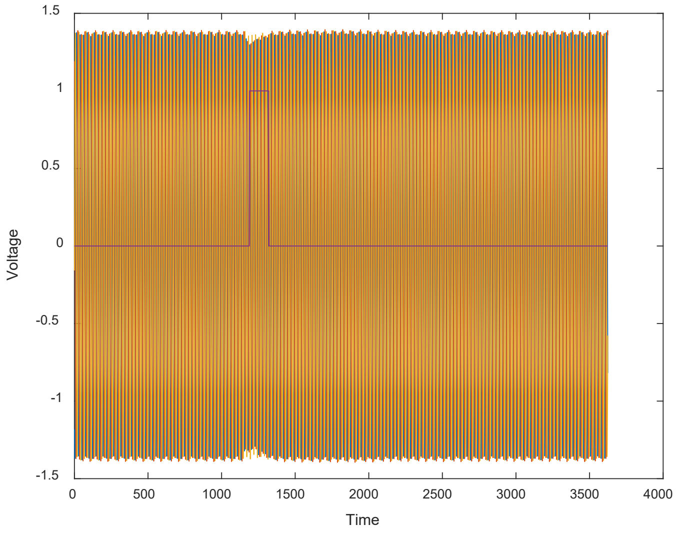


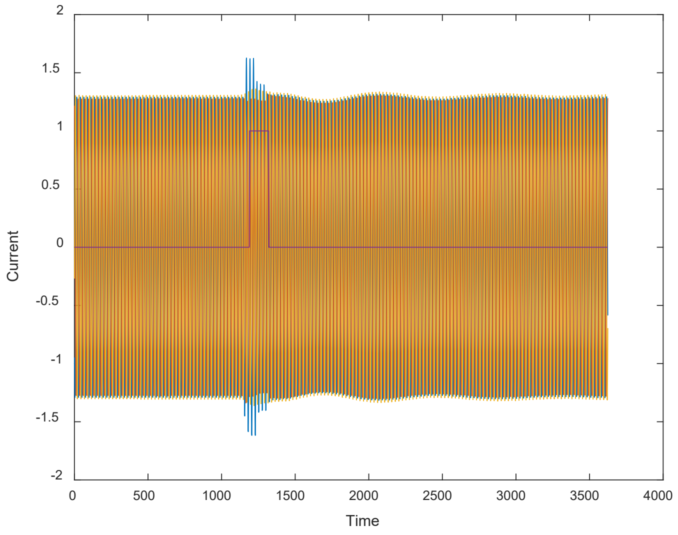
Sample 2





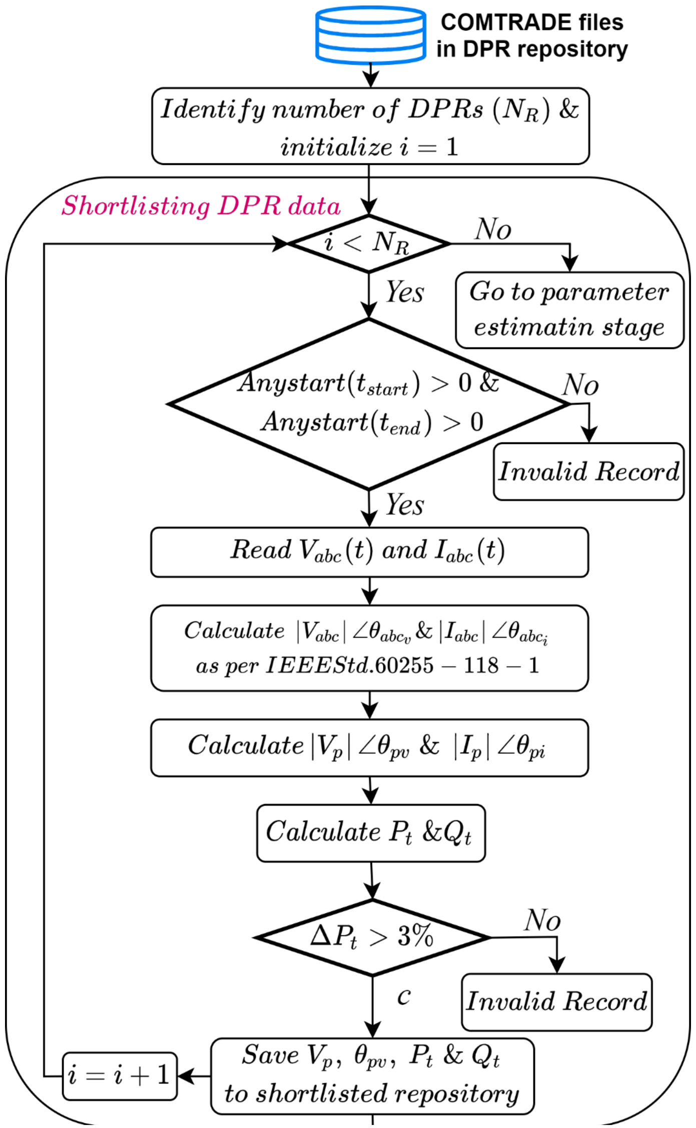
Sample 3



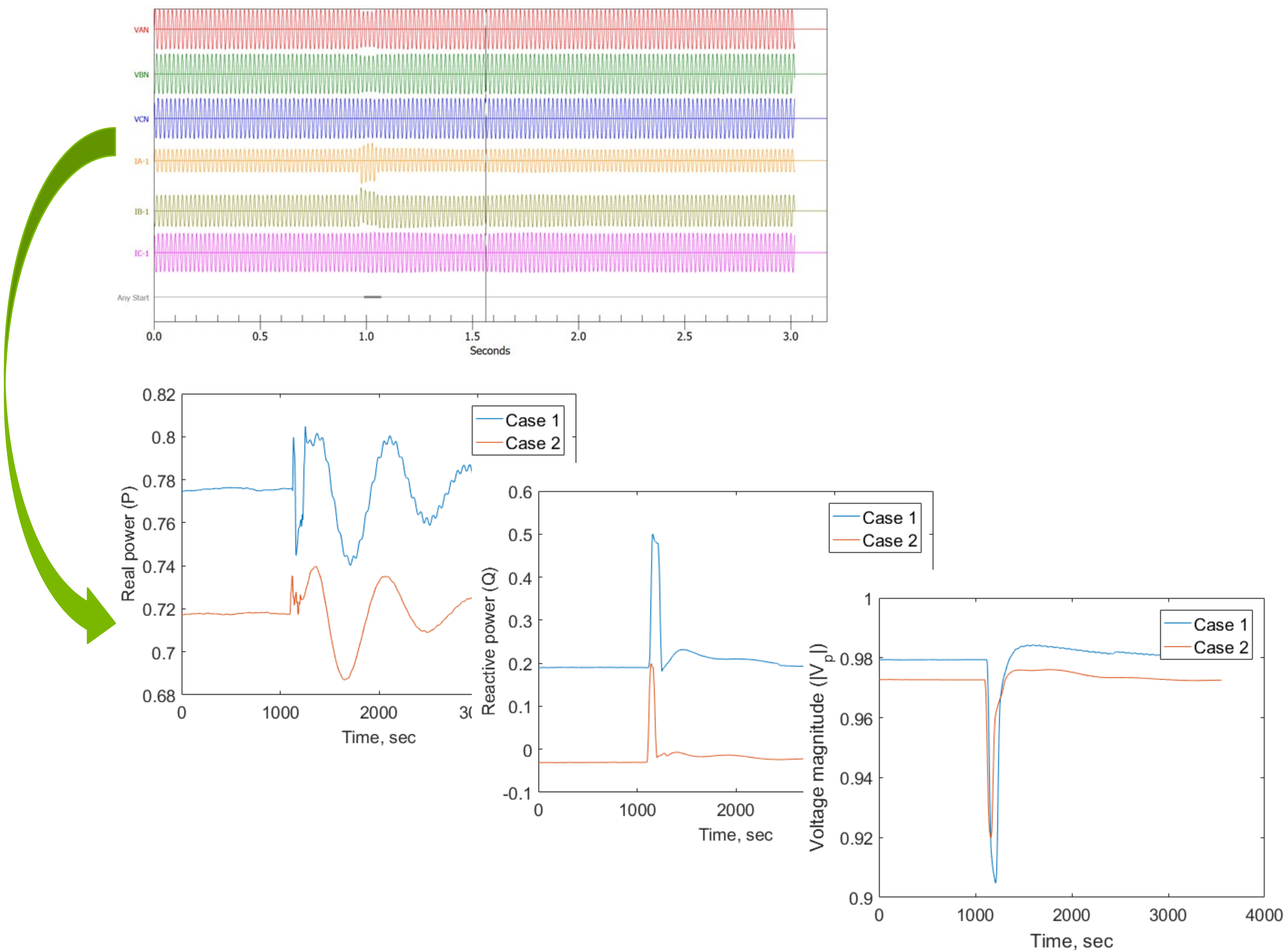


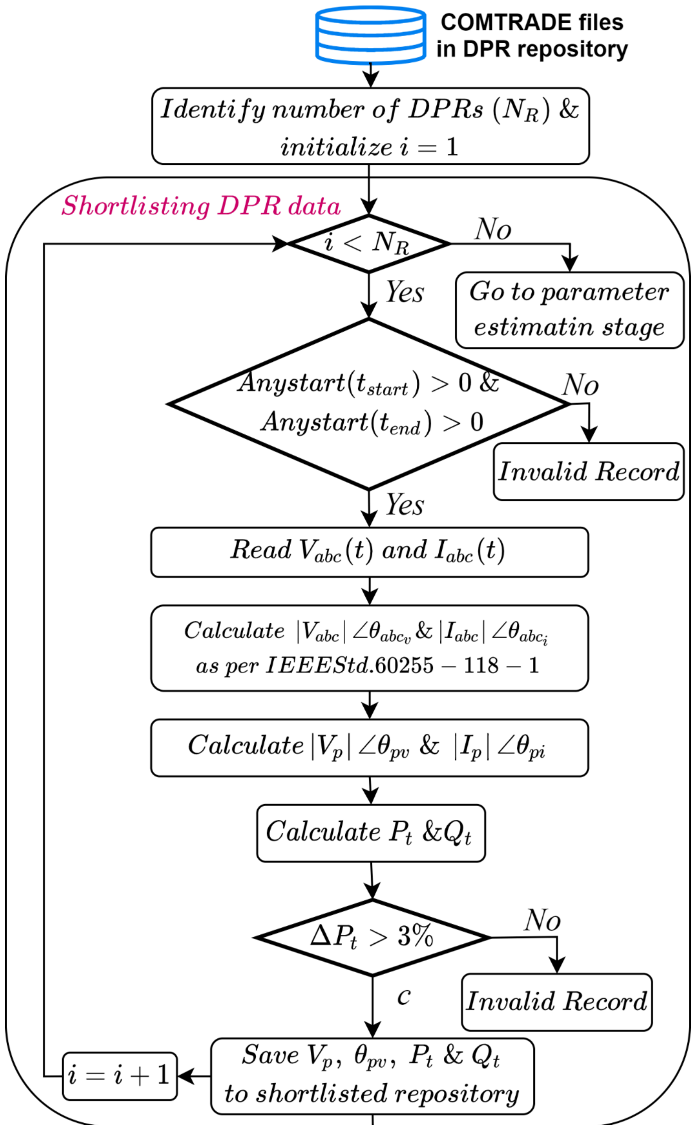
PROCESSING OF AMI 2.0 RAW DATA

- DPR records are available either as COMTRADE files, which consist of *.CFG* and *.DAT* files.
- Data in .DAT files need to be understood as per the .CFG file.
- After reading the instantaneous voltages and currents from .DAT files, positive sequence voltage phasor need to be calculated from voltages.
- All the calculations are performed using the per unit quantities.
- Individual processing of data is not preferred due to large number of available records.
- P, Q, V and theta are calculated not directly obtained from the records.
- An automated program is written to read all the COMTRADE files and calculate P,Q,V and θ of all the **useful records** in a matrix.



