The Perfect Power Prototype for the Illinois Institute of Technology

Progress Report

Year 2 (October 2009 - September 2010)

Project Sponsor:	U.S. Department of Energy
Award Number:	DE-FC26-08NT02875
Recipient:	Illinois Institute of Technology
Principal Investigator:	Mohammad Shahidehpour
Period Covered:	October 1, 2009 to September 30, 2010
Date of Report:	September 30, 2010

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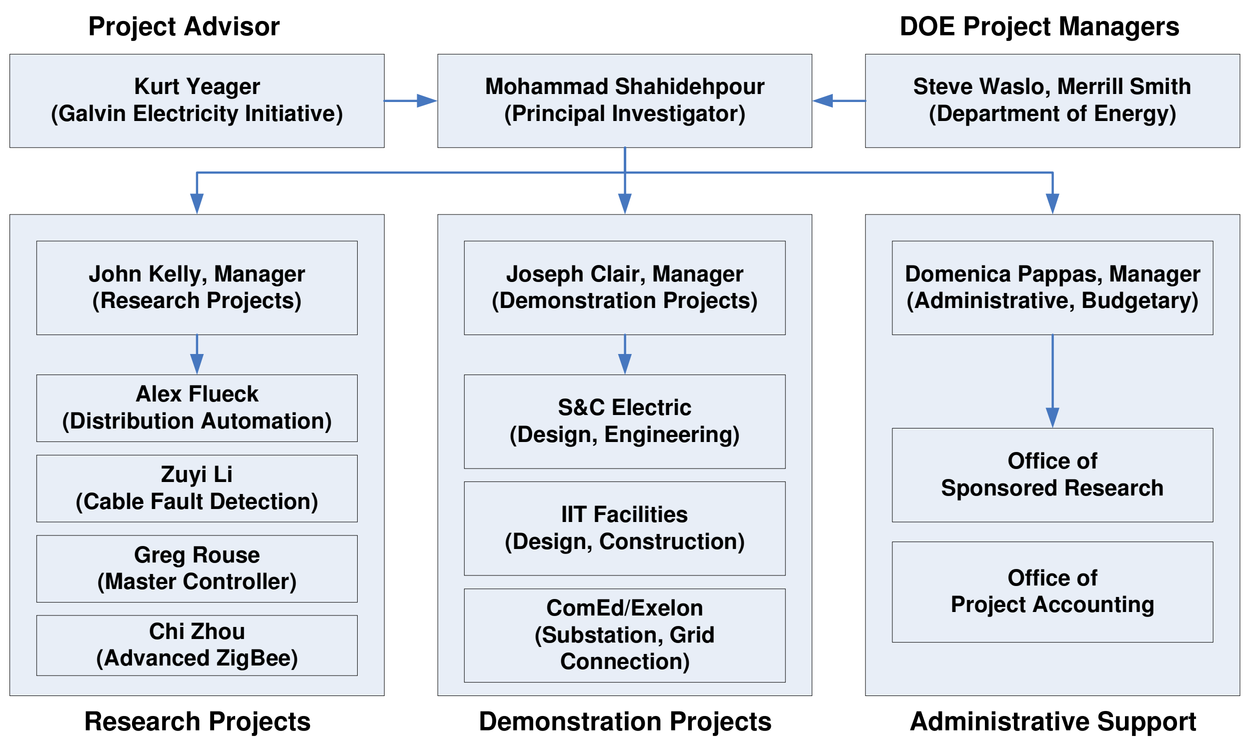
1 Executive Summary

Project Overview

- Funded by the U.S. Department of Energy
- $12M ($7M from DOE, $5M Cost Share)
- 5 year project
- Located at Illinois Institute of Technology (IIT)
- Involves the IIT main campus
- Partners: IIT, Galvin Electricity Initiative, Exelon, S&C, Schweitzer, Intelligent Power Solutions

Project Organization



Project Participants

- **Illinois Institute of Technology**: Mohammad Shahidehpour, Zuyi Li, Alex Flueck, Chi Zhou, Andrew Barbeau, Joseph Clair, Domenica Pappas, Robert LaPointe, Jatan Clark, Elzbieta Obiedzinska
- **S&C Electric**: Al Stevens, Jim Niemira, Dennis Bornancin, Dave Kearns
- **Intelligent Power Solutions:** John Kelly, Greg Rouse
- **Wiedman Power System Consulting**: Thomas Wiedman
- **EPRE**: Roberto Ferrero
- **Areva T & D**: Jay Giri
- **Trans-Elect**: Paul McCoy
- **Open Access Technology International**: Ilya Roytelman

Project Objectives

- 50% peak demand reduction
- 20% permanent demand reduction
- Demonstrate the value of Perfect Power
    - Cost avoidance and savings in outage costs
    - Deferral of planned substations
- New products and commercialization
- Replicable to larger cities
- Promotion of energy efficiency and cleaner cities

Project Tasks

- Phase I is to establish the basis for Perfect Power.
- Phase II is to address key technology gaps.
    - Task 1.0 – Advanced Distribution Automation and Recovery System
    - Task 2.0 – Buried Cable Fault Detection and Mitigation
    - Task 3.0 – Intelligent Perfect Power System Controller
    - Task 4.0 – Advanced ZigBee-Based Wireless
- Phase III is to prepare IIT for real time pricing and ancillary markets.
    - Task 1.0 – IPPSC, Version 1 Demonstration
    - Task 2.0 – Turbine Fast Start and ComEd/PJM Portal
- Phase IV is to deploy the advanced campus distribution system.
    - Task 1.0 – High Reliability Distribution System Installation
    - Task 2.0 – Substation Automation
    - Task 3.0 – IPPSC, Version 2 Demonstration
- Phase V is to deploy campus distribution level peak load reduction.
    - Task 1.0 – Peak Load Reduction Capability
    - Task 2.0 – IPPSC, Version 3 Demonstration
    - Task 3.0 – Solar PV
    - Task 4.0 – Install UPS at Critical Buildings

Phase I – Perfect Power Foundation

- All the tasks in Phase I have been completed.
    - Task 1.0 – Perfect Power Conceptual Model Development
    - Task 2.0 – ComEd/PJM Portal and Turbine Fast Start
    - Task 3.0 – Energy Efficiency Upgrades
    - Task 4.0 – Substation Supply Reliability
    - Task 5.0 – Perfect Power System Design and Engineering

Phase II, Task 1.0 – Advanced Distribution Automation and Recovery System

- Accomplishments
    - Year 1: Creation of a communication model in dNetSim
        - Developed communication latency model for agents
        - Integrated additional distribution network regulator models
        - Developed induction motor load model
        - Developed distributed electronic converter energy storage model
        - Verified unbalanced three-phase power flow solutions on IEEE Test Feeders
    - Year 2: Development of a Visualization Platform for dNetSim

        - Incorporated new communication models into the existing autonomous agent-based control system
        - Verified communication latency models via Monte Carlo simulation
        - Developed a visualization prototype based on Scalable Vector Graphics (SVG)
        - Created a visualization platform for displaying the dynamic network configuration
- Future Work
    - Year 3: Real-Time Control of Typical Distribution Systems
        - Fault detection, location and isolation
        - Service restoration for healthy feeder segments
        - Feeder reconfiguration for load balancing
        - Smart interconnection interface for distributed resources
        - Volt/VAR management for loss reduction
        - Emergency response to shed non-critical load
    - Year 4: Centralized Control vs. Distributed Control Modes
        - Centralized control (comprehensive command and control)
        - Decentralized control (fast decision making with local information)
        - Which yields the best performance under a variety of configuration and disturbance scenarios, including communication interruptions and outages?
    - Year 5: Pilot Demonstration

Phase II, Task 2.0 – Buried Cable Fault Detection and Mitigation

- Accomplishments
    - Simulation of IIT's Distribution Network
        - IIT's distribution network has been simulated.
        - Simulated faults have been imposed at selected locations to characterize the system.
- Future Work
    - Identification of the Best Fault Detection and Mitigation (FDM) for IIT's Distribution Network
        - An accurate, fast, and reliable FDM approach for IIT's distribution cable network will be identified based on criteria such as sensitivity, reliability, selectivity, and speed.
    - Pilot Demonstration of the Identified FDM in IIT's Distribution Network

Phase II, Task 3.0 – Intelligent Perfect Power System Controller

- Accomplishments
    - Version 1 Software Development
        - Built interfaces for electric pricing and weather data
        - Finished database retrieval and storage code
        - Finished background utilities required for running the program
        - Remote control of substation breakers on the loops
- Future Work
        - Agent to agent communications
        - Generator agent
        - Communications with turbine controllers
        - User and password management
        - Settings and preferences

        - Optimization and analytics
        - Reporting and user Interface

Phase II, Task 4.0 – Advanced ZigBee Wireless

- Accomplishments
    - Frequency-agility based Interference Avoidance Technique
    - Demonstration prototype
- Future Work
    - MAC layer protocol for integrated WiFi & ZigBee
    - Cyber security: key management
    - Energy-efficient routing protocol
    - Self-healing algorithm

Phase III – Ancillary Services Demonstration

- Task 1.0 – IPPSC, Version 1 Demonstration
    - To be completed by February 2011.
- Task 2.0 – Turbine Fast Start and ComEd/PJM Portal
    - Enable the two existing 4MW-Allison-Turbines to participate in the Perfect Power System: completed in August 2009.

Phase IV – Distribution System Automation Demonstration

- Task 1.0 – High Reliability Distribution System Installation
    - Accomplishments
        - Power system model for load flow studies and fault studies completed.
        - North Substation relay upgrade design and installation completed.
        - Loop distribution system designs completed for Loops 1, 2, and 3.
        - Loop 3 installation completed.
        - Loop 1 and Loop 2 installation ongoing.
    - Future Work
        - Design documents for substation interface computer and Ethernet switch
        - Loops 1 and 2 installation
        - Interface computer installation
- Task 2.0 – Substation Automation
    - North substation automation completed
    - South substation automation being planned
- Task 3.0 – IPPSC, Version 2 Demonstration
    - On schedule

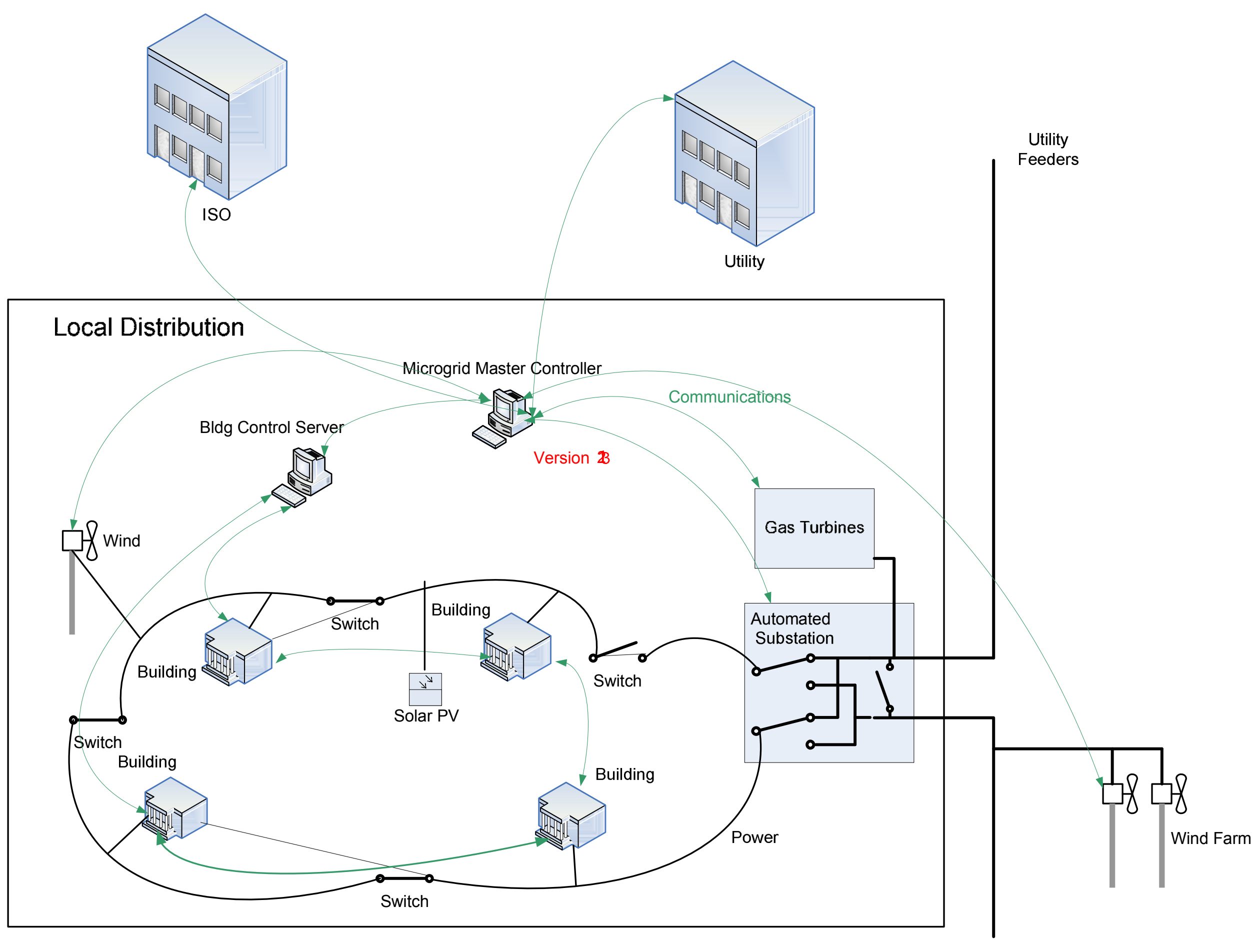
Phase V – Distribution Level Peak Load Reduction Demonstration

- Task 1.0 – Peak Load Reduction Capability
    - Provide load reduction capabilities for both blackstart during Island Mode and demand response during Grid Parallel mode.
    - The agents for the building controller and HRDS will coordinate the optimal load shedding scheme depending on local conditions.
- Task 2.0 – IPPSC, Version 3 Demonstration
    - On schedule.
- Task 3.0 – Solar PV

    - Purchase, install and integrate a Solar Photovoltaic System (PV) into the overall Perfect Power System: on schedule
- Task 4.0 – Install Uninterruptible Power Supplies (UPS) at Critical Buildings
    - On schedule.

