# DOE - Integrated Smart Distribution RD&D Project

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# DOE Integrated Smart Distribution (ISD) Project

## Objective

**The primary objective of this project is to leverage the intelligence of, and information provided by, sensors, energy boxes and smart meters to integrate DER for developing next generation DMS to enhance optimal performance of the emerging distribution system. This builds on the DOE Vision towards an Intelligent North American Grid by 2030.**
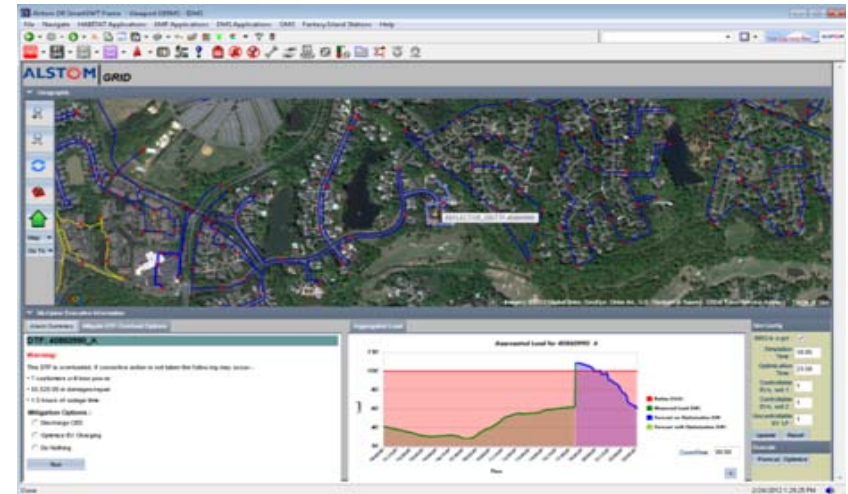


## Life-cycle Funding Summary ($K)

| Prior to FY 12 | FY12, authorized | FY13, requested | Out-year(s) |
|---|---|---|---|
| 124 | 2,800 | 1,700 | 1,376 |

## Technical Scope

Six prioritized areas of scope:
• Management and forecasting of DER (DG, storage, DR)
• Integration of network, market, and renewable resource models for next generation DMS.
• Advanced distribution modeling capability to accurately simulate/model smart grid operations.
• Accurate representation of the distribution system in real- or near real-time (capture real-time topology).
• Interoperability with and seamless communication between other management systems and data bases used by the utility
• Simulation of distribution systems based on real-time operational planning to analyze the benefits of smart grid assets.

# Significance and Impact

## Project's Quantitative Cost & Performance Targets

| Calendar Year | 2011 | | 2012 | | | | 2013 | | | | 2014 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| Cost ($k) | 88 | 118 | 443 | 661 | 1001 | 1428 | 1461 | 1489 | 1304 | 996 | 695 | 418 | 357 | |
| **Performance Targets** | | | | | | | | | | | | | | |
| Efficiency (%) National | 94 | | 94.15 | | | | 94.30 | | | | 94.45 | | | |
| Load Factor (%) Duke Energy | 65 | | 66.3 | | | | 67.6 | | | | 68.9 | | | |
| SAIDI (min) Duke's McAlpine Substation | 144 | | 141.12 | | | | 138.24 | | | | 135.36 | | | |
| Outage Reduction for Critical Loads (%) Duke's McAlpine Substation | 98.6 | | 98.62 | | | | 98.65 | | | | 98.68 | | | |

# Significance and Impact

Project's Cost/Performance Targets Supporting the Smart Grid R&D Goals and 2020 Targets
(Project milestones shown in the backup slides)

| Year | 2011 | | 2012 | | | | 2013 | | | | 2014 | | | | 2020 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | |
| Cost ($k) | 88 | 118 | 443 | 661 | 1001 | 1428 | 1461 | 1489 | 1304 | 996 | 695 | 418 | 357 | | |
| **Performance Targets** | | | | | | | | | | | | | | | |
| Efficiency (%) National | 94 | | 94.15 | | | | 94.30 | | | | 94.45 | | | | 97 |
| Load Factor (%) Duke Energy | 65 | | 66.3 | | | | 67.6 | | | | 68.9 | | | | 78 (↑20%) |
| SAIDI (min) Duke's McAlpine Substation | 144 | | 141.12 | | | | 138.24 | | | | 135.36 | | | | 118.08 (↓20%) |
| Outage Reduction for Critical Loads (%) Duke's McAlpine Substation | 98.6 | | 98.62 | | | | 98.65 | | | | 98.68 | | | | >98 98.85 |

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# Significance and Impact

- **Electric Utility Goals:**
    - Facilitate technical and market development for emerging technologies.
    - Explore new operational requirements and business models.
    - Verify the capability to integrate DER in real-time software and control systems and monitor/analyze distribution circuits.
    - Verify interoperability of solution using smart grid test tools.
- **DER Modeling**

- **Load Forecasting**

- **DER Scheduling**

- **Communication Architectures**

- **Advanced and Adaptive Protection**

- **Market Integration of DER**

# Technical Approach & Transformational R&D

**Alstom Grid:**
- <u>Integrated</u>: Conventional energy & grid resource integrated with new distributed energy resources & grid devices for holistic system performance.
- <u>Smart</u>: Intelligence in devices (self-healing) and resources (E-storage/EV local control).
- <u>Distribution</u>: DMS extended to provide advanced tools (effective UI with advanced analytics) to ensure effective solutions for distribution system operation.

**Duke:**
- Capture grid network modeling and real-time topology.
- The operational philosophy, changes, and challenges with increasing DER penetration and emerging technology and devices are truly fundamental and transformational.
- Requires quick response from operators to meet new operational changes at higher level.
- Safety is built into the design of the system as foundation for new technologies.
- Create an understanding of the grid's operational value once they have all the new technologies integrated. Customer focus is the key.

**Snohomish PUD #1:**
- Integrate variable distributed sources (including storage), with variable and possibly dispatchable loads.
- Optimize the configuration of our distribution circuits in real time. System will provide physical optimization for the first stage, and financial optimization as a later overlay.
- Utilize our smart grid test lab to validate interoperability of the solution through end to end testing.

**U.S. Utilities:**
- The concept of smart grid has fundamentally brought cultural changes in bringing various stakeholders within and outside each utility.
- These cultural changes are hard to quantify, but they do translate into business and operational challenges in meeting optimal performance goals.
- This project will pave the way for the next generation of DMS with DER integration.

# Technical Approach & Transformational R&D

- **DER Modeling:**
  - Modeling of DERs and their behavior followed by the forecasting of their availability down to the lowest practical level along the distribution feeder.
- **Load Forecasting:**
  - Forecasting of each feeder and substation will capture the spatial and temporal correlations. This approach can be extended to all substations in a given system.
- **DER Scheduling:**
  - Real-time scheduling and dispatching of DERs by adopting multi-tier optimization involving various levels of the distribution system.

# Technical Approach & Transformational R&D

- **Communications Architecture:**
  - Develop multi-tier, distributed intelligent communication nodes and corresponding architecture. This requires deeper understanding and selection of proper communication schemes, protocols and interoperability standards.
- **Advanced and Adaptive Protection:**
  - Analyze the new challenges brought by the penetration of DERs and the deficiency of the traditional protection paradigm.
  - Develop microgrid protection scheme and islanding operation controller to reduce outage time for critical loads.
  - Fast fault detection, location and outage restoration leveraging multiple types of information (from new devices, such as PMUs, line sensors, smart meters, fault indicators and others) and intelligent switching equipment.
- **Market Integration of DERs**:
  - Analyze the market rules and data flows to determine the impacts and necessary changes to facilitate the integration of DERs.
  - Adapt market models for the integration of DERs.