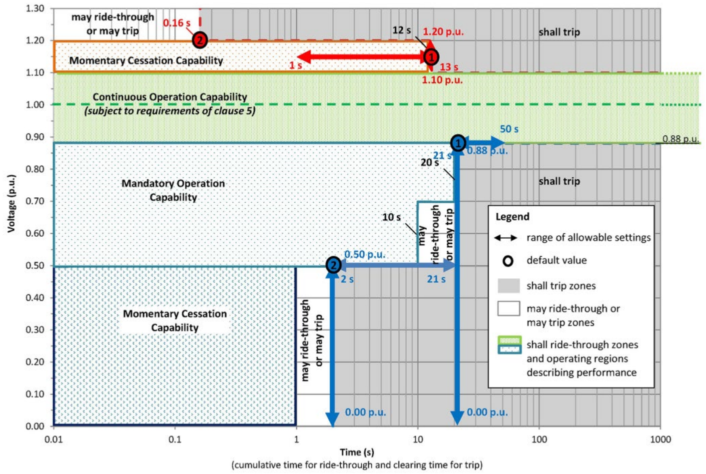
PROCESSING OF AMI 2.0 RAW DATA



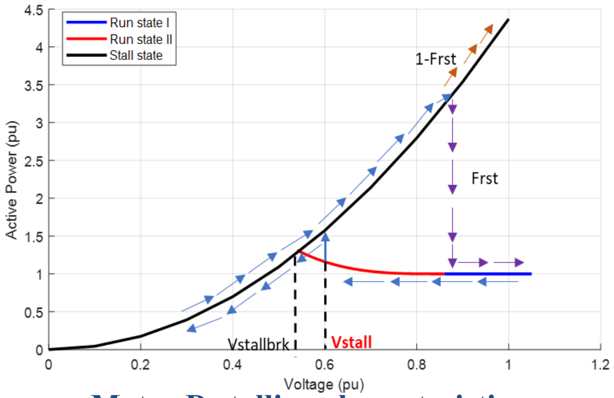


IMPORTANT DEVICES FOR DISTRIBUTION SYSTEM DYNAMICS: DISTRIBUTED GENERATION AND MOTOR-D

- Distributed resources are required to have specific voltage tripping and ride-through capabilities to maintain grid stability and reliability during disturbances as per IEEE 1547 [1].
- Stalling behavior of the single-phase induction motors leads to the delayed voltage recovery during the disturbances. This behavior of single-phase motors is modeled.



IEEE Standard 1547 Voltage Sensitivity of DERs



Motor D stalling characteristics

1. "IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces," in *IEEE Std 1547-2018 (Revision of IEEE Std 1547-2003)* , vol., no., pp.1-138, 6 April 2018, doi: 10.1109/IEEESTD.2018.8332112.

AGGREGATION OF DISTRIBUTION SYSTEM:
COMPOSITE LOAD MODEL

The WECC composite load model structure includes the aggregated representation of static loads, electronic loads, constant-torque three-phase motors (A), high inertia speed squared load motors (B), low inertia speed-squared load motors (C), constant-torque single-phase motors (D), and DGs.

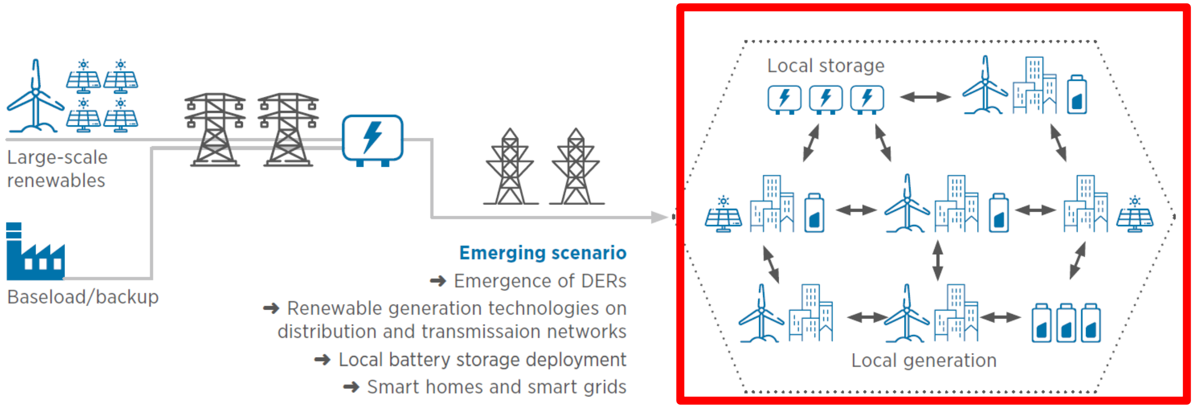
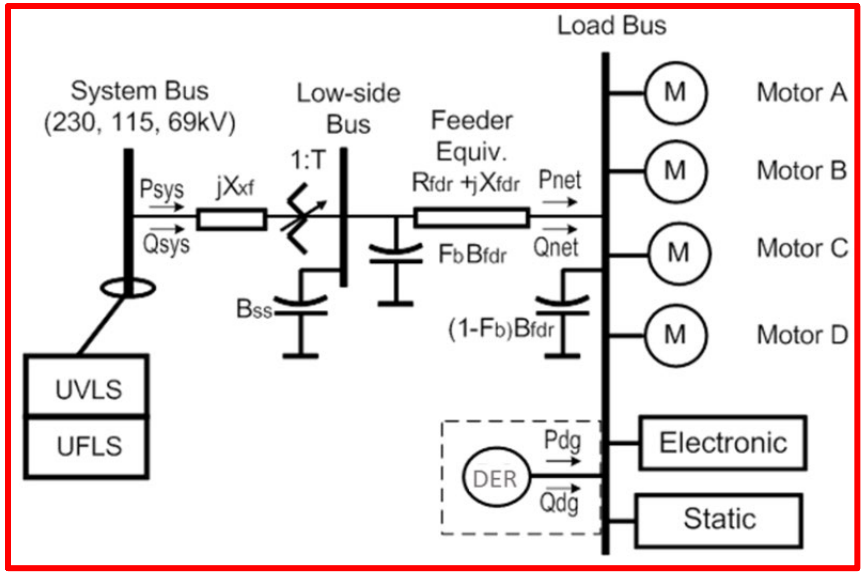


Fig 1. Power system due to the emergence of distributed energy resources [1]



[1] Arina Anisie, Francisco Boshell and Elena Ocenic, “Future role of distribution system operators: Innovation landscape brief”, The International Renewable Energy Agency (IRENA), 2019.
[2] Western Electricity Coordinating Council. "WECC Composite Load Model Specification“, Modeling and Validation Subcommittee, WECC, April 2021

DISTRIBUTION SYSTEM CLUSTERING AND AMI LOCATIONS

- This clustering is based on calculating the impact of each nodal injection on the voltage with the conditions set by the inherent structure of the distribution network (DS admittances).
- Consider the admittance matrix (Y), eigen value diagonal matrix ($diag(\lambda)$) and transition matrix (P). then

Admittance matrix can be represented as: $Y = P.diag(\lambda).P^{-1}$

Impedance matrix can be expressed as: $Z = P.diag\left(\frac{1}{\lambda}\right).P^{-1}$

Nodal voltages in the distribution network are: $V = Z.I$

$$V = \left[P.diag\left(\frac{1}{\lambda}\right).P^{-1}\right].I = \sum_{n}^{N} \frac{1}{\lambda_n}[S_n]^T.I$$