Demonstration Status

- 50% peak demand reduction when called upon by PJM/ComEd
    - Turbine fast start completed providing this capability
- 20% permanent demand reduction
    - Collected baseline data and normalized, HDD/CDD
- Demonstrate value of Perfect Power
    - 2010 ComEd/PJM DR valued at $450,000
- Loop 3:
    - Design, install and commission completed by 09/30/2009.
    - February 12, 2010: "Celebration of a Milestone at Illinois Institute of Technology: Completion of the First Phase of the Perfect Power Project."
- Loops 1 and 2:
    - Switches for Loop 2 were delivered and are being installed.
    - Currently on track for the February 2011 completion of both loops.
- South Substation:
    - RFP for South Substation project to be received.
    - Committee to meet to review and make recommendation.



2 Project Activities and Accomplishment

We divided our perfect power initiative at Illinois Institute of Technology (IIT) into two distinct groups of demonstration and research projects. The corresponding project reports are provided as follows:

2.1 Demonstration Updates

The demonstration projects are led by Mr. Joseph Clair, Director of Campus Energy and Sustainability at the Illinois Institute of Technology (IIT).

2.1.1 Demonstration Project Details in Year 2

Year 2 of the project started in October 1, 2009 and ran through September 30, 2010. The following results were accomplished in Year 2.

In the First Quarter (October-December 2009),

- Loop 3 was commissioned December 17, 2009.
- Single line drawings for Loops 2, 4, 5, 6, and 7 were issued for review.

In the Second Quarter (January- March 2010),

- Celebrated the completion of the First Phase of the Perfect Power Project on Friday, February 12, 2010 at IIT. Over 150 guests attended the ceremony and individuals participating in the Perfect Power project made several presentations as shown in **Appendix 1**.

In the Third Quarter (April-June 2010),

- A proposal was submitted by S&C Electric for Vista switches in Loop 2.
- S&C developed pricing proposals for converting two undercover units in Loop 1 to pad mounts.
- S&C developed a new proposal for the Vista units and engineering cost for Loops 4, 5, 6, and 7 so that final budgets can be developed.
- IIT awarded the installation contract for Loops 1 and 2 to Aldridge Electric. They subsequently coordinated with S&C to receive the Loop 1 Vista gear. Installation of the vaults on Loops 1 and 2 began in the summer 2009.
- The perfect power project team started the process of soliciting design-build contractors to work on the south substation project.

In the Fourth Quarter (July-September 2010),

- Construction meeting was held on August 13, 2010 for Loops 1 and 2. (Final installation of infrastructure for Loops 1 and 2 of HRDS was scheduled for the First Quarter of Year 3, October-December 2010.)
- Final drawings for the Loop 2 Vista units were submitted by S&C. (Switches for Loop 2 were delivered in November 2010)
- The black LVE color for the communication units and the light gray for the pad-mounted units were approved.

- There were some changes in both Loop 1 and 2 designs that required design and drawing changes. A manhole was added and the overhead line section was eliminated. A manhole was added and the overhead line section was eliminated.
- Vaults are being installed for Loops 1 and 2.

2.1.2 Next Steps

- Request for Proposal (RFP) for South Substation project was issued in Year 2. A committee will meet in the First Quarter of Year 3 to review and make the final recommendations.
- Complete installation and commission of Loops 1 and 2 by February 2011.

2.1.3 Percentage of Project Completion

- Modeling and conceptual design are 100% complete.
- Year one project installation was 100% complete.
- Year two project installation was 80% complete (Union worker strikes in Chicago put the project implementation behind schedule; all tasks are moving forward as planned.)

2.2 Research Updates

The research projects are led by Mr. John Kelly, Managing Director of Intelligent Power Solutions, LLC. There are four research tasks:

- Research Task 1: Advanced Distribution Automation and Recovery System led by Dr. Alex Flueck
- Research Task 2: Buried Cable Fault Detection and Mitigation led by Dr. Zuyi Li
- Research Task 3: Intelligent Perfect Power System Controller led by Mr. Greg Rouse
- Research Task 4: Advanced ZigBee Wireless led by Dr. Chi Zhou

2.2.1 Research Task 1 in Year 2

Research Task 2.1 – Advanced Distribution Automation and Recovery System is led by Dr. Alexander J. Flueck of Illinois Institute of Technology. Dr. Flueck's research group develops and demonstrates an advanced system for sensing distribution system conditions and automatically reconfiguring the system to respond to disturbances. The new autonomous agent-based architecture enables fault detection, location and isolation; service restoration; integration of renewables; feeder reconfiguration; volt/VAR management and emergency response.

Dr. Flueck collaborates with Tom Tobin, VP Research, S&C Electric and Mike Ennis, Director Advanced Technology, S&C Electric. The team has met roughly every month since the project began in the Fall of 2008. During the summer of 2009, the team met roughly every two weeks. The focus of Year 1 research effort was on fault detection, location and isolation; service restoration and integration of renewables. All aspects of the Year 1 objectives (which ended on September 30, 2009) were met and several additional achievements were accomplished in Year 1 of the project.

The Year 2 deliverables included enhancements to the existing autonomous agent-based smart grid controls and unbalanced three-phase distribution system simulator dNetSim, as well as a new visualization platform for dNetSim. The visualization platform accelerated the internal process of developing autonomous agent-based control systems and illustrates to engineers and operators the distributed decision-making process of the autonomous agent-based controls. These two research thrusts lead to the following extension of dNetSim:

- Incorporate the new communication models into the existing autonomous agent-based control system for fault detection, location and isolation, as well as service restoration.
- Create a visualization platform for displaying the dynamic network configuration.

2.2.1.1 Distributed Resource Models

Based on the electronic converter source model developed in Year 1, an electronic converter storage source was implemented in dNetSim. The storage source can operate in PQ set point mode, given the necessary user input data. Proper operation was verified for the storage source under normal conditions (voltage magnitude above 0.9 per unit), fault conditions (voltage magnitude below 0.5 per unit), and transient conditions in which the voltage magnitude is between the two other threshold values. In fact, the testing parameters of 0.9 per unit and 0.5 per unit are input values in the data file, so other threshold values can be defined by the user.

The PQ set point mode attempts to control the real and reactive power generation at all times. During a fault (e.g., voltage magnitude below 0.5 per unit), or during a transient (e.g., voltage magnitude below 0.9 per unit), the current output cannot instantaneously compensate for the reduced voltage magnitude. Therefore, the PQ set point will not be met during a large voltage deviation. However, if the PQ set point is not met within a user-defined time interval, then the storage source model will ramp up the current injection to try to restore the PQ output to its set point value. This behavior was tested and verified on a simple feeder model, derived from the IEEE 34 Node distribution test feeder.

In addition, a user-specified shutdown parameter was implemented. This plan enables a realistic simulation of an electronic converter storage unit that is overloaded for an extended period of time. The PQ set point control mode may not be able to restore the PQ output to its set point value if the voltage magnitude remains low. As the current injection ramps up to try to meet the PQ set point value, the storage source may hit its maximum current magnitude limit. If this occurs, then the current injection will be held constant at the maximum limit, as a shutdown timer is initiated. If the shutdown timer reaches the maximum time limit for current overloads, then the storage device will be tripped off-line by the controller. This mode of operation has been tested and verified on the modified IEEE 34 Node distribution test feeder.

2.2.1.2 Convergence Problem and Solution

During a Monte Carlo test run of the dNetSim code and the fault detection, location and isolation agent capabilities, S&C Electric discovered some power flow cases that did not converge within the default 0.1 mA mismatch tolerance. IIT began a detailed investigation into the potential causes of the non-convergence issue.

First, large mismatches seemed to appear on distribution nodes that were connected to the main line feeder through very short conductors. The test system, designed by S&C Electric, had some lateral feeders with large 100 kVA to 600 kVA constant power and constant current loads. Some of those laterals were inserted as simple models of a tapped load. The conductor lengths were 1.0 mm. However, in portions of the main line feeder, the conductor lengths were 1.0 mi. The range of conductor lengths was over six orders of magnitude. It was thought that the wide range of corresponding conductor impedances may be causing the convergence problem. Therefore, the 1.0 mm conductor lengths were changed to 1.0 ft.

Second, large mismatches continued to appear at nodes that had rather large constant power and constant current loads (200 kVA to 600 kVA). Since the three-phase unbalanced power flow solver could not find a solution to the network, a manual load shedding process was initiated. Eventually, 15 MVA of load was removed from the test system, which originally had 100 MVA of load. With the load reduced, dNetSim was able to converge to a power flow solution, within the default 0.1 mA current mismatch. At the solution point, it was discovered that several nodes at bus voltage magnitudes near 0.60 per unit. Clearly, the load levels for the test system were too high for the conductors. Due to the extremely high load and the relatively small conductor sizes, the system was beyond the collapse point. With 15 MVA of load removed, the system was still overloaded well beyond a reasonable level, but at least the problems could be readily identified. A revised system design with more realistic loading is under development in Year 3.

2.2.1.3 Large Scale Communication Latency Test

S&C Electric is interested in simulating a large system under a variety of fault scenarios with varying communication latency distributions. A target system has been created by combining three copies of the IEEE 123 Node Test Feeder system from the IEEE. The individual copies of the IEEE 123 Node system have been connected via “Normally Open” tie switches. Under permanent fault conditions, the system can be reconfigured by closing an open tie switch to pick up some isolated feeder segments.

The large-scale communication latency test is a Monte Carlo simulation in which the communication latency distributions are sampled during each trial with a different initial seed. This leads to a different sequence through the pseudo-random number generator, which varies the communication latency for each pair-wise message transfer.

The final output from the simulation includes the outage time for each load point during each scenario. Then, the raw data can be combined to generate performance indices such as the System Average Interruption Duration Index (SAIDI), the System Average Interruption Frequency Index (SAIFI), the Momentary Average Interruption Frequency Index (MAIFI), and the Expected Load Loss in kW, as well as other indices.

2.2.1.4 Communication Timeout Strategy

A new communication timeout strategy was considered for the autonomous switching agents. The existing agent code would wait for a response from another agent for an unlimited time. This “wait forever” strategy was developed to guarantee that communication failures would prevent agents from opening/closing switches without considering the status of the other switches in the same team. For example, if an agent wishes to close its switch, but has not heard from another team member regarding its status, then the first agent will not close its switch. In this way, we guarantee that the agent will not close into a fault, since it is possible that a fault could be inside the boundaries of the agent’s team.

The new communication timeout strategy adds a “timeout” counter to each agent communication. Then, if an agent sends a request to another team member, but the team member does not respond before the “timeout” duration expires, then the first agent can try to resend its message. This strategy still guarantees the safety features of the original communication strategy. In addition, the new strategy will be able to recover from temporary communication failures, such as temporary bandwidth reductions or temporary blocking of communication channels.

Each agent starts a “timeout” counter at the same time that a message is sent to a teammate. If the sending agent does not receive a response from the receiving agent within the “timeout” duration, then the conversation is dropped by the sending agent and any subsequent responses received by the sending agent will be ignored.

This timeout strategy complicates the communication processes, since a complex conversation can be disrupted by any communication fault along the way. If a communication fault occurs, then all of the agents involved in the conversation must recognize the failure and reinitialize their conversations. In some cases, an agent may need to wait for another agent to make the initial contact, but in other cases, an agent may need to restart the conversation by making the initial contact. In either case, the new timeout strategy enables fault-tolerant communication among the agents by recognizing communication failures and then restarting conversations.

2.2.1.5 Visualization Playback Platform

The summer 2010 programming team completed the Java FX visualization prototype, which includes the equipment models (source, node, line section, transformer, regulator, capacitor, load, and switches) and a simple implementation of the message transport process. The Java FX prototype has the ability to show a series of time snapshots, such that an engineer can step through the snapshots, either forward or backward, to see how the power system interacts with the autonomous agent-based controls. The entire sequence of snapshots is displayed via Java FX, so there is no need to cycle through separate files for each snapshot. A standard Java installation and the online provisioning of Java FX enables a sophisticated Java environment, on any computer with a Java Runtime Environment (JRE), for visualizing one-line diagrams and post-processed playback scenarios.