# Technical Accomplishments

- **DER Modeling:**
  - Identified and created an initial model for EVs.
  - Measured EVs charging at different voltage levels, states and voltage response characteristics not previously known in the literature.
- **Load Forecasting:**
  - Performed modeling and verification using actual data. Results show a low "mean absolute percentage error" when forecasting load in five minute intervals.
- **DER Scheduling:**
  - Formulated an optimization algorithm for ES charging and discharging that solves faster than current state-of-the-art methods based on advanced forecasts.
  - Developed an EV dispatch algorithm to flatten system power variations.
  - Demonstrated a prototype for an overload avoidance algorithm to dispatch DERs to prevent network overloads when detected.

# Technical Accomplishments

- **Communications Architecture:**
  - Started the development of a multi-tier, distributed intelligent communication nodes and corresponding architecture.
- **Advanced and Adaptive Protection:**
  - Performed a comprehensive analysis of the new characteristics in smart distribution systems and to address past, present and future protection and distribution schemes.
  - Developed a differential scheme for islanded microgrid protection.
  - Devised an islanding detection scheme using synchrophasor measurements.
  - Designed an optimal placement algorithm for protective devices.
  - Developed an adaptive overcurrent protection scheme in response to changing operational conditions including islanding.
- **Market Integration of DERs**
  - Began analysis of data sources that promote the integration of distributed energy resources.

# Technical Accomplishments (In Progress)

- **Secondary Distribution Modeling**
  - Feeder models of McAlpine substation are being converted to GridLAB-D.
  - Investigation of the GridLAB-D simulation model to be capable of handling weather-driven time-series power flows, with detailed models of the secondary distribution network.
  - Time-series models are being developed for: customer loads, demand response, and selected other smart grid assets such as electric vehicles, storage devices and distributed generations.
  - The purpose of this simulation model is to develop a smart grid simulation test bed enabling predictive control strategies and decision support tools for advanced DMS.

# Project Team Capabilities & Funding Leverage

List organizations that this project interacts and collaborates with, describing their expertise and complementary roles to this project.

**Primary Contractor:**
* Alstom Grid

**Host Utilities:**
* Duke Energy
* Snohomish PUD #1

**Subcontractors:**
* University of Washington
  * Communication infrastructure and interoperability standards, network and market models.
* PNNL
  * Development of DER assets and load models within GridLAB-D.
* University of Connecticut
  * Development of bottom-up load forecasting techniques for integration of DERs.

# Project Team Capabilities & Funding Leverage

1. **Present what unique role DOE is playing and what the added value is.**
- The DOE initiative and funding opportunity enabled this investigation to pave way for the next generation of DMS with DER and other technologies that would not have been otherwise initiated. The funding provided an unique opportunity to bring all the teams listed in the previous slides together with complementary skills and expertise needed to undertake this complex task.

2  **Present the project leveraging the DOE funding with other resources.**
- Alstom is providing almost 75% matching to the tune of $ 4.5 million for the 39-month project duration covering Phases I and II.
- Duke Energy is not only making the McAlpine facilities available for this investigation, they are also making more than 30 technical personnel to be part of the team. Their participation is truly priceless.
- Snohomish PUD is also providing similar support in terms of physical facilities and human resources.

3. **Present how the DOE funding catalyzes the industry/business.  If not, why not?**
- The results of this project should provide a business model and agile process for other electric utilities in the U. S. to meet the real-time operational needs of their smart distribution grid.

# Contact Information

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# Back-up Slides

Include any back-up slides you would like to provide to the peer reviewers and DOE program managers for additional information.  The back-up slides will not be shared with others, unless specifically stated by the presenter.

# Significance and Impact (backup slides)

- **Electric Utility Goals:**
  - Facilitate technical and market development for emerging technologies.
  - New operational requirements and business model.
  - Establish Duke Energy's public reputation as leader in understanding, developing and applying technology in the utility industry.
  - Software and control systems for integrating distributed resources and providing physical estimations for distribution circuits in real time.
  - Smart grid test tools for verifying interoperability of the solutions.
- **DER Modeling:** Develop voltage dependent terminal behavior models for different DER sources based on measurements. This will facilitate:
  - More accurate load forecasting
  - Better demand response
  - Increase operational efficiency

# Significance and Impact (backup slides)

- **Load Forecasting:**
  - Optimal planning and operation of distribution systems relies heavily on accurate forecasts
  - Feeder level forecasting is more difficult than forecasting the total system load because of the large number of substations, and the complicated spatial and temporal correlations of their load.
  - The presence of significant distributed energy resources and demand response in the future will add other levels of complexity
- **DER Scheduling:** Advanced optimization is being developed to schedule DERs, most notably community energy storage, electric vehicles, and demand response programs. This will allow:
  - Load factor improvement through peak shaving and valley filling
  - Loss reduction through load flattening
  - Outage reduction by decreasing overloads and increasing equipment life

# Significance and Impact (backup slides)

- **Communication Architecture:** Develop a multi-tier, hierarchical network topology and definition of associated communication protocols for a set of typical DERMS scenarios to enable flow of measurements to and from DERMS to DERs. This will aid in the controllability of the devices as well as the operability of the system.

- **Advanced and Adaptive Protection:** The penetration of distributed energy resources (DERs) has been driving the changes in protection strategies for distribution systems. This research aims to  develop advanced and adaptive protection schemes for distribution networks and microgrids to promote the integration of DERs and enhance the grid reliability by leveraging the information produced by the new devices.

- **Market Integration of DER:** Development of market models using the additional data provided from measurement systems to allow DER to be more responsive to real-time pricing signals. This will allow improvements in load factor and losses as well as reduction in operating costs.

# Technical Approach & Transformational R&D (backup slides)

- **DER Modeling:**
  - Measure DERs at different operating states and voltage levels to find terminal behavior characteristics.
  - Show why these detailed models are necessary for DERMS functionality.
- **Load Forecasting:** Short term load forecasting at the distribution level will be done in two steps to manage complexity while capturing the spatial and temporal correlations across substations.
  - Step 1: Zonal load and system load will be forecasted with appropriate inputs to capture the spatial and temporal correlations across zones.
  - Step 2: Substation load within a zone together with the zonal load will be forecasted with appropriate inputs to capture the spatial and temporal correlations across substations.

# Technical Approach & Transformational R&D (backup slides)

- **DER Scheduling:**
  - Modeling of residential DR resources owned by Duke Energy and their behavior followed by the forecasting of their availability down to the lowest possible level along the distribution feeder.
  - Scheduling and dispatching DR owned by Duke Energy in real-time by adopting a multi-tier optimization approach for solving the residential DR problem.
  - Work is on way to build decentralized control architecture with an instance of the DR optimizer running at each node namely distribution transformer, feeder head, substation and the entire system.
- **Communications Architecture:** Proposed greedy algorithm and integer programming methods to find the optimal synchrophasor device deployment with optimal estimation performance and investigated complexity-performance trade-offs among algorithm choice.
- **Market Integration of DER:** Comprehensive analysis of data sources and data sharing opportunities/barriers for robust DR baseline calculations and optimal secondary network aggregation models.

# Technical Approach & Transformational R&D (backup slides)

- **Advanced and Adaptive Protection:**
  - Analyze the new challenges brought by the penetration of DERs and the deficiency of the traditional protection paradigm;
  - Generate new requirements for advanced protection schemes;
  - Develop Microgrid protection scheme using digital relay and communication;
  - Seeks for optimal plan for deploying protective device;
  - Real-time protection validation in response to network topology and operation mode changes;
  - Island operation controller to reduce outage time for critical loads;
  - Fast fault detection, location and outage restoration leveraging multi-types of information (from new device, such as PMU, line sensor, smart meter, fault indicator, etc) and intelligent switching equipment;
  - Algorithms to optimally place protection devices.