Eigen value sensitivity matrix is given by: $[S_n] = \begin{bmatrix} \frac{\partial \lambda_n}{\partial Y_{11}} & \cdots & \frac{\partial \lambda_n}{\partial Y_{1N}} \\ \vdots & \ddots & \vdots \\ \frac{\partial \lambda_n}{\partial Y_{N1}} & \cdots & \frac{\partial \lambda_n}{\partial Y_{NN}} \end{bmatrix}$

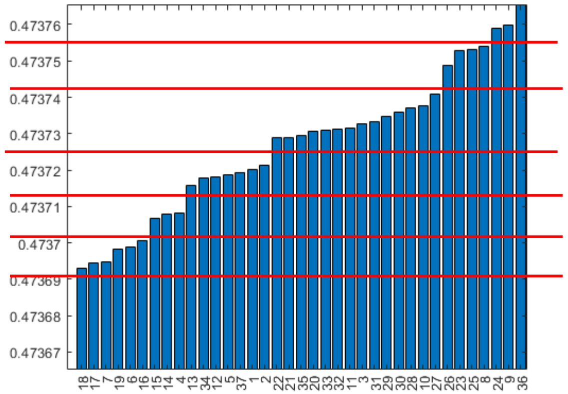


Fig. 1 Nodal sensitivity indices

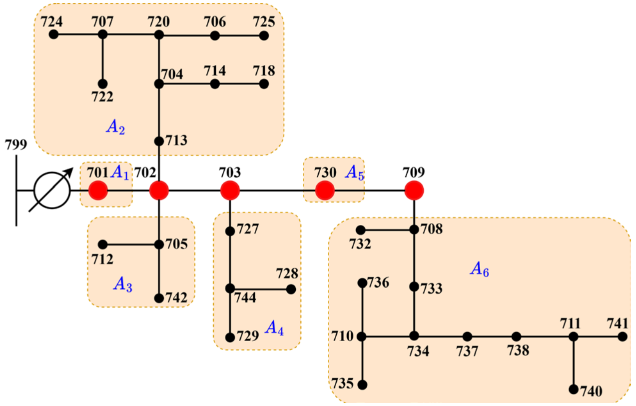
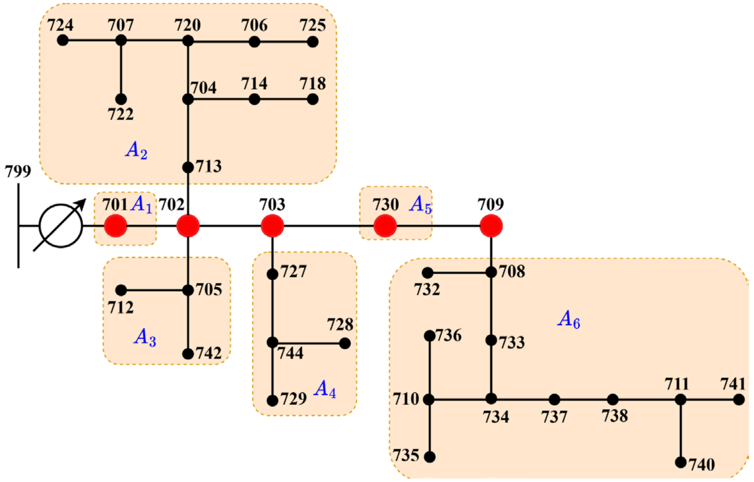


Fig. 2 DS with various components in the secondary circuits clustered based on electrical distance

[1]. J. R. Macedo and J. W. Resende, "The inherent structure theory of networks and admittance matrix sparsity relationship," *10th International Conference on Harmonics and Quality of Power. Proceedings (Cat. No.02EX630)*, Rio de Janeiro, Brazil, 2002, pp. 127-132 vol.1

DS CLUSTER REPRESENTATION

- A full DS is clustered into multiple sub-models using the steady state nodal voltage sensitivities.
- Each cluster in the distribution system is represented by an equivalent composite load model.



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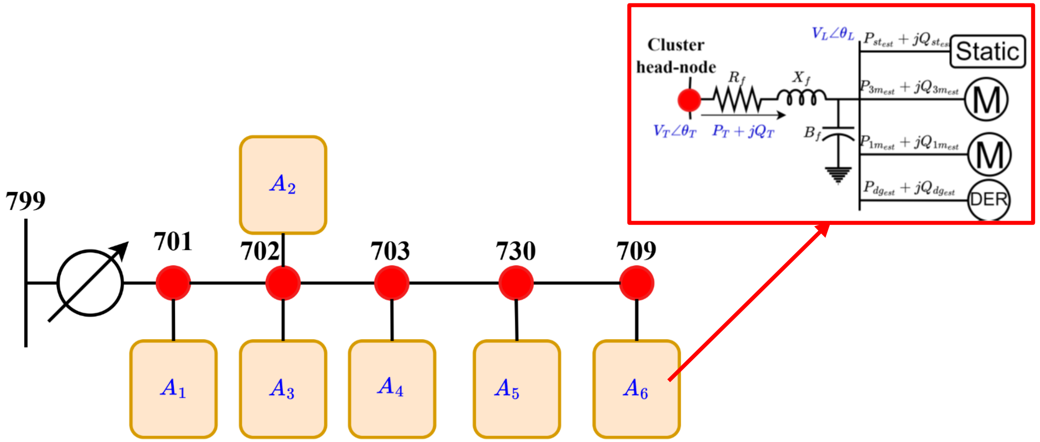


Fig. 2 Resulting DS-ROM with CLM sub-models

[1]. K. K. Challa, A. R. R. Matavalam, R. Venkatraman and V. Ajjarapu, "Accurate Representation of Distribution System Dynamics With DERs for Bulk System Studies," in *IEEE Transactions on Industry Applications*, vol. 61, no. 3, pp. 5187-5197, May-June 2025

DS CLUSTER REPRESENTATION

The parameters of the CLM corresponding to each sub-model in an aggregated DS shown in Fig. 2 are identified using the measurements at the cluster head node of the sub-model shown in Fig. 7 obtained through the simulated responses.