In addition to visualizing the network connectivity (overhead lines and underground cables), each significant piece of distribution equipment is shown in the one-line diagram (Figure 1). The one-line is built automatically from the input files, which include a CYME network file, load file, and optionally a MATLAB power flow results file, and JADE agent action results file. Figure 1 illustrates the basic one-line display in Java FX with an info box connected to a closed switch on the main line feeder. Additional info boxes can be connected to other equipment, such as nodes, overhead lines, underground cables, transformers, regulators, shunt capacitors and loads, to display various performance details. The nodes are represented by large colored circles. The color of the upper semicircle represents the node’s highest phase-neutral voltage magnitude, while the color of the lower semicircle represents the node’s lowest phase-neutral voltage magnitude. The user can modify the color scheme through a built-in color selector tool.

A fault is represented by a yellow lightning bolt within a black triangle, as shown in Figure 2. Note that the nodes have changed color due to the low feeder voltages caused by the three-phase fault. The substation bus is the only node that does not drop below the user-defined “low voltage threshold”. Lines and cables are also color-coded in the visualization tool, based on a user-defined color scheme and the line/cable loading relative to its rating. Note the path of high fault current in Figure 2 from the substation to the fault location. The laterals that are off the fault-path do not carry high current, so their colors remain green, which represents normal loading.

In Figure 3, the fault-interrupting switch on the main feeder detects the fault current and opens its contacts, thereby de-energizing all of the loads. Once the remaining load switches are open, then the unfaulted segments of the network can be restored. The autonomous agents send messages to their teammates to determine the state of the distribution system.

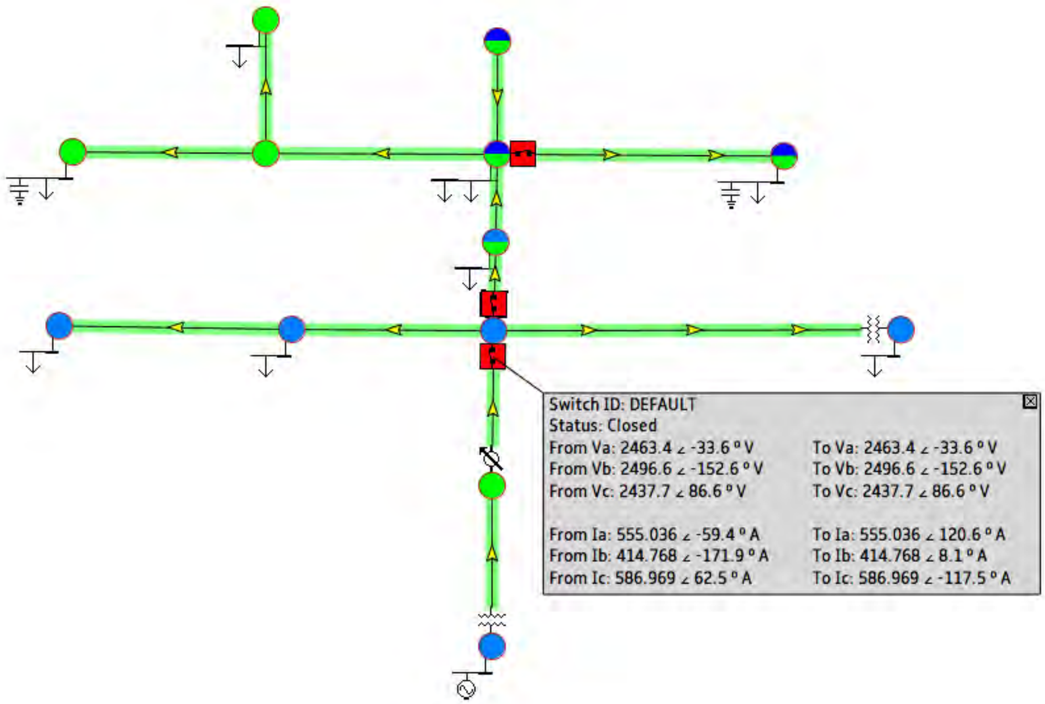


Figure 1: Java FX Display with Closed Switch Info Box at T=0 s

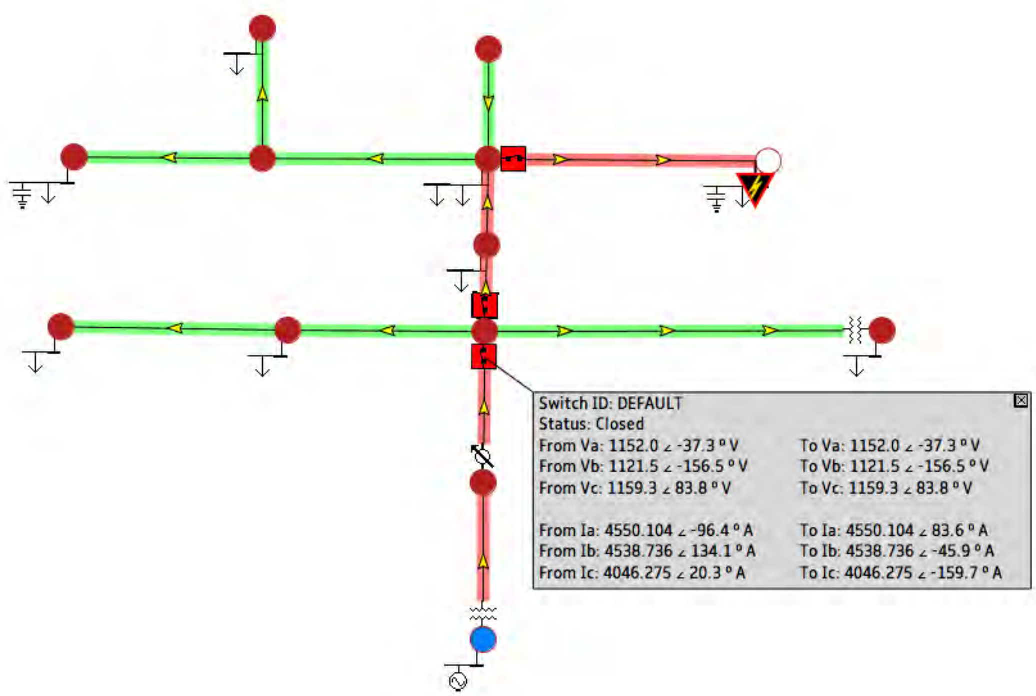


Figure 2: Java FX Display with Fault at T=1.0 s

The Java FX visualization prototype displays each agent message on the one-line diagram with a simple envelope symbol that appears at the sending agent and then moves to the receiving agent. Figures 3 and 4 illustrate the basic message transport in Java FX.

In Figure 3, the first main line switch is energized on one side by the substation and its contacts are open. To figure out if the switch can close its contacts, it must first confirm that the other switches on its team believe the segment in between them is clear. In other words, each switch on the team should answer "true" when queried whether the segment is clear. In this case, there is only one other switch for this de-energized segment, so the first main line switch sends a "QUERY-IF" message with content "isClear" to its teammate.

In Figure 4, the "QUERY-IF" "isClear" message has been received and the receiving switch has prepared a "INFORM" response of "true", which is being sent back to the first main line switch.

Once the first main line switch receives the "true" message in response to its "isClear" query, then it will close its contacts and pick up the load on the segment between the two switches. The partially restored feeder is shown in Figure 5.

This restoration process will continue to pick up unfaulted segments one at a time, until all eligible loads have been restored. The faulted segment will not be restored, unless the fault is cleared and the switch is informed that the fault has been repaired.

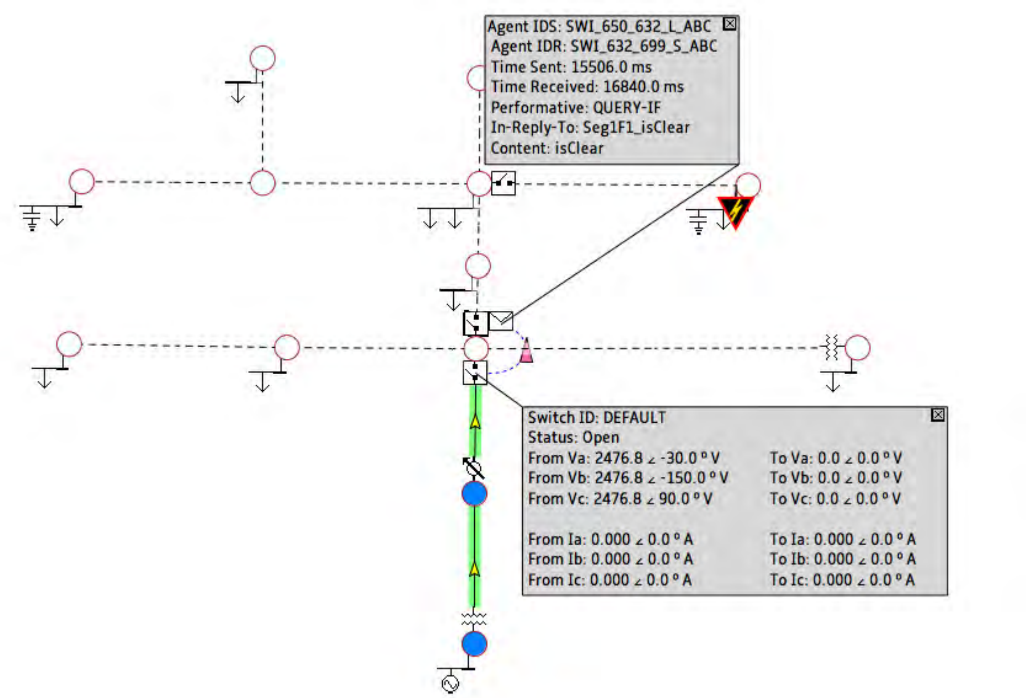


Figure 3: Java FX Display with Isolated Fault and Agent Messages at T=1.6840 s

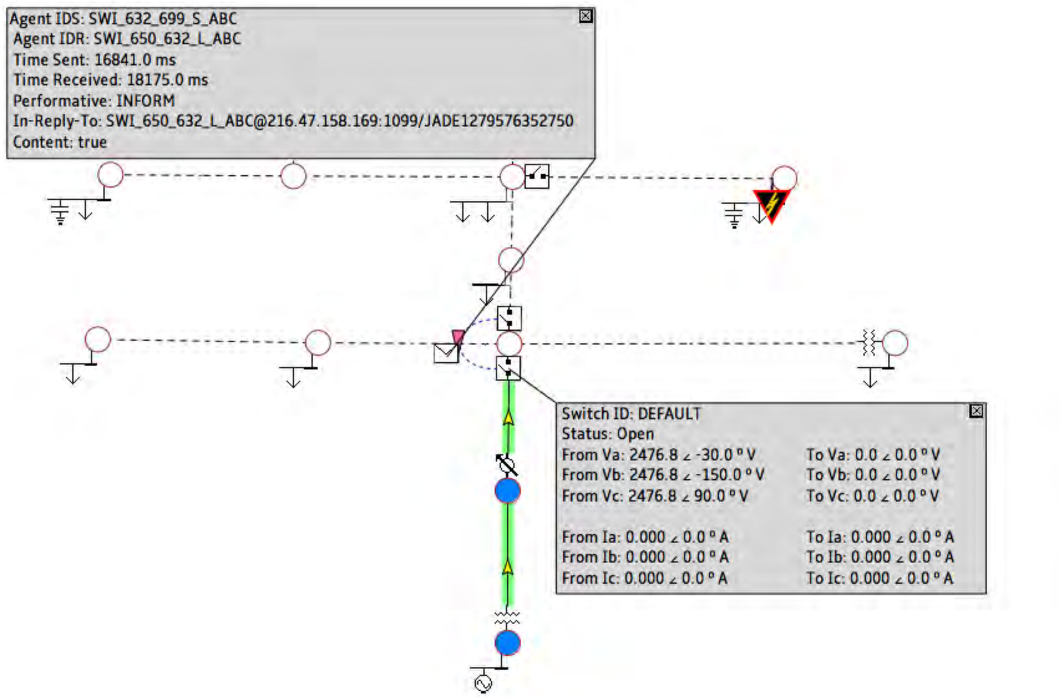


Figure 4: Java FX Display with Negotiating Agent Messages at T=1.7508 s

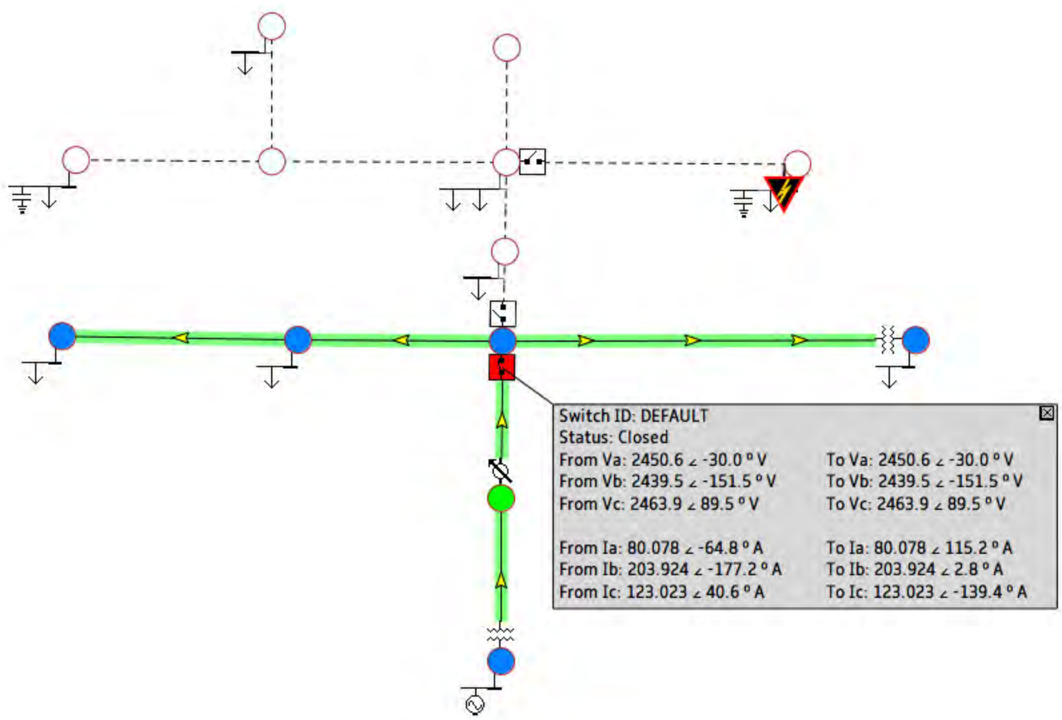


Figure 5: Java FX Display with Partially Restored Feeder at T=1.8178 s

The Java FX visualization platform has a timeline that allows an engineer to see when the various events occur. The timeline also enables the user to jump to a specific time step in the playback scenario. In addition, there are simple playback controls to step forward and backward through the scenario, as well as to jump to the beginning and end of the timeline.