# Project Team Capabilities & Funding Leverage

1. List organizations that this project interacts and collaborates with, describing their expertise and complementary roles to this project.

| | DOE Statement of Work and Project Objectives (SOPO) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| **Alstom Grid** | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ |
| **U of Washington** | | | | | | | Communications and Interoperability standards | | | | | Network, market and DER models |
| **U of Connecticut** | | | | | | Load Forecasting | | | | | | |
| **PNNL** | Load Model | | Asset Models | | | | | | | | | |
| **Duke** | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ |
| **SnoPUD** | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ |

# McAlpine SAIDI

| Without MEDs | 2008 | 2009 | 2010 | 2011 | 4 yr Ave | StDev | % of Mean |
|---|---|---|---|---|---|---|---|
| 01302407 | 590 | 24 | 154 | 72 | 210 | 259 | 123% |
| 01302408 | 200 | 32 | 26 | 25 | 71 | 86 | 122% |
| 01302410 | 318 | 49 | 204 | 242 | 203 | 113 | 56% |
| 01302412 | 396 | 102 | 50 | 84 | 158 | 160 | 102% |
| 01302414 | 97 | 26 | 44 | 123 | 72 | 45 | 62% |
| 01302415 | 335 | 139 | 88 | 36 | 150 | 130 | 87% |
| Substation Ave | 323 | 62 | 94 | 97 | 144 | 132 | 92% |
| | | | | | | | |
| Includes MEDs | 2008 | 2009 | 2010 | 2011 | 4 yr Ave | StDev | % of Mean |
| 01302407 | 591 | 69 | 155 | 742 | 389 | 328 | 84% |
| 01302408 | 200 | 41 | 26 | 29 | 74 | 84 | 113% |
| 01302410 | 322 | 125 | 212 | 324 | 246 | 96 | 39% |
| 01302412 | 396 | 102 | 50 | 489 | 259 | 216 | 83% |
| 01302414 | 97 | 26 | 44 | 132 | 75 | 49 | 65% |
| 01302415 | 335 | 139 | 88 | 37 | 150 | 130 | 87% |
| Substation Ave | 324 | 84 | 96 | 292 | 199 | 151 | 79% |
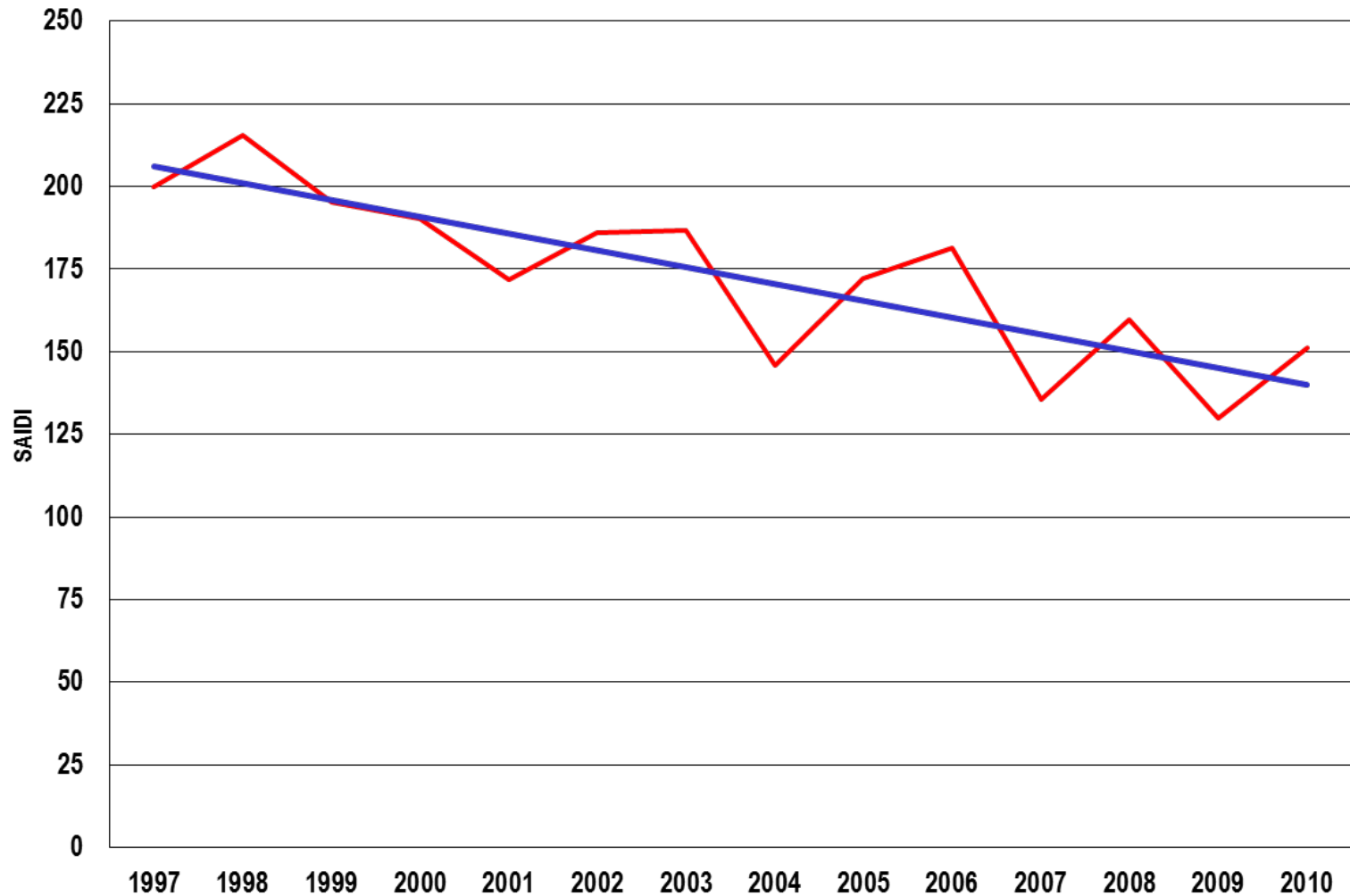
# Historical SAIDI Trend for Duke Energy Carolinas since 1997