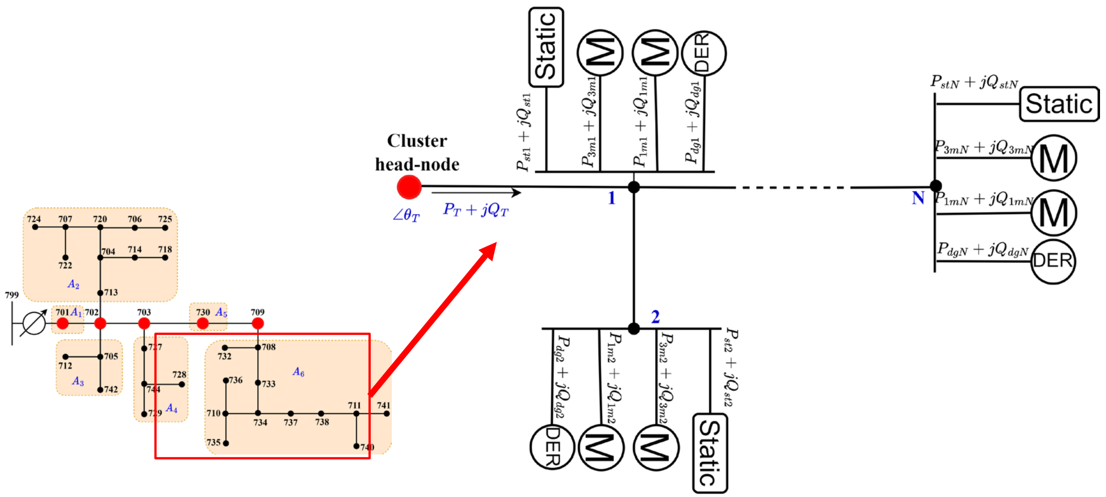


Fig. 1 Detailed representation of single cluster in DS

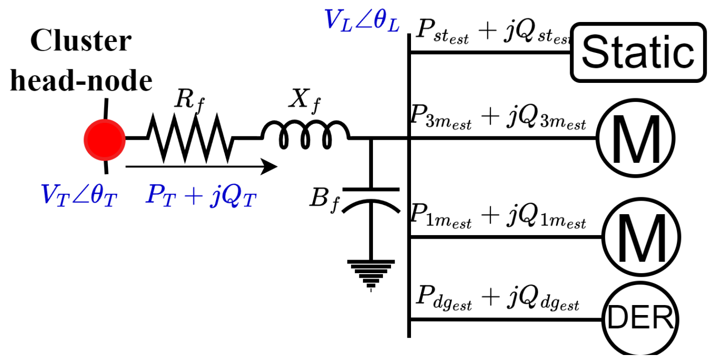


Fig. 2 Equivalent of a single cluster representation in DS

[1]. K. K. Challa, A. R. R. Matavalam, R. Venkatraman and V. Ajjarapu, "Accurate Representation of Distribution System Dynamics With DERs for Bulk System Studies," in *IEEE Transactions on Industry Applications*, vol. 61, no. 3, pp. 5187-5197, May-June 2025