2.2.1.6 Perfect Power Scale-Model Hardware Demonstration

During the summer of 2010, a team of IIT architects, commissioned by the Perfect Power project, constructed a detailed architectural scale-model of the Main Campus with approximately 50 IIT buildings including the North Substation, as shown in Figure 6. The main construction material is translucent acrylic, which provides a sophisticated level of realism to the layout. The scale model will be used as a teaching and outreach exhibit to help explain the intricacies of the Perfect Power System at IIT. To demonstrate the operation of the Perfect Power System, the team chose to build out Loop 3, which was the first smart grid loop installed at IIT. The Loop 3 closed-loop distribution circuit has been wired underneath the architectural model platform. Several low-power LEDs have been installed inside the Loop 3 scale-model buildings to serve as building load and to illuminate the buildings from the inside. When the buildings are energized by the Loop 3 feeder, the translucent acrylic glows brightly as if the buildings had all of their interior lights turned on. When the building feeders are de-energized, then the LEDs turn off and the buildings are dark.

Figure 6: Perfect Power Scale Model

The North Substation building has a 24 VAC single-phase distribution system fed by a 115/24 VAC transformer, which is plugged into a standard wall outlet. The 24 VAC distribution system mimics the actual 2400 VAC line-neutral distribution system on campus. Other than the factor of 100 difference in voltage, the scale-model has a single-phase distribution network, rather than the actual three-phase distribution system on campus. The total apparent power load on the scale-model of Loop 3 is approximately 6 volt-amperes. The substation load current is approximately 250 milli-amps (rms).

The goal of the Perfect Power scale-model hardware demonstration is to educate visitors about the benefits, as well as the necessary equipment, of the Perfect Power System. To understand the benefits, the team decided to implement two operating modes: traditional radial distribution system, and the Perfect Power System. A short-circuit fault switch has been included in the distribution scale-model, so that a fault can be placed on the system under the two different operating modes. The stark contrast in reliability is immediately appreciated by guests viewing the hardware demonstration.

The scale-model implementation of the smart switches in the North Substation (relay/breaker) and the S&C Electric Vista switchgear (relay/fault-interrupter) was accomplished with several Sun Microsystems SunSPOT microcontrollers. The SunSPOTs have a rechargeable battery, 4 input ADC ports that take 0-3 VAC peak, 4 output ports that supply up to 0.125 A DC each, and a wireless radio. The wireless communication is based on the IEEE 802.14.5 Standard, which is the same as the underlying standard for ZigBee. The radios are limited to a 10 meter separation, but in this case, they are less than a foot apart. The 2.4 GHz RF transmitter/receiver with digital direct sequence spread spectrum (DSSS) baseband modem has a 250 kbps bit rate. The breakers and fault-interrupters are implemented with standard industrial electro-mechanical relays with a 12 VDC activation coil.

Potential transformers have been used for monitoring the AC voltage waveforms. Instead of current transformers, the team has used Allegro hall-effect current sensors with a 5 Amp rating. Several op-amp circuits condition the raw voltage and current signals before being sampled by the SunSPOT microcontrollers. The sampling period is 2 ms. Signal processing functions (Discrete Fourier Transform) have been applied to the conditioned voltage and current waveform samples to obtain both magnitude and angle of the periodic voltage and current signals.

A basic PC has been connected to a SunSPOT basestation via USB port. The PC can deploy Java code to the SunSPOT microcontrollers via the wireless radios, but the PC is not involved in the real-time operation of the system. The fault switch creates a short circuit fault in combination with two 50 Watt power resistors. The fault current is roughly 4 Amps (rms). All of the wiring is attached to terminal strips mounted on the underside of the detailed scale-model of the Main Campus.

Two operating modes have been implemented via Java code: 1) traditional radial system with protection only in the substation, and 2) Perfect Power High-Reliability Distribution System (HRDS) with smart switches deployed throughout the Loop 3 closed-loop feeder. A Permissive Over-reaching Transfer Trip (POTT) scheme is implemented on the SunSPOT microcontrollers. In addition to the building interior LEDs, red-colored circuit indicator LEDs have been incorporated to aid understanding of the Perfect Power HRDS operation.

During a demonstration of the post-fault behavior of the distribution system under a fault scenario, the entire scenario occurs in real-time on physical hardware. There is no simulation. In the traditional radial system operating mode, the short-circuit fault is detected and isolated by the relay/breaker in the North Substation. All of the buildings on Loop 3 are blacked out, as the radial feeder is de-energized at the substation. In the Perfect Power System operating mode, the same exact fault is detected, located and isolated by two smart switches on either side of the fault. In this case, the SunSPOT microcontrollers detect the fault current and communicate with each other to figure out where the fault is located. Once a decision has been reached by the microcontrollers, the associated fault-interrupters are opened. However, only the faulted section of cable is de-energized, while the buildings all remain online, thereby dramatically improving system reliability.

2.2.2 Research Task 2 in Year 2

Research Task 2 – Buried Cable Fault Detection and Mitigation is led by Dr. Zuyi Li of Illinois Institute of Technology. Dr. Li's research group develops and demonstrates a fault detection and mitigation system with the following features: sensitivity, reliability, selectivity, and speed.

See **Appendix 2** for the additional information on IIT's distribution system that includes the open circuit and short circuit study results.

2.2.3 Research Task 3 in Year 2

Research Task 3 – Intelligent Perfect Power System Controller is led by Mr. Greg Rouse of Intelligent Power Solutions. Mr. Rouse's research group develops and demonstrates Intelligent Perfect Power System Controller (IPPSC) for the IIT campus.

- First Quarter Activities: Initiated the software architecture design
- Second Quarter Activities: Initiated the software program which includes the development of the following functions:
    - Designed basic user interface to be refined after review by IIT.
    - Developed user interface control methodology to decouple user interface processes from program core.
    - Tested Labview web server functions on basic user interface to make sure this function can be incorporated once the program is completed.
    - Developed software modules for handling config files which store the programs settings.
    - Developed software module for handling user security settings and levels.
    - Developed internet interfaces for retrieving weather forecasts, current weather conditions and wholesale market prices from various webservers on the internet.
    - Developed error handler for giving warnings and logging internal errors in the program.
    - Developed detailed requirements for IPPSC database functions.
    - Developed methodology and started coding database modules for storing and retrieving data for IPPSC databases.
    - Developed a timing module for coordinating activities within the program.
- Third Quarter Activities: Continued software programming activities.
    - Completed prototype version 0.1 which displays weather data and real time prices.
    - Developed process map for user interface design
    - Revised user interface layout
    - Added screens for setting up user defined and site specific settings
    - Added audit file function to log changes to program settings

- Added programming to manage long term historical database
- Developed data flow diagram to track what data is needed for what calculation
- Completed programming for carbon and electric rate calculations
- Added function to check that measured parameters are within their proper range before writing them to the database
- Streamlined some of the database management code to simpler and more flexible.
- Coded state machine to build ANN models and compare their predictions to baseline data and lookup tables.
- Developed code from producing state models for and estimate future loads, generator output, and generator fuel flow.
- Finished coding analytical part of Supervisor Agent including calculations short term database management, and conversion of data from short term database to storage in long term database.
    1. Completed short term database to long term database conversion software
    2. Completed generator and campus load modeling
    3. Completed make or buy decision making and dispatch scheduling based on real time prices.
- Contracted person to help out with inter agent communications and reporting modules.

- Fourth Quarter Activities
    - Finished coding first draft of software for Supervisor and Generator Agents
    - Currently testing and debugging both agents
    - Started on new user interface
    - Started researching requirements for Version 2

See **Appendix 3** for the IPPSC Communications Outline, the IPPSC Requirements Overview, and several screenshots of the current IPPSC.

2.2.4 Research Task 4 in Year 2

Research Task 4 – Advanced ZigBee Wireless is led by Dr. Chi Zhou of Illinois Institute of Technology. Dr. Zhou's research group develops and demonstrates advanced ZigBee wireless technology for a robust wireless communications network to be utilized by the Perfect Power system in controlling the building loads which participate in load reduction and energy savings programs.

2.2.4.1 Interference Detection and Mitigation

Base on the performance evaluation of Zigbee and WiFi coexistence, frequency agility is proposed by the team to mitigate interference. In order to minimal adjust existing IEEE 802.15.4 standard and reduce the usage of system resources, a PER-LQI based interference detection scheme in Zigbee network and a Classified Energy-Detection based interference avoidance scheme are proposed. The proposed algorithm is implemented on 2.4 GHz Meshnetics ZigBit development kit to evaluate the performance of ZigBee under the WiFi interference in real world.

In PER-LQI based interference detection scheme, regular packet transmissions are utilized to detect interference to minimize redundant procedure. End device record PER during a period which minimum number of packets transmitted is 20.When PER achieved 25% end device report it to router. Router checks the LQI (Link quality indicator) between router and end device, if the LQI smaller than 100 which map to PER 75%, we can consider the packet loss due to weak link quality rather than node out of power. In this case, router will do energy detection on current channel to ensure it is interference that causes the weak link quality. Once energy detection result RSSI exceeds threshold 35 which reflect noise level is between -65dBm to -51dBm, it means interference detected and router report it to coordinator. Then the coordinator calls corresponding interference avoidance scheme and initiates migration to a safe channel. Our proposed scheme emphasizes simplicity and efficiency, with low network overheads.

In order to reduce the detection time in our protocol, we propose the classified Energy Detection base divide all ZigBee channels into three classes based on offset frequency. Class 1 has highest priority and class 3 has the lowest priority. Upon receipt of an interference detection report, the coordinator sends an energy detection scan request to all routers in the PAN to check the status of channels from high priority to low priority till an available channel is found. Coordinator choose the best channel with weight of energy detection result from different router. Location and topology are two important factors relate to weight. In comparison to having all the devices in the PAN performing an energy detection scan, our algorithm minimizes the complexity of decision algorithm.

Upon completion of the energy detection scan, all routers in PAN commence an active scan on the proposed migration channel selected by the coordinator. They send out a Beacon Request to determine if any other ZigBee or 802.15.4 PAN’s are currently active in that channel within hearing range of the radio. If a PAN ID conflict is detected, the coordinator selects a new channel and unique PAN.

According to large amount of test, 138ms energy detection is an appropriate choice which can balance the time efficiency and accuracy. From the test result we can find 100% percent of best channel are in class 1 when the team scans all 16 channels. Basic interference avoidance algorithm is completed on 2.4 GHz Meshnetics ZigBit development kit. Energy consumption is calculated based on PER and battery life analysis.

The team continues the work on the implementation of frequency agility to mitigate interference for Zigbee networks. The team aims to adjust existing IEEE 802.15.4 standard at the minimum level as well as minimizing the network overhead. Some tune-up procedures have been implemented into the proposed PER-LQI based interference detection scheme and the Classified Energy-Detection based interference avoidance scheme. The proposed algorithm is implemented on 2.4 GHz Meshnetics ZigBit development kit to evaluate the performance of ZigBee under the WiFi interference in real world.

The team is examining the integration of Zigbee radio’s into Building management systems, with a view to facilitating room level power management. The objective is to achieve granular power control and measurements within buildings throughout the IIT campus. The team is examining the feasibility of using Zigbee enhanced Digitally Addressable Lighting Interface (DALI) equipped ballasts as a means of reducing energy usage on lighting, and facilitating remote monitoring and control of room lighting within Siegel Hall.

The team is working on the next phase of the Zigbee demo, the integration smart metering capabilities to the existing demonstration platform. The objective is to measure the power utilization by attached devices and use the measured data as inputs to the load control strategy. This goal is realized by the development of a smart power strip with current and voltage sensing circuitry. The strip also includes a microcontroller and Zigbee radio to enable the transmission of measured data back to the central system controller for display, logging and processing. The proposed system extends the demo to include the following Energy Management System (EMS) capabilities:

- Power measurement and display of:
    - Current
    - Voltage
    - Real and apparent power
    - Power consumption
- Load scheduling
- Remote control of electrical loads

2.2.4.2 Smart Plug System

The proposed perfect power system is able to monitor demand, allow users or operators to access the information directly, and control the load automatically or when needed. The monitoring and control devices are flexible in a way that they could be easily installed and removed whenever needed. Therefore, there is a need to design and develop plug-and-play devices.