# Historical SAIDI Trend for Duke Energy Carolinas since 1997



Actually, about a 30% SAIDI reduction.
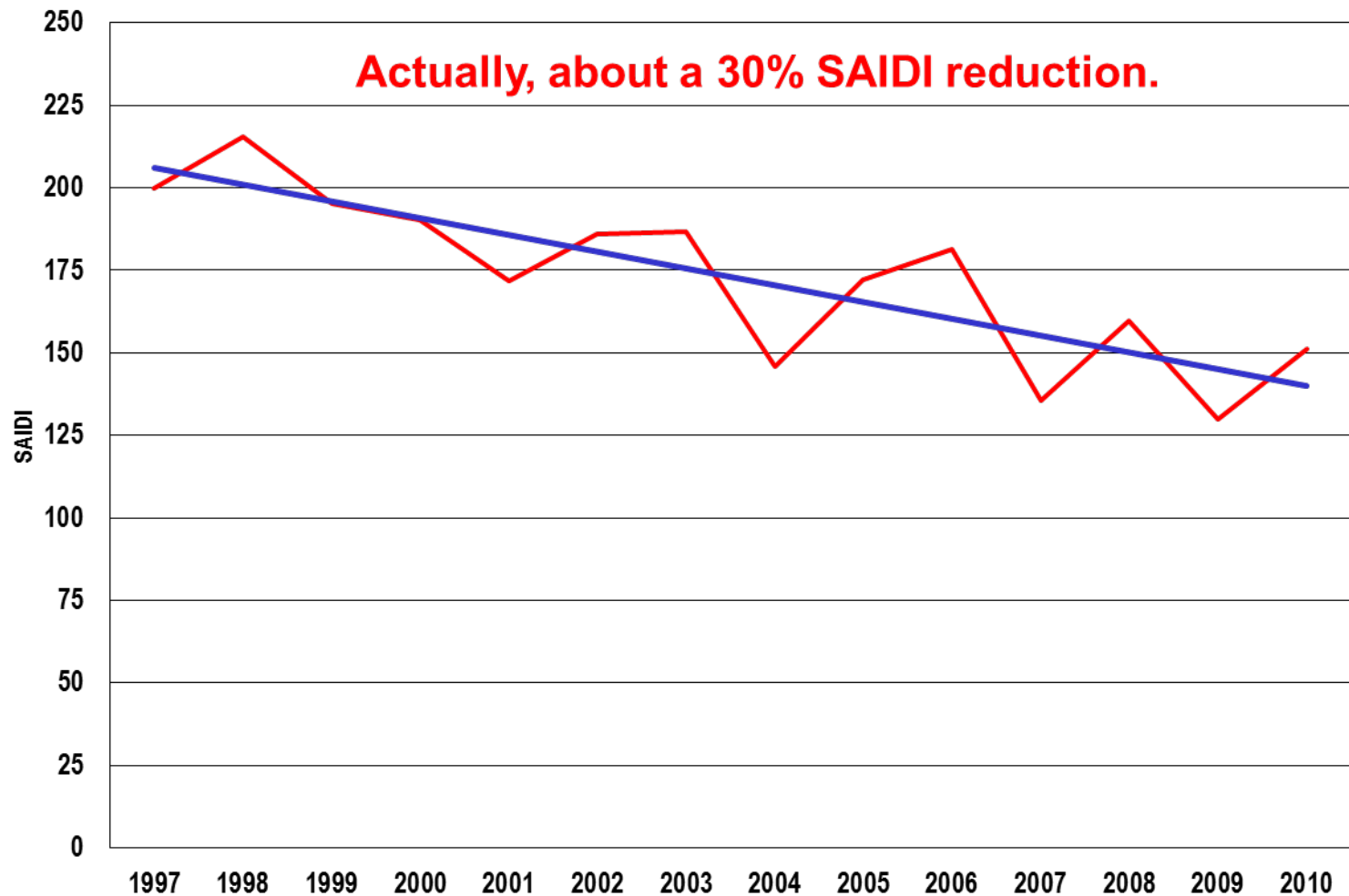
# Historical SAIDI Trend for Duke Energy Carolinas since 2003



DE Carolinas SAIDI (2.0% Annual Improvement Rate)

Target for 2012 based on 8 year improvement rate.
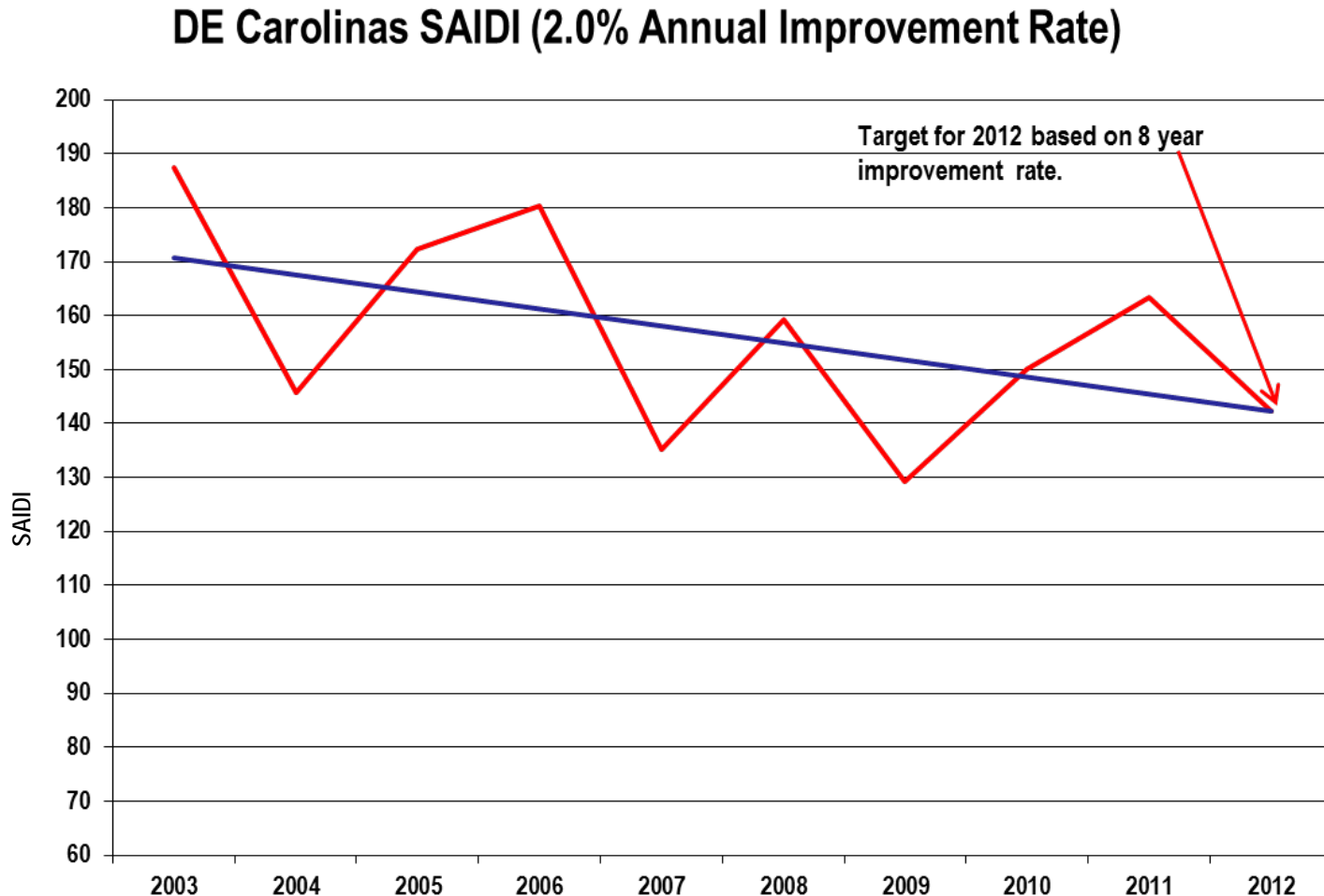
# DER Modeling

- Measurement equipment for capturing EV charging behavior.

# DER Modeling

- Power measurements on the Nissan LEAF with varying voltage
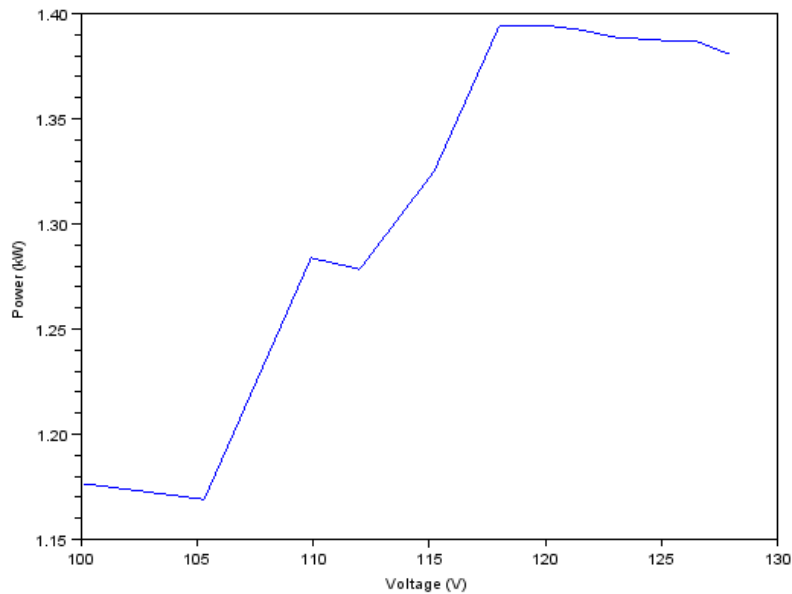