DS CLUSTER MODEL IDENTIFICATION: DER PARAMETER SELECTION

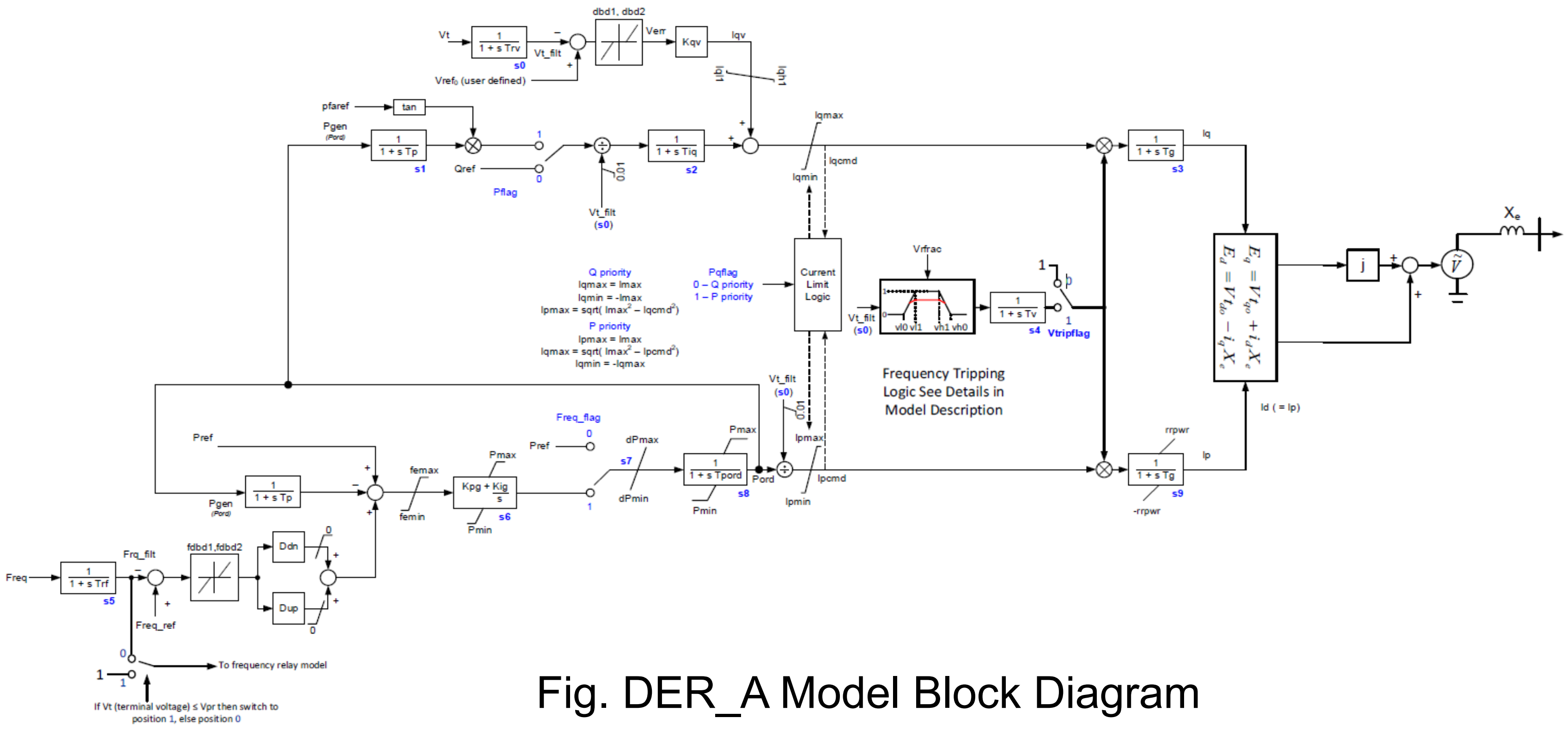


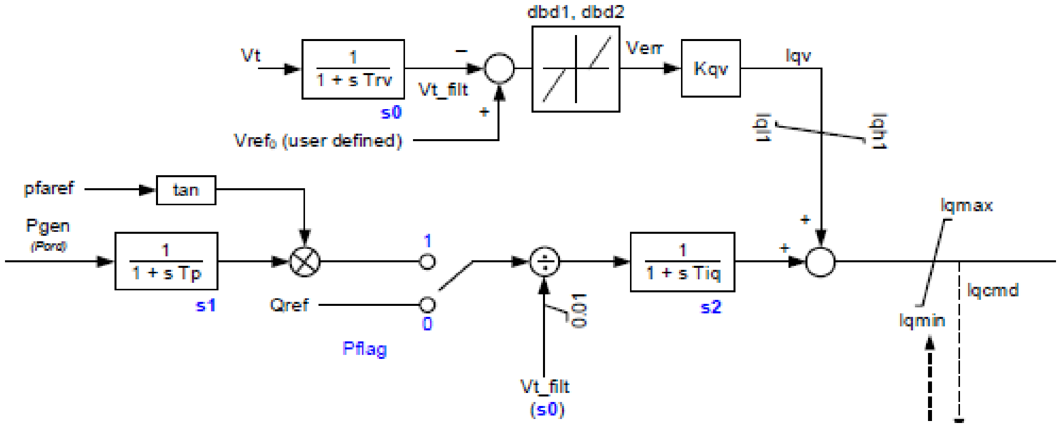
Fig. DER_A Model Block Diagram

- Fixing a control mode of operation, current limiting priority, and fault ride-through capability characteristics will limit the number of variable parameters in the model.
- Shortlisted few parameters for the estimation of CLM for each cluster.

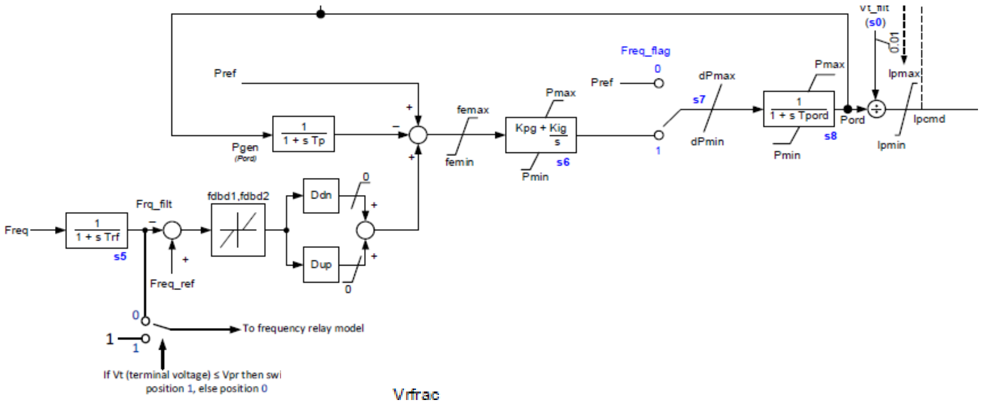
[1]. North American Electric Reliability Corporation (NERC), “Reliability guideline: Parameterization of the der_a model for aggregate der, dynamic load modeling,” Dec. 2023

DS CLUSTER MODEL IDENTIFICATION: DER PARAMETER SELECTION

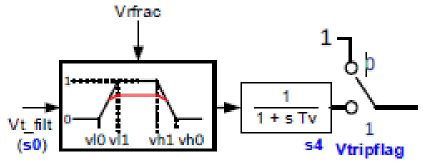
- Consider that the DERs in the test system to be operated in voltage control mode with constant reactive power reference, reactive power- voltage control loop consists of T_{rv}, K_{qv} and T_{iq} as variables.



- When a DER is not responding to the frequency variations with the fixed real power reference, then the active power-frequency controls consist of T_{pord} as a variable.



- V_{pr} and T_v represent the emulation of fractional tripping that is intended to represent a portion of the DER tripping due to voltage violations.



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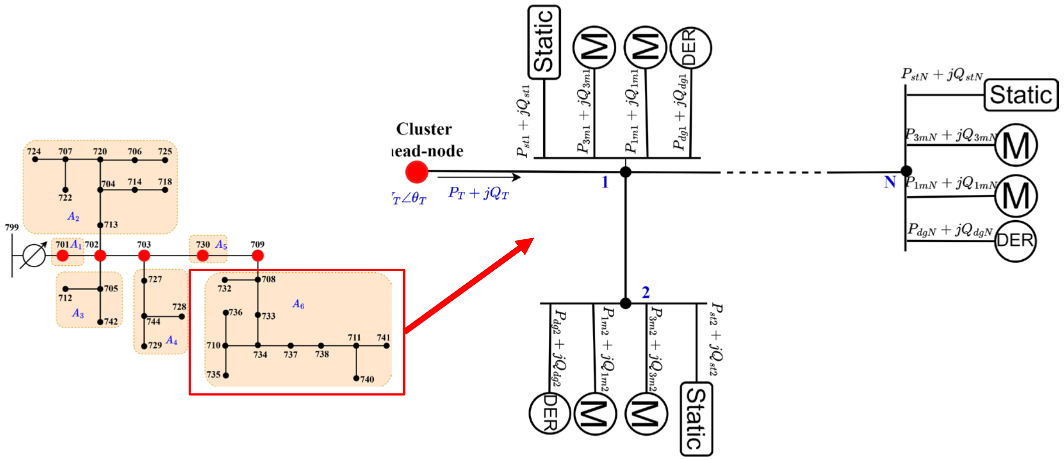
DS CLUSTER MODEL IDENTIFICATION: EVENT PLAYBACK

- The time series data of VT , PT , and QT for every head-node of the cluster through the TD+DS simulations is utilized for the dynamic parameter identification of each cluster’s CLM using a white-box model.
- The white-box model considers the voltages at the head node as input and real and reactive powers in each cluster as outputs.

$$\mathcal{O}(\boldsymbol{p}) = \sum_{i=1}^{k} \left|P_{rec,i} - P_{cal,i}(\boldsymbol{p})\right|^2 + \left|Q_{rec,i} - Q_{cal,i}(\boldsymbol{p})\right|^2$$