The team designs a smart plug system, which enables plug-and-play monitoring and control. The prototype includes a remote controller and one power outlet (called Smart Plug) that integrates current sensor, relay, and wireless Zigbee radio. The team designs and deploys a network with multiple smart plugs. The remote controller is capable of a two-way communication with the smart plug through wireless Zigbee link. Instead of plugging directly to the wall outlet, the load is plugged to the smart plug, which is plugged into the wall outlet, shown Figure 7. The current and power consumption of the load can be monitored by the sensor in the smart plug and then collected to the controller via the wireless link. Basic ON/OFF power switch function can be remotely instructed by the remote controller to control the load.

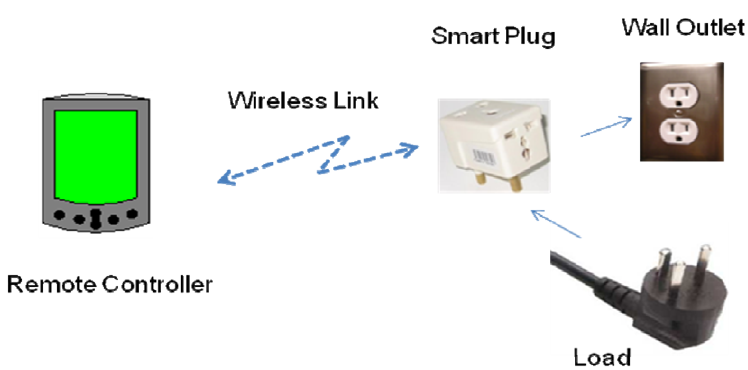


Figure 7: Smart Plug System

Remote controller prototype: A 16x2 LCD screen, an ATMega328P microcontroller, a XBee module and their peripheral circuits constitute the remote controller. Users can send commands to power outlet terminals remotely by selecting menu items displayed on LCD screen. The current and power consumption information of the load, which is read by remote terminals, can be shown on LCD if needed.

Smart Plug prototype: The power outlet integrates a XBee module, a solid-state relay, a current sensor and an ATMega168 microcontroller. It will receive command sent from controller and perform corresponding actions such as turning power supply ON/OFF, transmitting the current data back to remote controller, etc.

Building automation system based on Zigbee wireless is only one of a variety of systems that make up the smart grid. Due to the multiplicity of networks and protocols within the Smart Grid, interoperability is a key issue. The availability of an interoperability framework is essential to end to end communication across and within smart grid domains, so a significant amount of work is being invested in interoperability frameworks for the Smart Grid.

The usage of IP within wireless sensor networks facilitates easy interconnectivity with existing networks, enables the re-use of existing TCP/IP protocols, tools and programming paradigms and permits the usage of IP friendly protocols such as BACnet and Modbus over WSN nodes. These goals sparked research into the use of IPv6 over WSN's, as the ability to connect even tiny wireless sensor nodes to the internet would facilitate ubiquitous computing in the home and throughout the smart grid.

The team surveyed the related work in the utilization of IPv6 for wireless sensor networks interconnectivity, especially the 6LoWPAN protocol and CAP. The team adopts the protocols to enable Zigbee Application profile usage over any IP network. The team works on the framework design and then implements it in the testbed.

In ZigBee networks, sensor nodes are often powered by batteries with limited energy. It is difficult, if not impossible, to replace or recharge the batteries in many practical scenarios. As a result, improving energy efficiency is of great importance for the design of ZigBee networks.

Considering the features of ZigBee messages for smart grid application, most messages are control signal and real-time sensor data, so reliable and timely data delivery are the primary challenges for Zigbee networks in smart grid environments. The team has solved the reliability issue by using interference avoidance scheme. How to balance the power and delay is the challenge.

When the channel is bad, ZigBee consumes more power to send the data. Therefore, the node can choose to give up the transmission opportunity and wait a better channel to send the message with lower transmission power. But a long waiting time may lead to large delay and affect Quality of Service (QoS). Thus the team would formulate this problem for balancing power and delay. The team applies the theory of optimal stopping, which is an effective optimization tool to help find the tradeoff between the power and delay. The problem is formulated as an optimization problem for maximizing an expected reward or minimizing an expected cost subject to a set of constraints.

For the demonstration, the team is working on the single Zigbee node performance evaluation with multiple WLAN access points present and on the Zigbee network performance.

2.2.4.3 Intelligent Energy Management

Intelligent energy management (IEM) plays a key role in saving energy for future smart grid systems. For a system with multiple utilities which have different power consumption and real-time requirements, the scheduling problem is quite challenging. In this work, the team proposes a novel distributed opportunistic scheduling scheme based on the optimal stopping rule approach. The objective is to minimize the total energy consumption while satisfying the power and timing requirements of each utility. The team shows that the optimal scheduling schedule is a pure threshold policy, i.e., each utility need to be turned on when the electric price is lower than a certain value; otherwise, remains idle. The experimental results show that the proposed low-complexity distributed scheduling scheme can dramatically reduce the energy usage. The results can also be implemented to the problem of maximizing profit with a fixed amount of energy, which is, in fact, the dual of the energy minimization problem.

About 30% of the electricity generated in the US is consumed by buildings, so any energy savings achieved will have significant impact on national energy usage. Lighting systems account for a major energy consumption in buildings, constituting between 30 to 40% of all electricity usage. Intelligent buildings are characterized by two objectives – minimizing the total energy usage and improving the occupancy comfort. Unfortunately, the attainment of such goals was hampered by high costs and the complexity of retrofitting existing lighting systems, lack of granular control offered by fixed wiring for lighting systems, and difficulty in accurate workspace lighting measurements. The integration of wireless sensor and actuator networks (WSAN's) into lighting control systems promises to overcome these issues and provide additional functionality. The team is conducting a survey of the use of WSAN's for intelligent lighting control applications, providing a holistic overview of the various sensing, actuation and decision-making schemes utilized for WSAN-based intelligence lighting control. The team also examines the challenges faced by WSAN-based lighting and highlight the open areas and future research directions. The survey is to be submitted for a journal publication.

3 Educational Activities and Outreach

3.1 Mini Symposium

A mini symposium on Smart Grid: Perfect Power Implementation, Education, and Research at IIT is planned on October 1, 2010. This is part of the 2010 Midwest Regional Conference of the American Institute of Chemical Engineers (AICHE).

Perfect Power Implementation, Education, and Research at IIT

Friday, October 1, 2010: 9:30 AM
Trustee Room (Illinois Institute of Technology)

Description:
The Perfect Power project has several goals in three categories: technical, financial and leadership. The technical goals include the demonstration of the key capabilities of Perfect Power with respect to reliability, demand response load reduction, energy efficiency load reduction and integration of renewable sources. The financial goals include the deferral of major capital costs, the reduction of energy and outage costs, as well as the influx of ancillary services' revenues. The leadership goals include the reduction of the university's carbon footprint, the creation of a living laboratory and the opportunity to lead Smart Grid development through the Perfect Power project.

Chair:
Mohammed Shahidehpour

9:30 AM
Perfect Power Implementation at Illinois Institute of Technology
Joseph Clair

10:00 AM
Autonomous Agents for Advanced Distribution Automation In Perfect Power Systems
Alex Flueck

10:30 AM
Update on IIT Microgrid Master Controller
Greg Rouse
11:00 AM
Application of Zigbee Wireless In Smart Grid
Chi Zhou

11:30 AM
Illinois Institute of Technology Smart Grid Education and Workforce Training Center
Melissa Gordon

3.2 New Course on Smart Grid

A new graduate level course was offered by Dr. Mohammad Shahidehpour in the Fall 2010 semester: ECE581 Elements of Smart Grid. This course covers cross-disciplinary subjects on smart grid that relates to energy generation, transmission, distribution, and delivery as well as theories, technologies, design, policies, and implementation of smart grid. Topics include: smart sensing, communication, and control in energy systems; advanced metering infrastructure; energy management in buildings and home automation; smart grid applications to plug-in vehicles and low-carbon transportation alternatives; cyber and physical security systems; microgrids and distributed energy resources; demand response and real-time pricing; and intelligent and outage management systems.

Outline

- Smart Grid Definition (5 presentations)
- Microgrids (3 presentations)
- Distributed and Renewable Generation (2 presentations)
- Building Energy Management System (6 presentations)
- Communication / AMI / Security (6 presentations)
- Smart Transmission System (5 presentations)
- PHEV and Electric Storage (5 presentations)
- Conclusions and Future of Smart Grid (1 presentations)

4 Project Budget and Schedule

Budget/Cost share update report is provided in **Appendix 4** by the Project Accounting Office at IIT. The report summarizes the expenditure and the cost share provided in Year 2.

5 Project Concerns and Challenges

5.1 Concerns with Demonstration Tasks

Summer work stoppage due to union strike put us behind schedule, but all tasks are moving forward now.

Pursuing Perfect Power at IIT remains a university priority, and has already begun to shape the way we approach managing energy resources in pursuit of our education missions. As IIT meets the challenge of the Campus Sustainability Vision, to "become the most sustainable urban university in the United States", making swift, permanent reductions in energy resource use will serve as a centerpiece of that challenge. As the prototype perfect power project moved from a concept to reality, cost overruns in equipment and installation have increased the price of the project by seventy-five percent, reducing the amount of implementation work that IIT can complete for the available DOE funding. Despite the cost overrun, IIT has already met some of the milestones and will meet all the remaining milestones, listed in the DOE proposal, by the end of the project period.

In order to meet the stated goals of the demonstration project, and to maintain the benefits associated with having a smart-grid on campus, in Year 2 IIT proposed to reduce the size of the campus to be covered with the high-reliability distribution system (HRDS). Within that reduced area, IIT will implement fully the project directives. The Year 1 of the project included automation of the North Substation and the installation of the first HRDS loop (Loop 3) including service to IIT's Hermann Hall, Perlstein Hall, Alumni Hall, Wishnick Hall and Siegel Hall. Siegel Hall houses the university's Department of Electrical and Computer Engineering (ECE) and will remain a demonstration facility for advanced building control integration. The revised scope will complete the Loops 1 and 2 that serve the far north end of campus, including Stuart Hall which houses our Office of Technology Services main data center, and the loop that serves the north half of the housing side of campus which includes the hallmark McCormick Tribune Campus Center. In this way, IIT will have all four campus functions covered within the installed loops: academic, housing, research, and student support. This coverage will allow for full understanding of the benefits of Perfect Power, and will serve to demonstrate its application to the campus environment. Additionally, IIT will upgrade and automate the south substation so that all of the incoming electrical service and over ninety percent of existing on-site generation will be under control of the Integrated Perfect Power System Controller (IPPSC).

Specifically addressing the goals as stated in the grant proposal, they are affected as follows:

- The achievement of system-wide Perfect Power and demonstration of its technological viability (through the implementation of distributed energy and advanced sensing, switching, feeder configuration and controls, IIT's electric power conditions will always meet or exceed each end user's requirements); **Goal remains, but now applies only to the north half of campus and the south substation**.
- 50% peak on-demand reduction capability when called upon by Exelon/PJM; **Goal achieved**
- 20% permanent peak demand reduction from the 2007 annual peak demand; **Goal remains**
- Deferral of ComEd planned substation upgrades due to the demand reduction achieved; **Goal remains**
- Demonstration of the economic value of Perfect Power, specifically the avoidance of outage costs and the introduction of significant savings and revenue from providing ancillary services; **Goal remains**
- A design that can be replicated to any microgrid; **Goal remains**
- Promote the Perfect Power prototype via the Galvin Electricity Initiative, Vanguard Communications (hired by GEI to promote the Initiative and IIT prototype), the website (www.galvinpower.org) and key partners. **Goal remains**

Pursuing a research project by definition means that those involved enter the realm of the unknown. For the Perfect Power at IIT demonstration project, this unknown resulted in almost six million dollars in cost overruns that cannot be absorbed by the university without abandoning other mission-critical objectives. Within this constraint, the university will provide the full cost share as stated in the grant proposal, remains committed to the goals stated in the grant proposal, and looks forward to working with DOE as the project moves forward.

5.2 Concerns with Research Tasks

There are no concerns with research tasks that need to be reported.

5.3 Updated Milestones

The following table shows the updated milestone log.