Power vs. voltage measurements
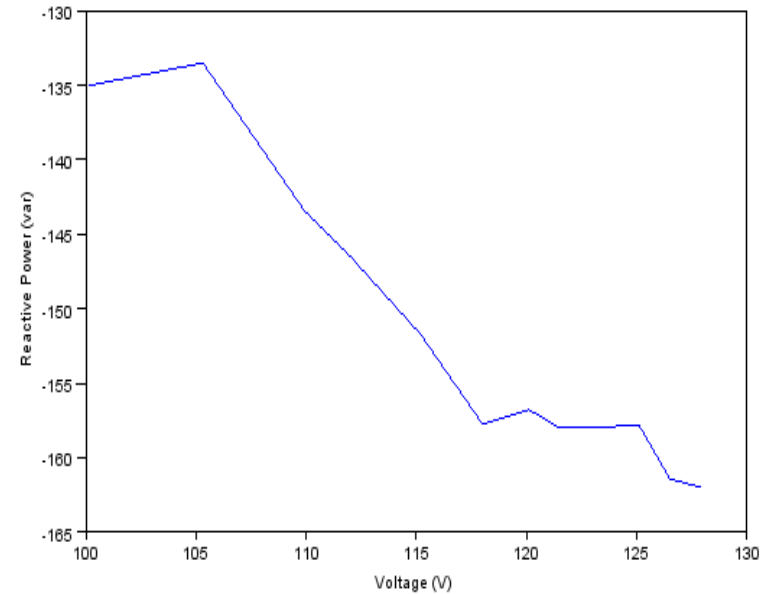


Reactive power vs. voltage measurements

# Load Forecasting

- Load forecasting at the distribution level will be done in two steps to manage complexity while capturing the spatial and temporal correlations across substations.
    - Step 1: Zonal load and system load will be forecasted with appropriate inputs to capture the spatial and temporal correlations *across zones*.
    - Step 2: Substation load within a zone together with the zonal load will be forecasted with appropriate inputs to capture the spatial and temporal correlations *across substations*.
- Distributed energy resources could be owned by customers and used to satisfy customer demand thereby affecting substation load.
- Solar and wind contributions will be captured based on weather data, while others based on prices
- To capture the intermittent nature of wind generation for example, data will be analyzed and then properly transformed. The method of generalized autoregressive conditional heteroscedastic (GARCH) will be investigated to improve predictions with good estimated confidence intervals.

# Load Forecasting

- To capture the intermittent nature of wind generation for example, data will be analyzed and then properly transformed.  The method of generalized autoregressive conditional heteroscedastic (GARCH) will be investigated to improve predictions with good estimated confidence intervals.
- Demand response is a reduction in the consumption of electricity by customers from their expectation.
- For non-dispatchable demand response, the key idea is to extend our current neural networks trained by Kalman filters to capture the features of the prices and load considering their dynamic relations.
- To provide forecasting accuracy, confidence intervals will be estimated for both predictions.

# Load Forecasting

- Decoupled-Extended Kalman Filter (DEKF) helps to reduce the computation time because of the block-diagonal form in the covariance matrix.
- Decoupling strategy
- An extreme case: Diagonal EKF
- Decoupling based on the analysis of covariance matrix
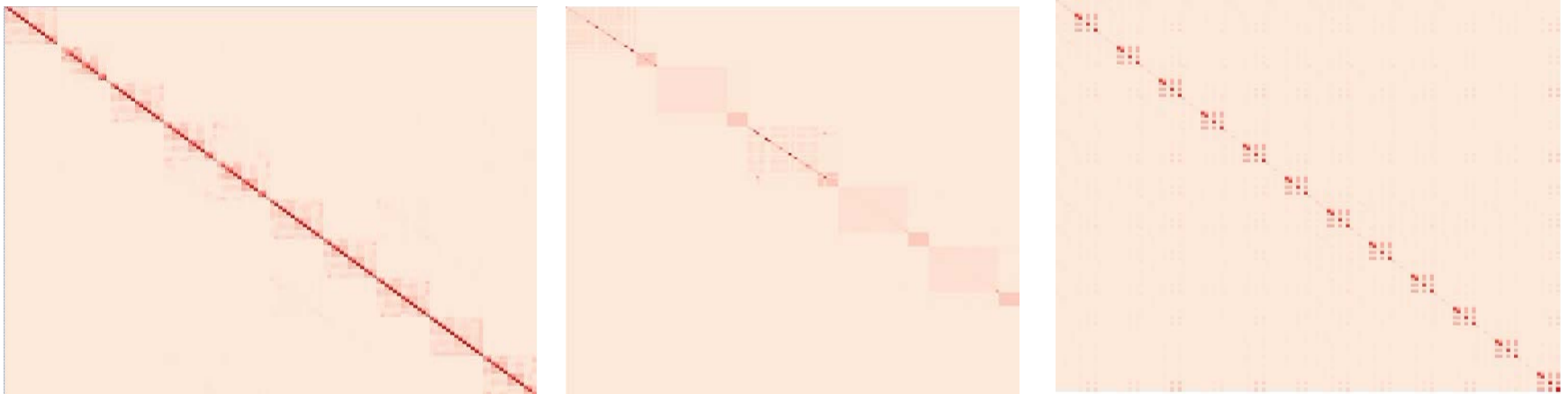


Fig. 1. Correlations of weights obtained from weight covariance matrix

# DER Scheduling: Overload Mitigation



CES and EV Optimization for Overload Mitigation

Legend: Load_BaseCase, Load_Optimized, Transformer_Rating, CES_Discharge, EV_Charge_BaseCase, EV_Charge_Optimized
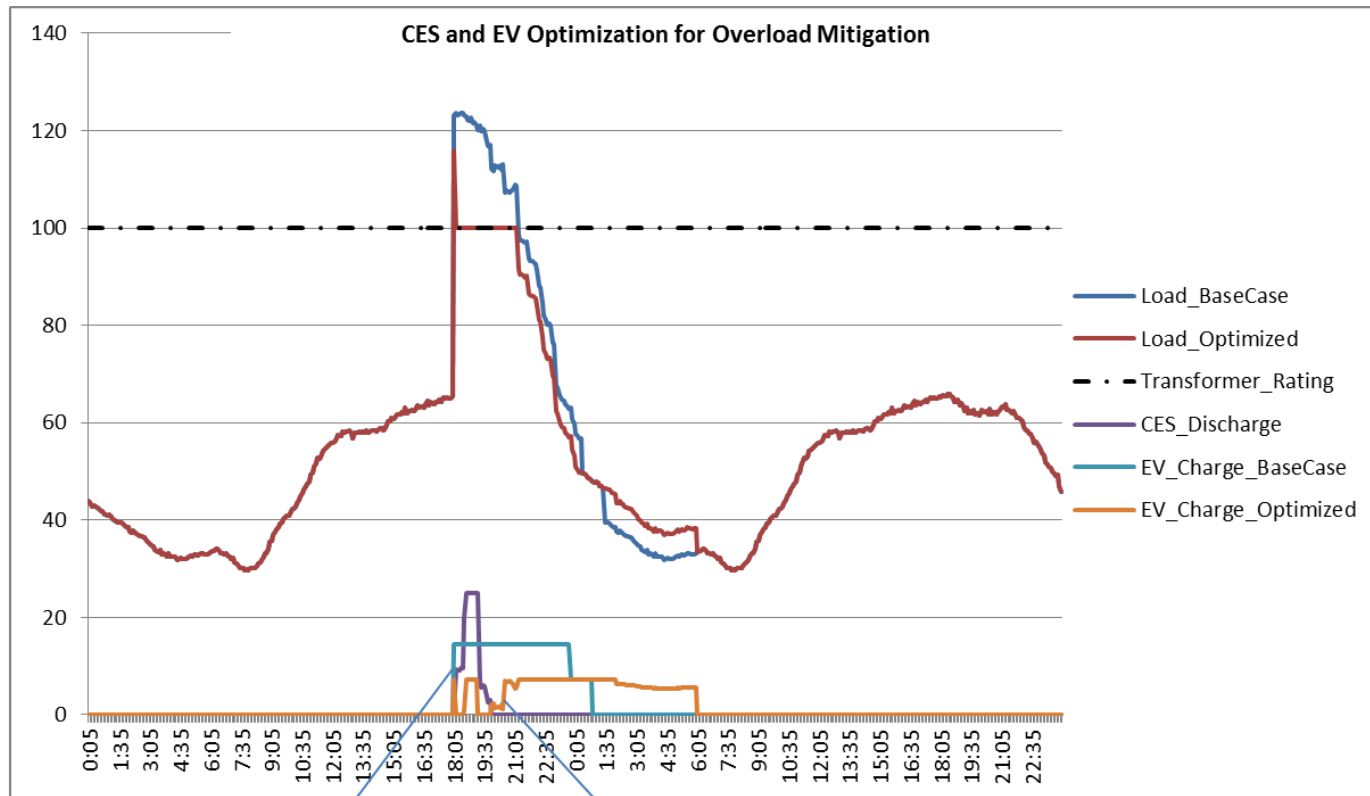
Battery does not discharge much during high priced