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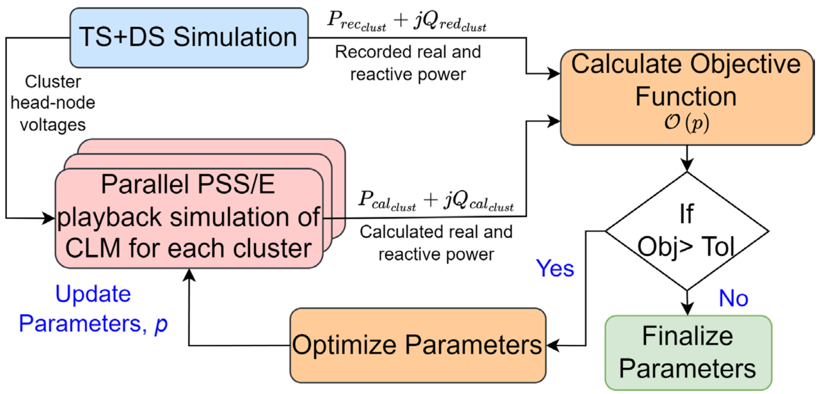

Fig. 2 The flowchart of the python based iterative parameter estimation methodology of the CLM Sub-models

[1]. K. K. Challa, A. R. R. Matavalam, R. Venkatraman and V. Ajjarapu, "Accurate Representation of Distribution System Dynamics With DERs for Bulk System Studies," in *IEEE Transactions on Industry Applications*, vol. 61, no. 3, pp. 5187-5197, May-June 2025

DS CLUSTER MODEL IDENTIFICATION: RESULTS

- Test system with IEEE 14-bus TS + 37-node DS is simulated to validate with proposed representation of distribution system [1].
- Voltage at 14th bus and real power from DG in DS for a fault at 6th bus after representing distribution system with ROM-DS are presented in Fig. 2.

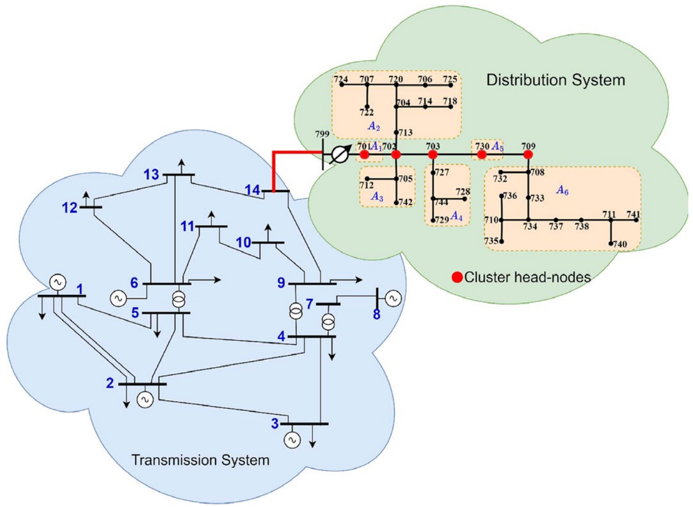

Fig. 1 TS+DS simulation setup to generate data from DS

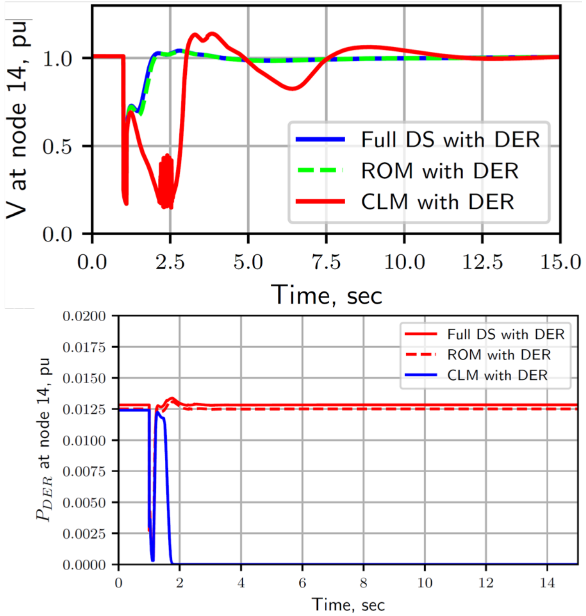

Fig. 2 Voltage at 14th bus and real power from DER

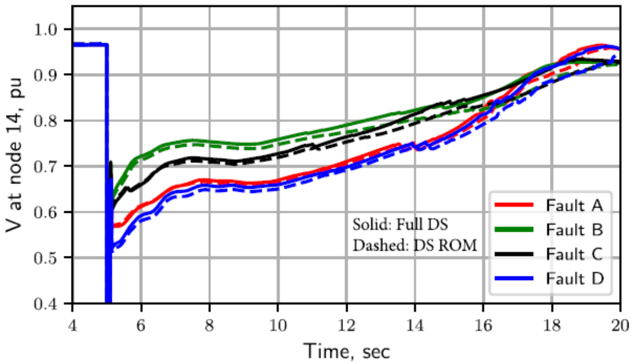

Fig. 3 Voltage at 14th bus for different faults

[1]. K. K. Challa, A. R. R. Matavalam, R. Venkatraman and V. Ajjarapu, "Accurate Representation of Distribution System Dynamics With DERs for Bulk System Studies," in *IEEE Transactions on Industry Applications*, vol. 61, no. 3, pp. 5187-5197, May-June 2025

DS CLUSTER MODEL IDENTIFICATION: RESULTS VALIDATION

- A feeder from a real distribution test system supplied by a 69 kV substation located in the Midwest region of the U.S with 240 nodes is considered in this study.
- The feeder is modified to have 12.4 MW load with 30% of 1-ϕ induction motors (motor-D) and 30% DER penetration.