Phase/Task	Milestone	Planned Completion Date	Current Status
Phase I – Perfect Power Foundation	Milestone P1: Completion of Perfect Power Design	April 30, 2010	Completed
Phase II – Multi-year Research Phase			
Task 1.0 – Advanced Distribution Automation and Recovery System	Milestone P211: Completion of dNetSim Communication Model	September 30, 2009	Completed
	Milestone P212: Completion of dNetSim Visualization Platform	September 29, 2010	Completed
	Milestone P213: Autonomous Agent Infrastructure for Real Time Control	September 29, 2011	On schedule
	Milestone P214: Autonomous Agent Infrastructure for Centralized and Distributed Control	September 27, 2012	On schedule
	Milestone P215: Pilot Demonstration of Autonomous Agent Infrastructure	September 27, 2013	On schedule
Task 2.0 – Buried Cable Fault Detection and Mitigation	Milestone P221: Completion of the Simulation on IIT's Distribution Network	April 1, 2010	Completed
	Milestone P222: Identification of the Best FDM for IIT's Distribution Network	September 29, 2011	On schedule
	Milestone P223: Pilot Demonstration of FDM in IIT's Distribution Network	September 27, 2013	On schedule
Task 3.0 – Intelligent Perfect Power System Controller	Milestone 231a: Completion of IPPSC Version 1 Software Specification	July 15, 2009	Completed
	Milestone 231b: Completion of IPPSC Version 1 Software	December 31, 2009	Delayed

Phase/Task	**Milestone**	**Planned Completion Date**	**Current Status**
	Milestone 231c: Completion of IPPSC Version 1 Bench Testing	April 30, 2010	Delayed
	Milestone 232a: Completion of IPPSC Version 2 Software Specification	March 5, 2010	Delayed
	Milestone 232b: Completion of IPPSC Version 2 Software	July 21, 2010	Delayed
	Milestone 232c: Completion of IPPSC Version 2 Bench Testing	November 24, 2010	To be delayed
	Milestone 233a: Completion of IPPSC Version 3 Software Specification	March 4, 2011	To be delayed
	Milestone 233b: Completion of IPPSC Version 3 Software	July 11, 2011	To be delayed
	Milestone 233c: Completion of IPPSC Version 3 Bench Testing	November 15, 2011	To be delayed
Task 4.0 – Advanced ZigBee Wireless	Milestone P241: Completion of the Design and Development of Interference Avoidance Techniques	September 30, 2009	Completed
	Milestone P242: Completion of the Design and Development of Self-forming and Self-healing Cluster-tree ZigBee systems	September 29, 2010	Completed
	Milestone P243: Completion of the Design and Development of MAC Layer Protocol to Achieve Energy-efficient Access for Cluster-tree Networks	September 29, 2011	On schedule
	Milestone P244: Completion of ZigBee Installation Plan and Energy Efficient Routing Algorithm	September 27, 2012	On schedule
	Milestone P245: Pilot Demonstration of ZigBee Wireless Technology for Implementing Energy Efficiency Programs	September 27, 2013	On schedule
Phase III – Ancillary Service	Milestone P31: IPPSC V1 Installed	February 18, 2011	On schedule

Phase/Task	**Milestone**	**Planned Completion Date**	**Current Status**
Demonstration	Milestone P32: Engine Start to Full Load within 10 Minutes	August 2, 2009	Completed
Phase IV – Distribution System Automation Demonstration	Milestone P41: HRDS Installed	January 19, 2013	On schedule, but now applies only to the north half of campus and the south substation
	Milestone P42: Substation Automation Compatible to HRDS	January 19, 2011	On schedule
	Milestone P43: IPPSC V2 Installed	August 3, 2011	On schedule
Phase V – Distribution Level Peak Load Reduction Demonstration	Milestone P51: Load Reduction Controller Installed	April 5, 2012	On schedule
	Milestone P52: IPPSC V3 Installed	December 27, 2012	On schedule
	Milestone P53: Solar PV Installed	December 20, 2011	On schedule
	Milestone P54: UPS Installed at Critical Buildings	December 21, 2011	On schedule
Overall Project	Milestone PRO: 50% Peak Load Reduction Capability	September 27, 2013	On schedule

6 Technology Transfer

6.1 Media Reports

Appendix 5 lists all the Websites and Media Reports.

- The cover story of the Energy Today (Winter 2010 Issue) featured IIT's Perfect Power System. See more details in the appendix.
- Press Release: Perfect Power at IIT Celebrates Phase I Completion of Five Year Project. http://www.iit.edu/departments/pr/mediaroom/article_viewer_db.php?articleID=409. See more details in the appendix.
- A GreenTech Media story on Wednesday discussing smart grid technology mentions that IIT has recently completed phase one of its Perfect Power project. http://www.greentechmedia.com/articles/read/smart-grid-tuesday-gainspan-gets-new-ceo-hara-lines-up-safeway-as-customer/. See more details in the appendix.
- A Smart Meters story on Thursday also discusses the completion of phase one of Perfect Power at IIT. http://www.smartmeters.com/the-news/821-new-power-system-completes-first-phase.html. See more details in the appendix.
- The article, "Microgrids: Utility vs. Private Ownership," discusses the rise of microgrids and highlights Perfect Power at IIT as an example of "the evolving relationship between utilities and their customers," on earth2tech. http://earth2tech.com/2010/02/24/microgrids-utility-vs-private-ownership/. See more details in the appendix.
- An Electric Light and Power article on Tuesday explains that the first phase of Perfect Power at IIT has recently been completed. http://www.elp.com/index/display/article-display/5283797320/articles/electric-light-power/smart-grid/2010/02/Smart_grid__Perfect_Power_at_IIT_completes_phase_I_construction.html. See more details in the appendix.
- An *EE Times* article on April 8, 2010, discussing the recent announcement that the U.S. Department of Energy has awarded a total of nearly $100 million in grants to train workers in smart grid technologies, explains that IIT, a grant recipient, will establish a Smart Grid Education and Workforce Training Center. The article also discusses Perfect Power at IIT. See more details in the appendix.
- A YouTube video on Perfect Power Virtual Tour is available at http://iit.edu/perfect_power/virtual_tour.shtml. See more details in the appendix.
- The Midwest Construction websites features "Perfect Power System Proves Worth" on June 1, 2010. http://midwest.construction.com/features/2010/0601_PerfectPower-1.asp. See more details in the appendix.
- A mini symposium on Smart Grid: Perfect Power Implementation, Education, and Research at IIT is planned on October 1, 2010. This is part of the 2010 Midwest Regional Conference of the American Institute of Chemical Engineers (AICHE). http://aiche.confex.com/aiche/mrc10/webprogram/Session15025.html. See more details in the appendix.

6.2 Presentations and Publicity Activities

Appendix 6 lists all the Networking Activities.

- Dr. Mohammad Shahidehpour attended 2009 Chicago Midwest Regional AIChE Conference October 5th, 2009 and made a presentation titled "Smart Grid: A New Paradigm of Power Delivery." See the appendix for the abstract of the presentation.
- Dr. Mohammad Shahidehpour made a presentation titled "Islanding of a microgrids" in National Seoul University, South Korea (October 2009)
- Dr. Mohammad Shahidehpour made a presentation titled "Campus microgrids" in University of Bologna, Italy (September 2009)
- Dr. Mohammad Shahidehpour was the Technical Program Chair of the first Conference on Innovative Smart Grid Technologies (ISGT), sponsored by the IEEE Power & Energy Society (PES) and hosted by the by the National Institute of Standards and Technology (NIST, January 2010, Washington, DC.
- Dr. Mohammad Shahidehpour gave a presentation on February 18, 2010 regarding IIT Perfect Power project at the C2ST (Chicago Council on Science and Technology) "Storing Alternative Energy" Program. See more details in the appendix.
- Dr. Mohammad Shahidehpour gave a presentation on April 6, 2010 regarding IIT Perfect Power project at the Spring 2010 DCEO (Illinois Department of Commerce & Economic Opportunity) Peer Exchange.
- Dr. Mohammad Shahidehpour gave a presentation on April 26, 2010 at the CEESI (Clean Energy & Environmental Sustainability Initiative) Colloquium, Boston University. The presentation is titled "Restructured Electric Power Systems – What is the Impact of the Microgrids?" See the appendix for the brochure.
- Dr. Mohammad Shahidehpour gave a presentation at the SBSE2010 - Simpósio Brasileiro de Sistemas Elétricos, Belém, State of Para, Brazil, May 18-21, 2010. The presentation is titled "Smart Grid: A New Paradigm for Power Delivery?" See the appendix for the brochure.
- Dr. Mohammad Shahidehpour was a Keynote Speaker on microgrid reliability in the 2010 ICEE, Isfahan University of Technology, May 2010, Iran.
- Dr. Mohammad Shahidehpour made a presentation titled "Microgrid Development and Operation" in Sharif University of Technology, May 2010, Iran
- Dr. Mohammad Shahidehpour gave a presentation on May 21, 2010 at the 41st Energy Information Dissemination Program at the Oklahoma State University.
- Dr. Mohammad Shahidehpour gave a presentation on June 3, 2010 at the Technical Conference on Unit Commitment Software, hosted by The Office of Energy Policy and Innovation, Federal Energy Regulatory Commission. The presentation is titled "Stochastic Security-Constrained Unit Commitment in a Volatile Environment." See the appendix for the brochure.
- Dr. Mohammad Shahidehpour was the keynote speaker at the 11th International Conference on Probabilistic Methods Applied to Power Systems (PMAPS2010) in Singapore, Grand Copthorne Waterfront Hotel, 14 – 17th June 2010. The presentation is titled "Reliability of Restructured Electric Power Systems: What is the Impact of Smart Grid?" See the appendix for the brochure.

- Dr. Mohammad Shahidehpour made a presentation titled "Role of Smart Microgrid in a Perfect Power System" during the IEEE Power and Energy Society General Meeting 2010, held in July 2010 in Minneapolis, Minnesota.
- Dr. Mohammad Shahidehpour and Mr. John Kelly met with KC Poulos and Jordan Cutler of the Village of Oak Park, and Chris Thomas of Citizen's Utility Board at IIT on August 13, 2010 discussing the possibility of implementing Perfect Power in the Village of Oak Park, Illinois.
- John Stremel, Chief Technology Officer and Vice President, Jay Crookston, Vice President of Sales, and Terry Schuster, Regional Sales Director of EnergyConnect Inc. made a presentation during the September 10, 2010 Perfect Power monthly meeting at IIT. They introduced and discussed the demand response program.
- Dr. Mohammad Shahidehpour made a presentation titled "Perfect Power Project" during the *2010 EEI Conference*, held on October 4, 2010 in Denver, Colorado.
- Dr. Mohammad Shahidehpour made a presentation titled "Restructured Electric Power Systems – What is the Impact of Smart Grid?" during the *2010 Nebraska Research & Engineering Conference: Renewable Energy: Building a Sustainable Future for Nebraska*, held on October 5, 2010 in Lincoln, Nebraska.
- Dr. Mohammad Shahidehpour was the Keynote Speaker ("Innovative Solutions for the Smart Electric Power System") of the first Conference on Innovative Smart Grid Technologies (ISGT) Europe, sponsored by the IEEE Power & Energy Society (PES) and hosted by Chalmers University of Technology, October 11-13, 2010, Gothenburg, Sweden.
- Dr. Mohammad Shahidehpour was a Keynote Speaker on "Applications of Microgrids to the Grid Security" at the IEEE@IIT event organized by the IEEE Chicago Section, October 1, 2010.

6.3 Research and Technical Publications

Appendix 7 lists all the Publications.

- Dr. Chi Zhou published two papers on the 2010 Conference on Innovative Smart Grid Technologies, sponsored by the IEEE Power & Energy Society (PES), hosted by the National Institute of Standards and Technology (NIST), and technically co-sponsored by the IEEE Communications Society (ComSoc), the IEEE Computer Society, the IEEE Power Electronic Society (PELS), the IEEE Signal Processing Society (SPS) and IEEE-USA , and held January 19-21, 2010 in Gaithersburg, Maryland.
    - Peizhong Yi, Abiodun Iwayemi and Chi Zhou, "Frequency Agility in a ZigBee Network for Smart Grid Application." See a copy of this paper in the appendix.
    - Abiodun Iwayemi, Peizhong Yi, Peng Liu, Student Member, and Chi Zhou, "A Perfect Power Demonstration System." See a copy of this paper in the appendix.
- Dr. Zuyi Li published one paper on the IEEE Transactions on Smart Grid.
    - Yanling Yuan, Zuyi Li, and Kui Ren, "Modeling Load Redistribution Attacks in Power System," To Appear, IEEE Transactions on Smart Grid. See a copy of this article in the appendix.
- Dr. Alex Flueck published an article "Perfect Power at Illinois Institute of Technology" in the July 2010 issue of *Powergrid International Magazine*. See a copy of this article in the appendix. An

online version is available at http://www.elp.com/index/display/article-display/3834456319/articles/utility-automation-engineering-td/volume-15/Issue_7/Features/Perfect_Power_at_Illinois_Institute_of_Technology.html.

7 Summary and Additional Information

7.1 Benefits of Completion of IIT Microgrid

- Demonstration of distributed renewable generation integration with community storage solutions.
- Demonstration of community microgrid by incorporating commercial, industrial and residential buildings into the microgrid, extending the microgrid beyond the original academic facilities.
- Demonstration of day-time / peak plug-in electric vehicle charging from renewable sources and storage.
- Demonstration of large-scale load-shifting and utility load-shedding.
- Demonstration of distributed storage to improve reliability.