Most of the battery is discharged to mitigate DTF overload, hence profit from battery discharge is low

Controlled and Optimized Charging by EVs to mitigate overload

Note: Controlled charging from EV is insufficient to mitigate over 20% Overload

# DER Scheduling: CES Peak Shaving

- Initial Test Results:
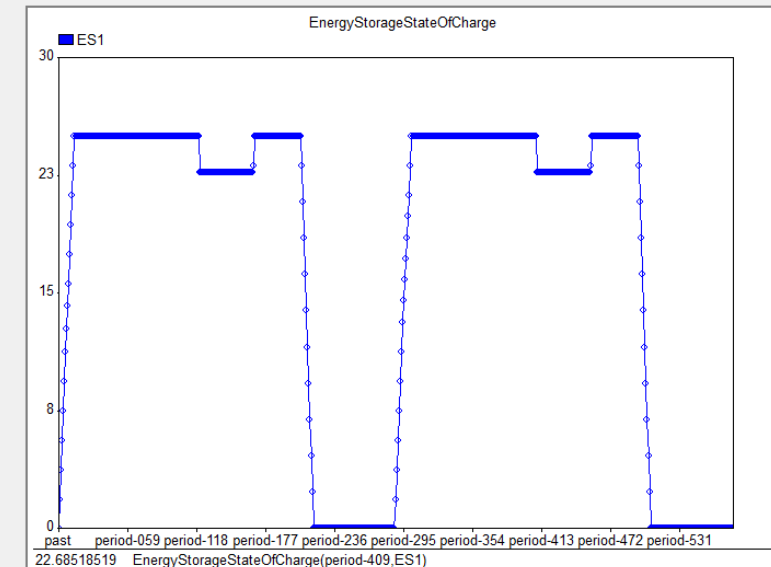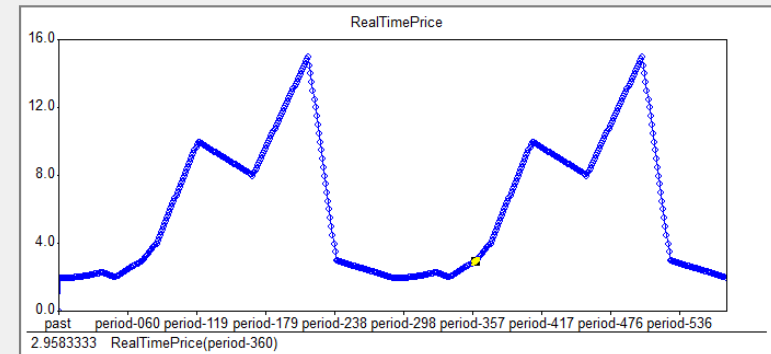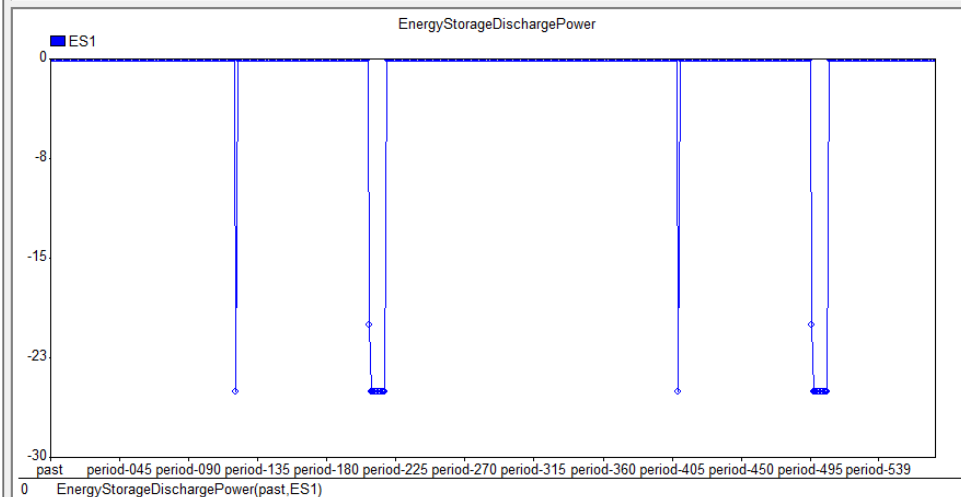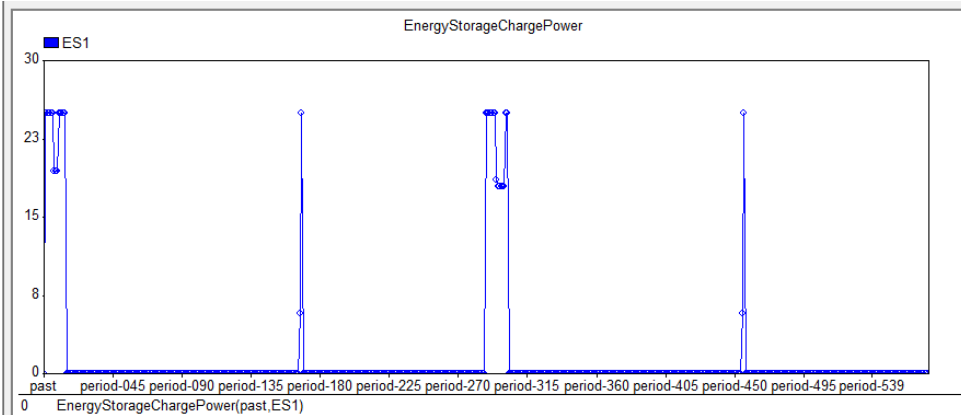
# Communication Architecture