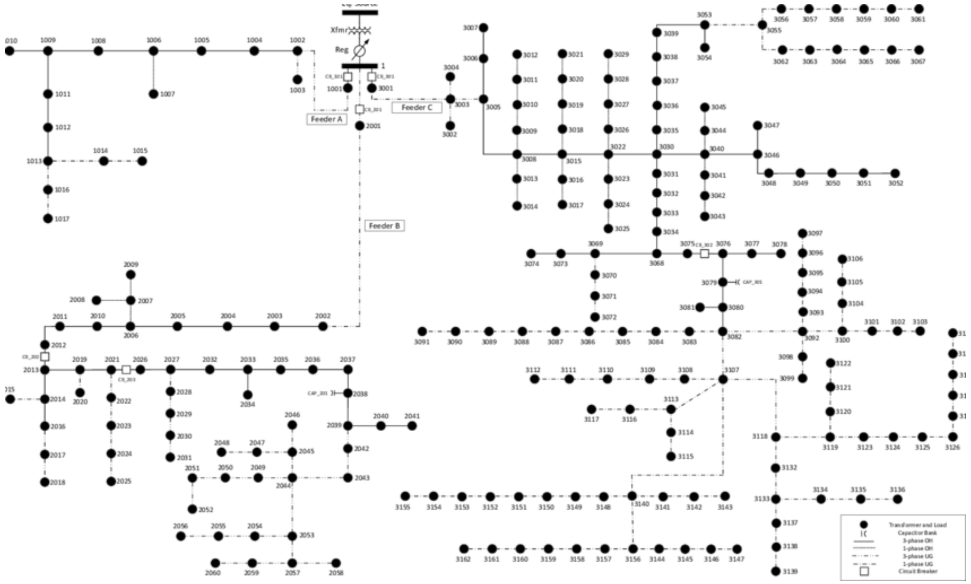

Fig. 1 240 Node Practical DS

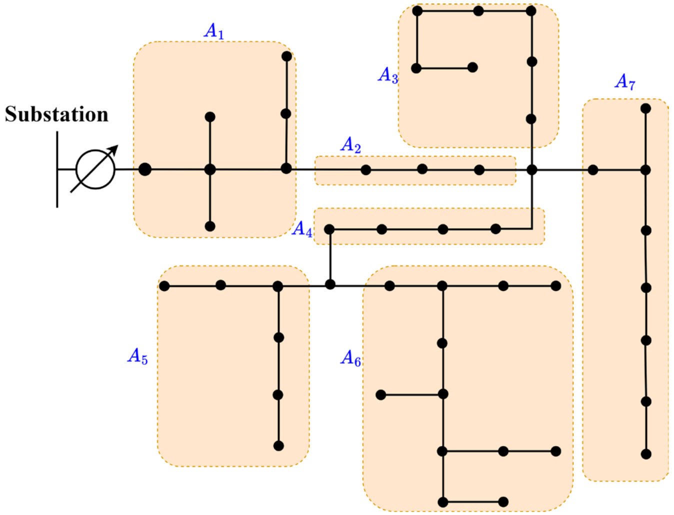

Fig. 2 Resulting DS-ROM with CLM sub-models

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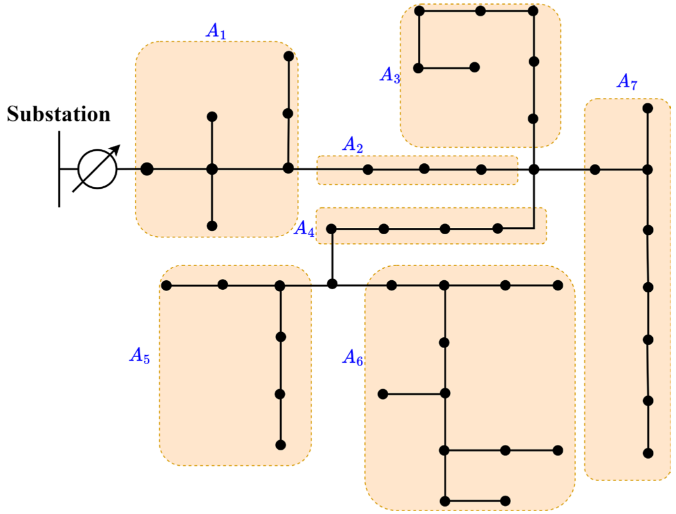

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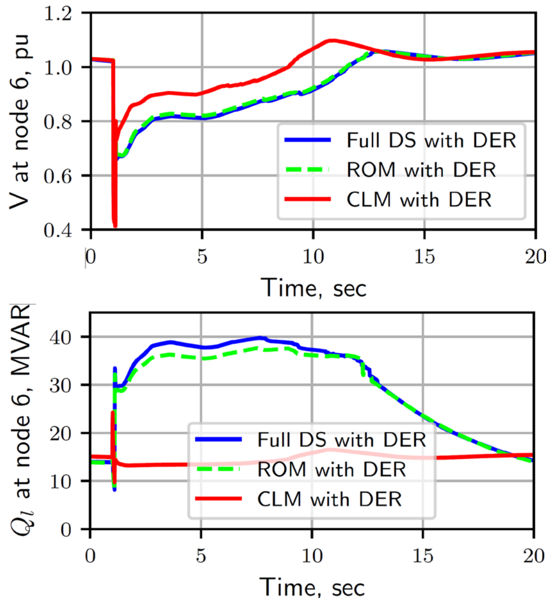

Fig. 2 Voltage at 6th bus and reactive power from DS

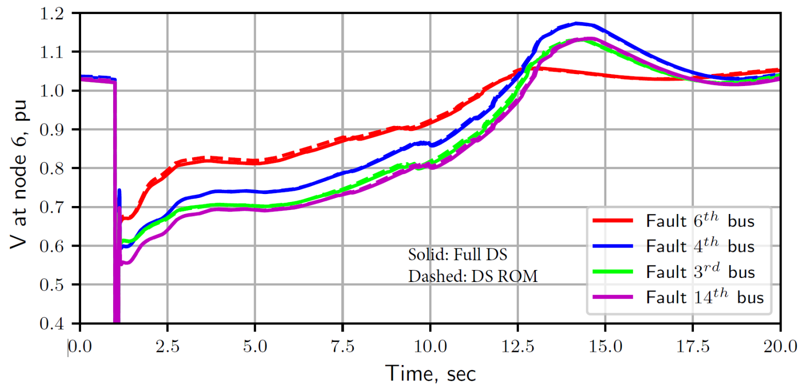

Fig. 3 Voltage at 6th bus for different faults

[1]. K. K. Challa, A. R. R. Matavalam, R. Venkatraman and V. Ajjarapu, "Accurate Representation of Distribution System Dynamics With DERs for Bulk System Studies," in *IEEE Transactions on Industry Applications*, vol. 61, no. 3, pp. 5187-5197, May-June 2025

CONCLUSIONS

- **Evolving Grid Dynamics:** High penetration of **IBRs in TS and DS** are shifting distribution systems from passive loads to **active grid participants**
- **Stronger Need for** ISOs to have **sufficient visibility and data** to Model, dispatch and maintain reliability
- **Event records from AMI 2.0** helps characterize **aggregated DG dynamic** behavior and variability.
- **Point-on-wave data from AMI** can be utilized to identify the model parameters of the DS clusters.
- A systematic approach is presented to **utilize the AMI 2.0 data** for the aggregated DS dynamics.

FUTURE DIRECTIONS

- Develop a tool that processes the local AMI 2.0 data to obtain phasor information suitable for aggregated DS model identification.
- Explore advance AI to extract features in the event records and direct the users in sensitive parameters to be identified with the specific record.
- Validate the developed approaches using the utility AMI data.

THANK YOU