7.2 IIT Investments in Microgrid Beyond Scope of Original Grant

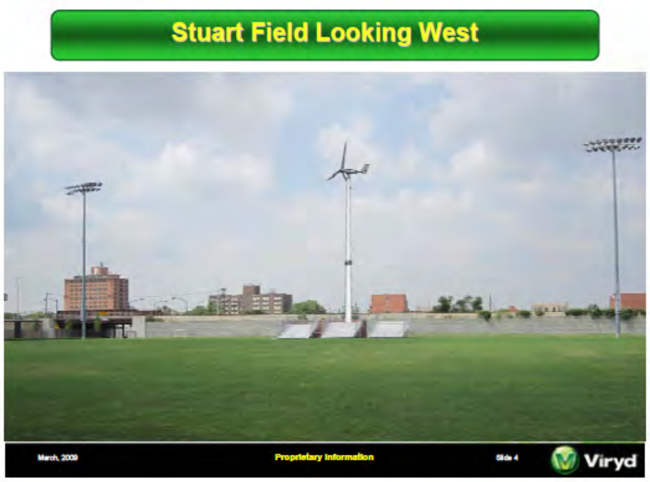
- $1.3 million is being invested by IIT to install AMI in all campus buildings to create real-time metering of consumption, provide near-instantaneous feedback for demand response, and create a tool to engage the community in energy reduction.
- $300,000 is being invested by IIT for lighting retrofits to increase efficiency, implement energy efficiency across sources and end users (lighting upgrades, motor replacement, system balancing, etc.)
- $705,000 is being invested to initiate a PMU deployment research project on the microgrid.
- $40,000 is being invested by IIT to install a Siemens Building Energy Management System demonstration.
- $1,000,000 was invested by IIT to upgrade the onsite gas-fired clean generation plant for "quick start" capability to allow for microgrid islanding and minimized downtime in the event of service disruption on the utility feeder.

7.3 Complementary Projects:

- **SMART GRID WORKFORCE EDUCATION & TRAINING CENTER** – In 2010, the Center initiated a $12.6 million project, supported by the Department of Energy ($5 million) and the State of Illinois ($2.5 million), to educate and train the nation's workforce to meet the global challenges and opportunities of the smart grid. As part of the project, a 16,000 sq.ft. Smart Grid Training Center and Demonstration Center is being built in the University Technology Park at IIT.
- **ILLINOIS SMART GRID REGIONAL INNOVATION CLUSTER** – IIT is leading the development of an innovation platform for Smart Grid technology that recently was awarded $600,000 from the

Small Business Administration. The Cluster will provide technical and business support to speed new Smart Grid technologies on the path to commercialization. Ten start-up companies have just joined the Cluster, are located in the University Technology Park at IIT, and will prototype and demonstrate their technology on the microgrid.

- **IIT WIND CONSORTIUM** – In 2010, the Center was awarded an $8 million grant from the U.S. Department of Energy to establish a University-Industry Consortium for Wind Energy Research, Education, and Workforce Development. The Center was also awarded $750,000 from DOE to study wind integration into the grid. As part of the project, $100,000 is being invested by the U.S. Department of Energy to install an 8kW Wind Turbine demonstration on Loop 2 as part of the IIT Wind Consortium project.



Appendix 1

Celebration of a Milestone at Illinois Institute of Technology

Completion of the First Phase of the Perfect Power Project

Friday, February 12
Siegel Hall Lobby
IIT

3301 South Dearborn Street
Chicago, IL 60616

Morning Agenda

10:00	Welcome Remarks	Alan Cramb (IIT)
10:05	Introduction	Mohammad Shahidehpour and Zuyi Li (IIT)
10:10	DOE Project at IIT	Steve Waslo (US DOE)
10:15	Perfect Power Initiative	Bob Galvin and Kurt Yeager (GEI)
10:20	Smart Grid at ComEd	Terry Donnelley and Fidel Marquez (ComEd)
10:25	HRDS Design for IIT	Tom Tobin (S&C Electric)
10:32	Reliability of Perfect Power Systems	Alex Flueck (IIT)
10:40	Control System for Perfect Power	John Kelly and Greg Rouse (Intelligent Power Solutions)
10:47	Perfect Power Demonstration	Chi Zhou and Abiodun Iwayemi (IIT)
10:55	Perfect Power Implementation	Joseph Clair (IIT)
11:05	Virtual Campus Tour	Amy Henson and Alex Flueck (IIT)
11:10	Smart Grid Initiative at IEEE	Mohammad Shahidehpour (IIT)
11:18	Q&A Session	Mohammad Shahidehpour and Joseph Clair (IIT)
11:30	Tour of Loop 3 Installation	Joseph Clair and John Collins (IIT)

Perfect Power at IIT will result in a power system that will not fail the end user. The system consists of smart microgrids featuring a loop design and redundant electricity. It will allow IIT to eliminate costly outages, minimize power disturbances, moderate an ever-growing demand, and curb greenhouse gas emissions. Phase one of the system is complete, in which the first HRDS loop was constructed and became operational.

Perfect Power Prototype for Illinois Institute of Technology

Mohammad Shahidehpour, PhD

Principal Investigator

Project Overview

- Funded by the U.S. Department of Energy
- $12M ($7M from DOE, $5M Cost Share)
- 5 year project
- Located at Illinois Institute of Technology (IIT)
- Involves the entire campus
- Partners: IIT, Exelon, S&C, Schweitzer, Endurant

Project Uniqueness

- IIT is essentially a town in an urban setting
  - 120 Acres with public roads, streetlights, and public transportation
  - Owns its electric infrastructure with an 8MW gas turbine plant
  - 600 Residential units
  - 80 Commercial Tenants
  - Public buildings: admin/office spaces, auditorium spaces, Campus Centers ("Town Halls"), Libraries, Laboratory spaces

Vision for Perfect Power

"The perfect power system will ensure absolute and universal availability of energy in the quantity and quality necessary to meet every consumer's needs. It is a system that never fails the consumer."

Bob Galvin

Project Objectives

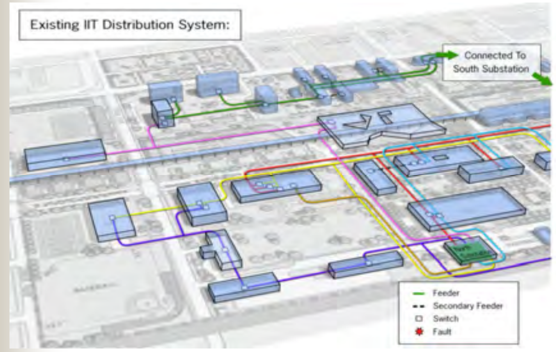
- 50% peak demand reduction
- 20% permanent demand reduction
- Demonstrate the value of Perfect Power
  - Cost avoidance and savings in outage costs
  - Deferral of planned substations
- New products and commercialization
- Replicable to larger cities
- Promotion of energy efficiency and cleaner cities

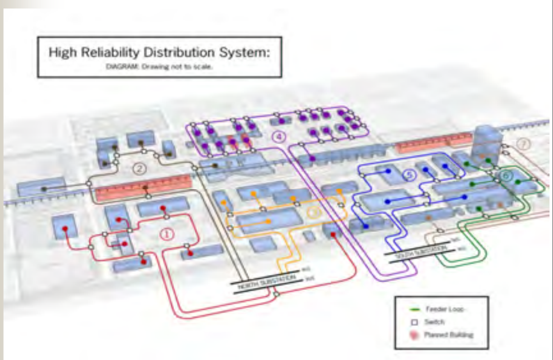
Project Challenges

- At least three power outages per year
  - Costs = up to $500,000 annually in restoration costs, lost productivity and ruined experiments
- Electricity costs were doubled within the last decade
- Addition of two new resident halls require more power
- Campus electricity infrastructure would need to be upgraded
- Electricity demand is growing with increased student population
- Installation of additional building equipment adds to energy use
- Renegotiating electricity contract will allow real-time pricing

Proposed Solutions

- Self-sustaining infrastructure
- Intelligent distribution system
- On-site electricity production
- Demand response capability (A/C, lighting, major loads)
- Intelligent perfect power system controller
- Sustainable energy systems and green buildings
- Technology ready infrastructure



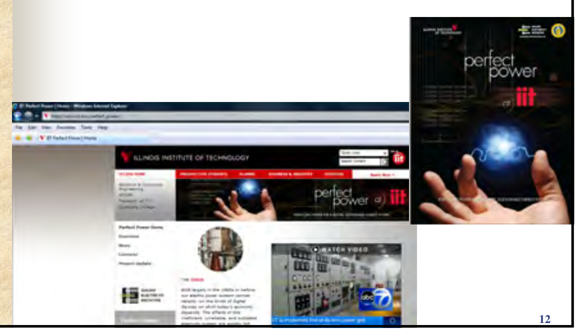


Project Tasks

- Phase I is to establish the basis for Perfect Power
- Phase II is to address key technology gaps
  - Task 1.0 – Advanced Distribution Automation and Recovery System
  - Task 2.0 – Buried Cable Fault Detection and Mitigation
  - Task 3.0 – Intelligent Perfect Power System Controller
  - Task 4.0 – Advanced ZigBee-Based Wireless
- Phase III is to prepare IIT for real time pricing and ancillary markets
- Phase IV is to deploy the advanced campus distribution system
- Phase V is to deploy campus distribution level peak load reduction

Project Updates

- Completed the conceptual design for year one
- Initiated manufacturing of switchgear for High Reliability Distribution System
- Completed the cost estimating of installation projects
- Began underground location work and site coordination for the project installations
- Established autonomous agent-based perfect power controls and unbalanced three-phase distribution system simulator
- Designed the IPPSC for campus energy and control system
- Completed the design of ZigBee sensor controls and wireless communications for the building automation



A Smart Grid Future

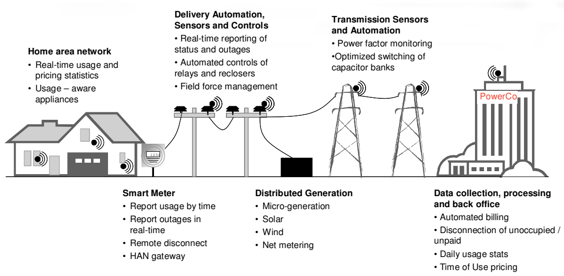
February 12, 2010

What is Smart Grid – The Customer Perspective

Enhancing customer value with cost-effective technological advancements that empower customers in ways that lead to:

- More efficient utilization of electricity
- Reductions in future demand growth
- Improvements in the environment
- A more reliable and secure system

Smart Grid – Future Model ComEd's Perspective



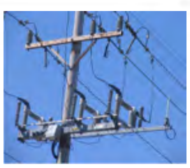
Smart Grid will deliver enhanced reliability and create new opportunity for customer control of energy usage and spend

Present Industry Challenges

- ✓ Changes in Technology - Smart Grid
  - Distribution Automation (DA)
  - Automated Metering Information (AMI)
  - Distributed Generation (DG)
  - Plug-in-Hybrid Vehicles (PHEV)
- ✓ Environmental Focus
  - Carbon Reduction
  - Sustainable Energy
- ✓ Stakeholder Expectations
  - Customers – Reliability, Transactional
  - Regulatory – Rate Recovery
  - Shareholders – ROE
- ✓ Aging Infrastructure
- ✓ Economic Downturn
  - Impact on revenues

ComEd – A Future Perspective

- ✓ The distribution grid will become more intelligent;
  - The electric distribution grid will be self-diagnosing and self-healing
  - The emerging technologies will impact all aspects of the distribution value chain
- ✓ We will have to manage a more complex future distribution system
  - The mix of people and skills will change
  - Customers will demand more from the utility
- ✓ The focus will be on customer choice, affordability, reliability and power quality



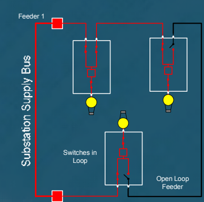
Questions / Comments?

High-Reliability Distribution System (HRDS)

Illinois Institute of Technology
February 12, 2010
Thomas J. Tobin

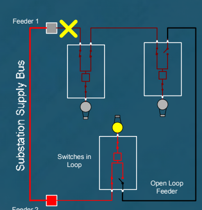
 www.sandc.com

Open-Loop – Manual Switching



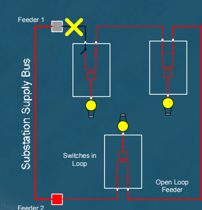
- Two Feeders
- Radial Feed
- Alternate Loop Supply
- Manual Switching

Open-Loop – Manual – Fault/Outage



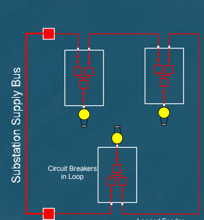
- Substation Breaker Clears Fault
- Feeder knocked out
- Outage to loads

Open-Loop – Manual – Restoration



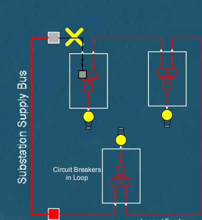
- Respond – 1 to 4 hrs
- Locate fault – 1 to 4 hrs
- Isolate fault – Manual Switching – 1 hr
- Close tie – Manual Switching – 1 hr
- Outage = 4 to 10 hours

High-Reliability Distribution System HRDS



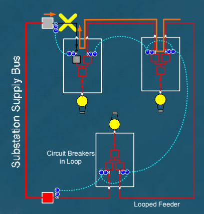
- Closed Loop = Single Feeder
- Simultaneous Dual Feeds to Loads
- Circuit Breaker Protection
- Faults on Main Feeder Cleared Without Outage

HRDS – Fault but NO Outage



- Breakers Isolate Fault to Only One Section
- Location – Instantaneous
- Isolation – 0.1 seconds
- **Restoration - Instantaneous**
- Outage = Zero Seconds
- Loop Remains Energized

HRDS – Smarts Required



High-Speed Relaying for Fault Detection

High-Speed Communications Between Breakers

Coordinated Operation – the "Right" Breakers Open

High-Speed Interruption – Fault Cleared without Outage

High Reliability Distribution System HRDS

- **The Smart Grid in Action**
  - High-Speed Relaying
  - High-Speed Communications
- **Fault Cleared Without Outage**
  - High-Speed Fault Interrupters
  - Coordinated Protection
  - Zero (0) Outage Time For Any Main Feeder Faults

Research Thrust: Advanced Distribution Automation

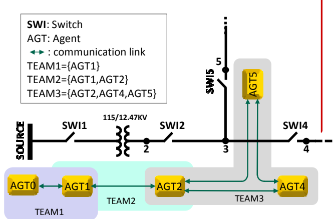
Prof. Alex Flueck
PhD Student: Cuong Nguyen
In collaboration with S&C Electric

Advanced Distribution Automation

- Modeling
  - Conductors, communication and control
- Distributed Autonomous Agents
- Communication Latency
- Future Work
  - Visualization
  - Preventing Outages with Distributed Generation & Storage
  - Optimizing Resource Allocation

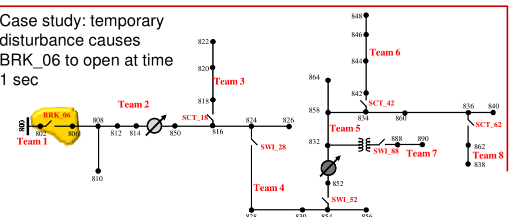
Multi-agent System (MAS) in Advanced Distribution Automation

- Fault detection & isolation, then reconfiguration
- Agents send messages
- Communication latency - critical!