- Communication Architectures for Smart Distribution Grid  (in progress)

  o Blueprint of a  hierarchical network  topology and definition of  associated communication protocols for a set of typical DERMs scenarios.
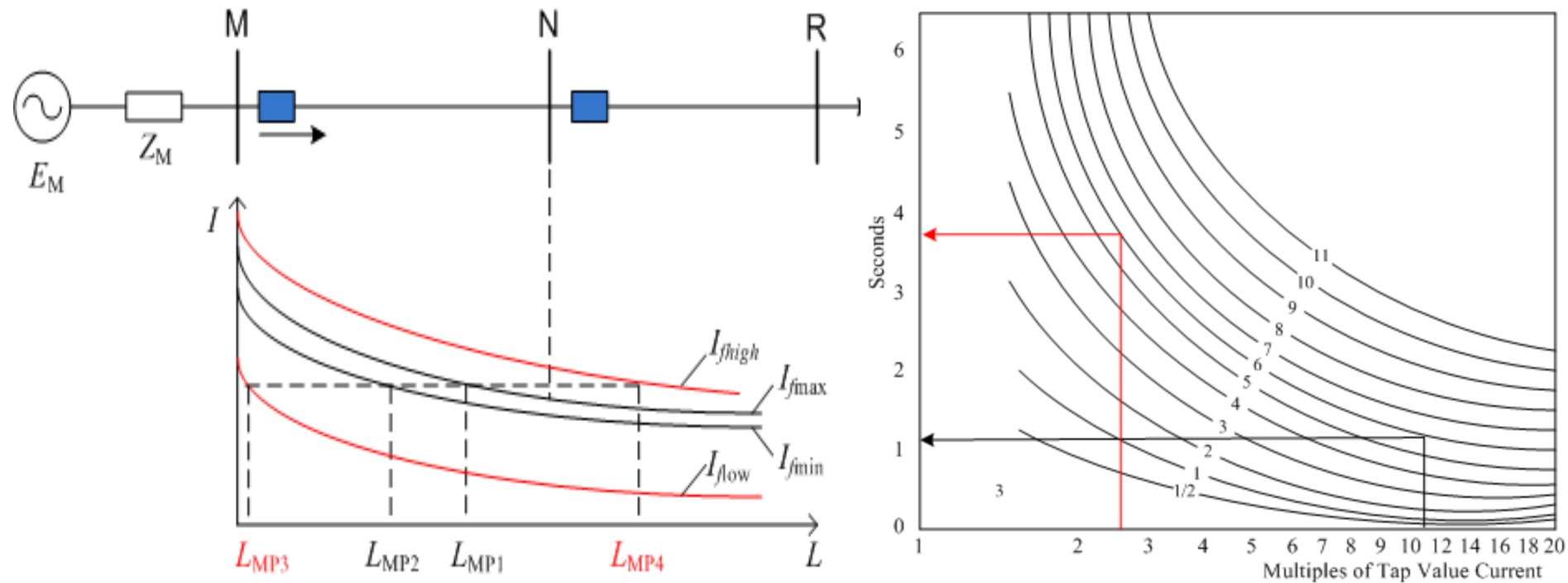
# Advanced and Adaptive Protection

- Optimal PMU Deployment (in progress)

    o Significant prior art focused on finding the minimum number of PMUs for a given network topology that achieves full observability.

    o Our approach: for a given a-priori number of PMUs, find the best (min. state estimation error) PMU deployment for the topology. (irrespective of observability)

    o Our algorithm for optimal PMU deployment is distinct from prior art answers what is the best (in terms of state estimation error) that is achievable for a given cost the number of PMU outlay.

# Advanced and Adaptive Protection

- State estimation model:

  - Describes the states of unobservable and observable buses in the grid (generalizing previous approaches); assume PMUs that measure complex voltage phasor and all line currents at the bus at which they are placed.

  - Seeks to find the set of PMU locations for a given number of PMUs that minimize the mean-squared state estimation error.

  - Proposed greedy algorithm and integer programming methods to find the optimal PMU deployment with optimal estimation performance.

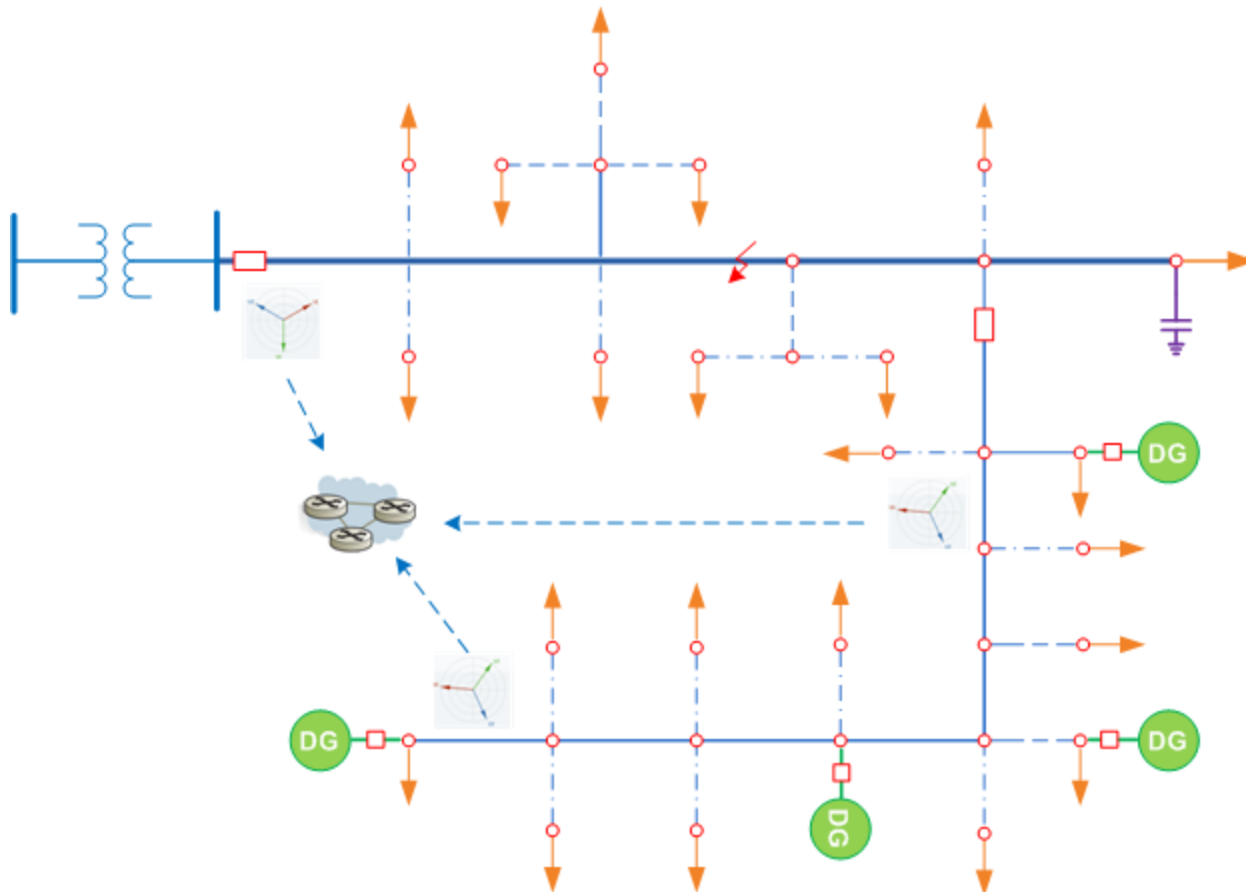  - Investigated complexity-performance trade-offs among algorithm choice.

# Advanced and Adaptive Protection

- An example for adaptive overcurrent protection for a feeder:
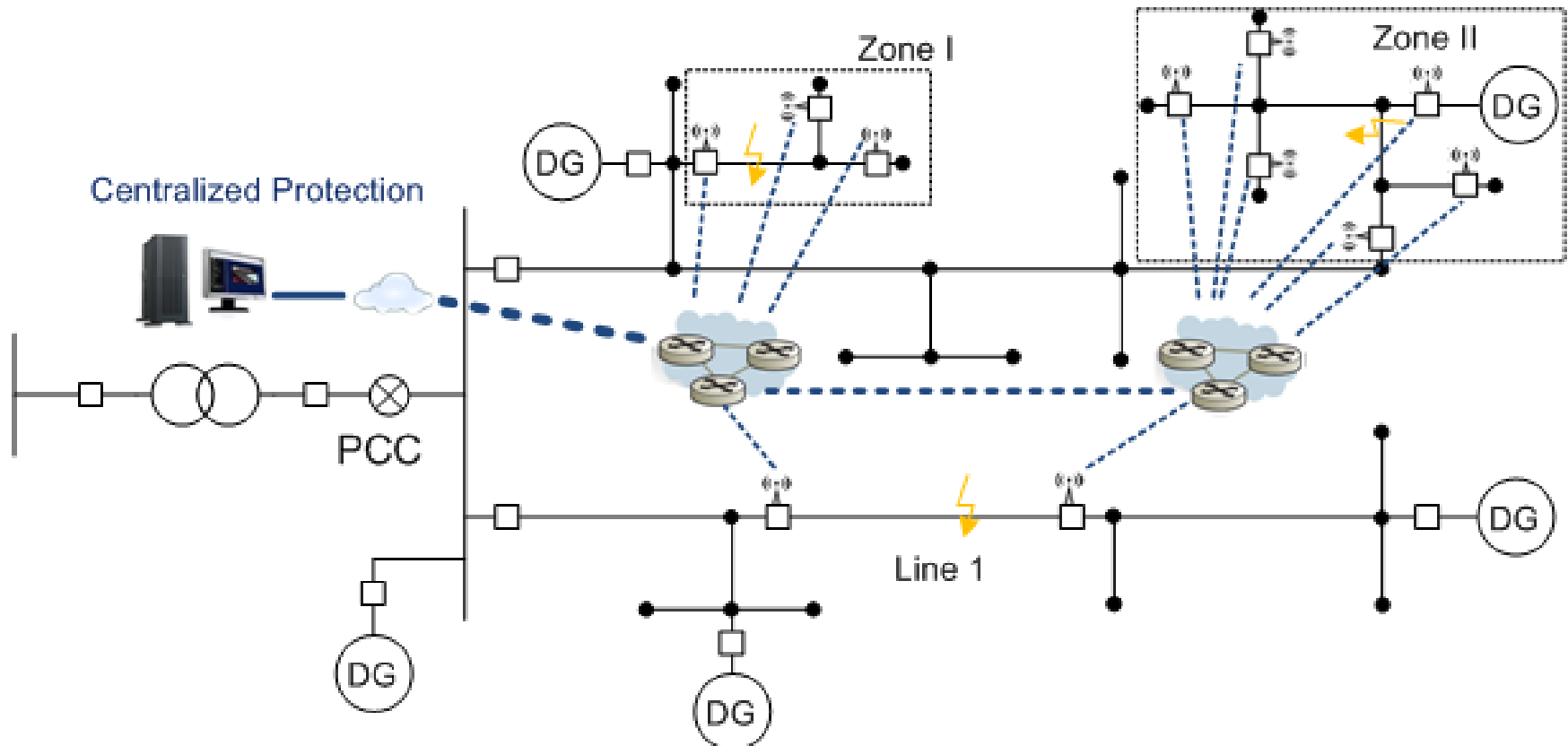
# Advanced and Adaptive Protection

- An example of synchrophasor based islanding detection scheme:
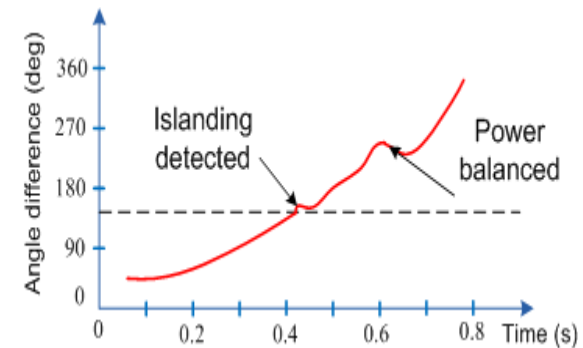


- Angle difference

- Frequency slip

- Rate of change of frequency (ROCOF)

- Over/Under voltage
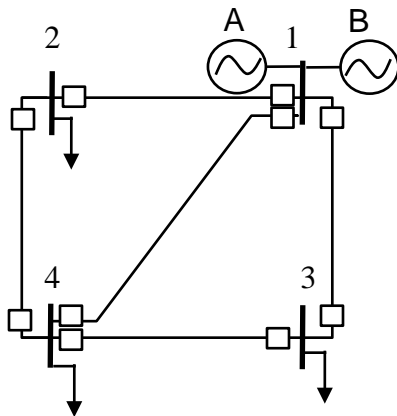
# Advanced and Adaptive Protection

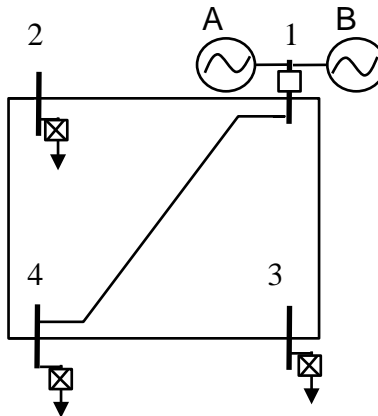- An example of differential current (zone) based scheme:

# Advanced and Adaptive Protection

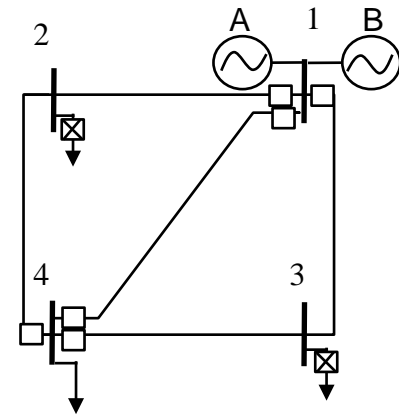- An example of optimal placement of protective devices:



Most Reliable

Least Reliable

Optimal

| | Expected Customer cost | | Equipment Costs | Total |
|---|---|---|---|---|
| Protection Scheme | per year | 10 years | 10 Years | 10 year cost |
| Least Reliable | $815.60 | $8,155.98 | $1,600.00 | $9,755.98 |
| Most Reliable | $0 | $0 | $10,000.00 | $10,000.00 |
| Optimal | $5.16 | $51.59 | $6,400.00 | $6,451.59 |

# Market Integration of DER

- The smart grid is characterized by the exchange of data amongst various entities, including the customer and possibly, the customer's actual electric appliances and devices. The research seeks to exploit data, newly available due to smart metering and pervasive monitoring, to promote the integration of DER and to enhance and expand distribution management functionalities.

- A comprehensive analysis of data sources and data sharing opportunities/barriers is the first step in helping the objectives of this project, as it gives us a deeper understanding of what information will be available for modeling.

- Currently there is limited modeling of the distribution network.  Smart meter data (as well as other distribution monitoring data) can be used to allow for more accurate modeling of individual feeders as well as their aggregates. This information can be useful for developing outage prevention/prediction schemes that can be coordinated with DR and DER resources.

# Market Integration of DER

- The research seeks to develop models for:
  - Aggregated Demand Response (DR) Forecasting
  - Robust DR Baseline Calculations
  - Optimal secondary network aggregation models (including DER models)
- Investigation of the emerging technology trends related to distribution monitoring, demand response, and energy management systems as well as the data that they will/do produce.
- Comparison of emerging data regulation in various markets ranging from vertically integrated to fully deregulated retail competition and how that may, or may not, affect/limit DMS functionalities.
- Identify potential novel uses of smart distribution data that promote the integration of distributed energy resources.
- After a comprehensive analysis of data sources and data sharing, the economic and technical modeling of demand response has been identified as a first step.