Simulation on IEEE 34 node feeder

Case study: temporary disturbance causes BRK_06 to open at time 1 sec

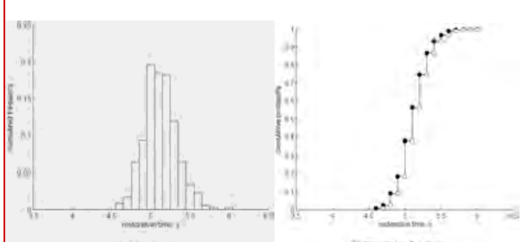


NORMAL RANDOM DISTRIBUTION OF COMMUNICATION LATENCY

Point	1	2	3	4	5	6	7	8	9	10
Latency (s)	0.0333	0.0667	0.1000	0.1333	0.1667	0.2000	0.2333	0.2667	0.3000	0.3333
Probability	0.0060	0.0120	0.0361	0.1265	0.6328	0.1265	0.0361	0.0120	0.0060	0.0060

Simulation Results

- Statistical results after 500 simulations with same event.



Why DESS is needed ?

- In "Grid 2030 Vision" report, Department of Energy has identified two of the top five concerns for the future smart grid:
  - **Distributed Energy Storage System(DESS)**
  - **Distributed Intelligence and Smart Control(DISC)**
- DESS application is very flexible:
  - Generation system: **spinning reserve, firm up intermittent renewable energy sources**
  - Transmission system: **support load carrying capacity and stability, support voltage dip, peak shaving**
  - Distribution system: **peak shaving, power quality improvement; dynamic islanding**

Reference DESS Installations (Electronic Converter Storage)

Three 2MW NaS Battery installations in AEP distribution system, 2008

Source: American Electric Power

1MW NaS Battery installation for 11MW Wind Farm in Xcel Energy, 2009

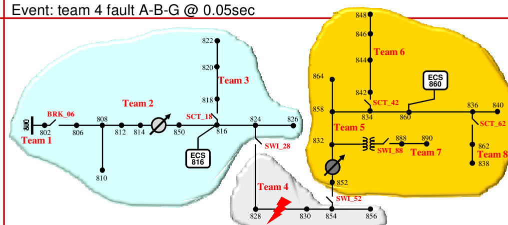
Source: SandC Electric

34 MW NaS battery installation for 51MW Wind Farm, Japan, 2008

Source: www.ngk.co.jp

Simulation on IEEE 34 Node Feeder

Event: team 4 fault A-B-G @ 0.05sec

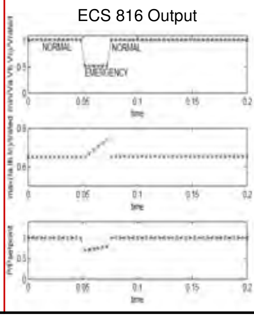


Electronic Converter Storage Data

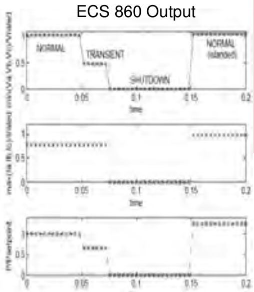
Equipment ID	RatedKVA KVA	Rated KV KV	Stored KWH KWH	MaxKW KW	Setpoint Power, KW	Power Factor, %	Tinc, sec	Tover, sec	Tshut, Cycles
ECS 816	750	24.9	1000	750	500	100	0.100	4.000	2
ECS 860	1500	24.9	1700	1500	1200	100	0.067	2.000	3

Simulation Results

ECS 816 Output



ECS 860 Output



Perfect Power at IIT
Master Controller Update

Greg Rouse
Project Manager

IIT Microgrid Master Controller Purpose

- Provide for Island Mode Capability
- Manage System Demand
- Minimize Costs
- Automate and Optimize Ancillary Services
  - Demand response
  - Day ahead
  - Capacity
  - Power Quality
- Minimize Carbon

2

How?

- Interface with Key Campus Controllers
  - Distributed generation
  - Building controllers and meters
  - Distribution system smart switches
- Interface with utility and Independent System Operator
- Monitor weather and other external conditions
- Place the campus in the optimal mode

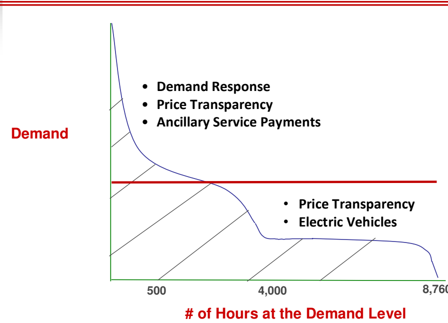
3

Microgrid Master Controller Versions

- Version 1:
  - Facilitates use of generators in demand response and real time/day ahead markets
  - Software infrastructure is developed (file management, database management, modeling, ect.)
- Version 2:
  - smart distribution for fault monitoring
  - remote control of substation breakers on the loops
- Version 3:
  - coordinates responses for demand reduction modes for pricing, demand response, and island mode events

4

Flatten the Curve – Improve Asset Utilization



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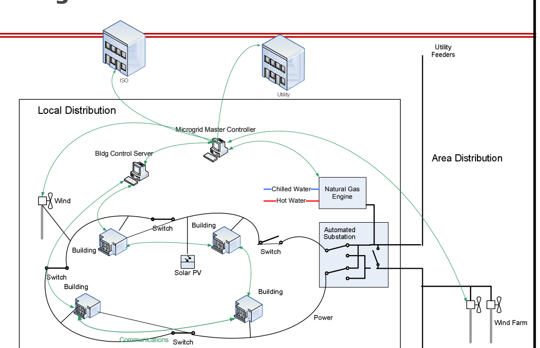
Microgrid Master Controller



6

Project Status

- 2009
  - Completed Version 1 software specification and conceptual design
- 2010
  - Version 1 Software Development and Deployment
  - Version 2 Software Specification

7

ILLINOIS INSTITUTE OF TECHNOLOGY

Perfect Power Demonstration

Abiodun Iwayemi, Peizhong Yi, Peng Liu , Chi Zhou

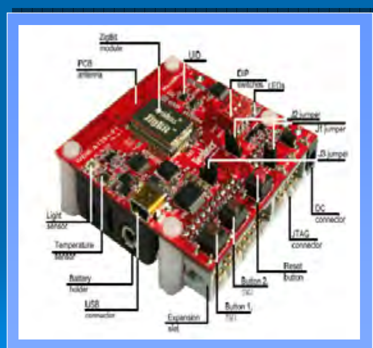
Department of Electrical and Computer Engineering
Illinois Institute of Technology
Chicago, Illinois

Demonstration Objectives

A proof of concept for:

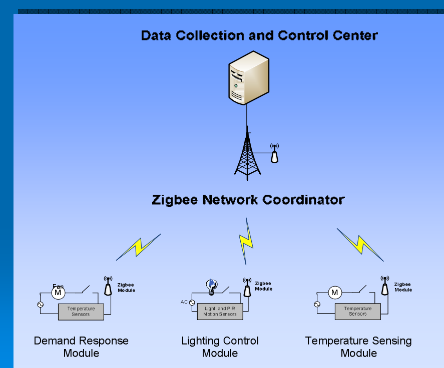
- The Perfect Power system controller
- Building energy management system
- Campus wide wireless networking using Zigbee for Smart grid applications

Zigbee

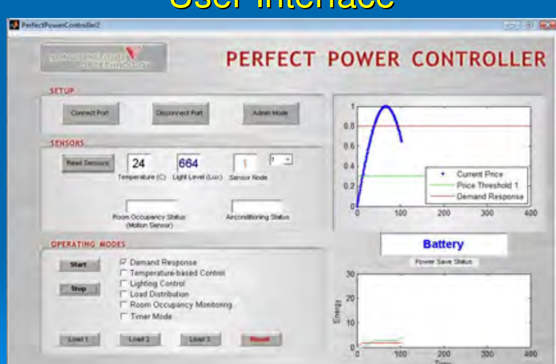


Meshbean2 Zigbee Mote

Test Bed Architecture



User Interface



Lighting Sensing & Control

Lighting sensing and actuation module is developed to turn on/off lighting using the following inputs:

- Room occupancy sensing result (via PIR sensor)
- Ambient lighting sensing result (onboard light sensor)
- Time of day

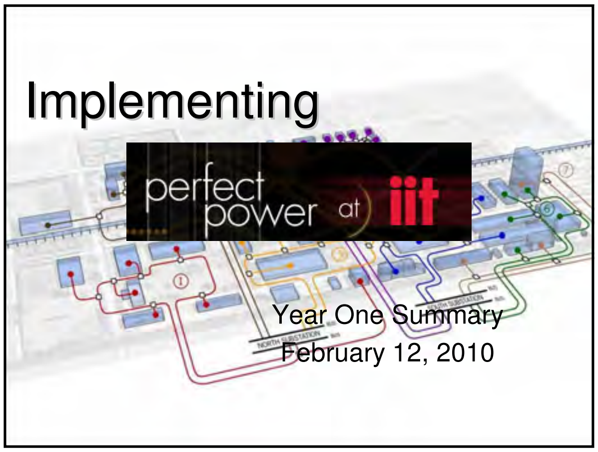
Temperature Monitoring & Control

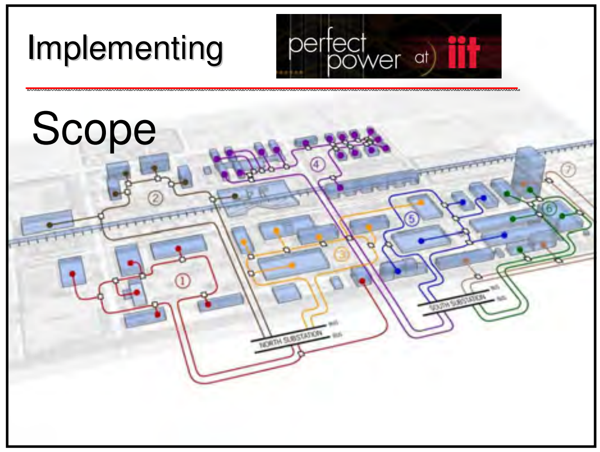
Ambient temperature monitoring and control performs

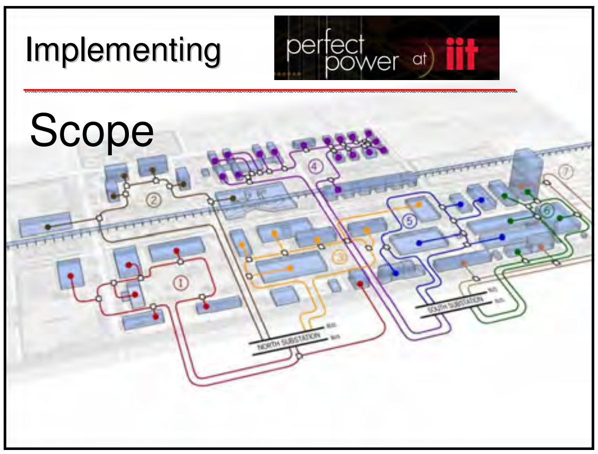
- Periodic temperature measurements using the on-board temperature sensor on Zigbee motes
- Load actuation by comparing the temperature with a user configured threshold value

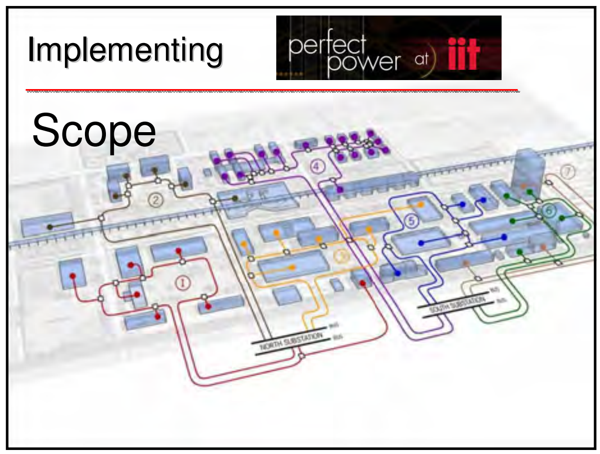
Work in Progress

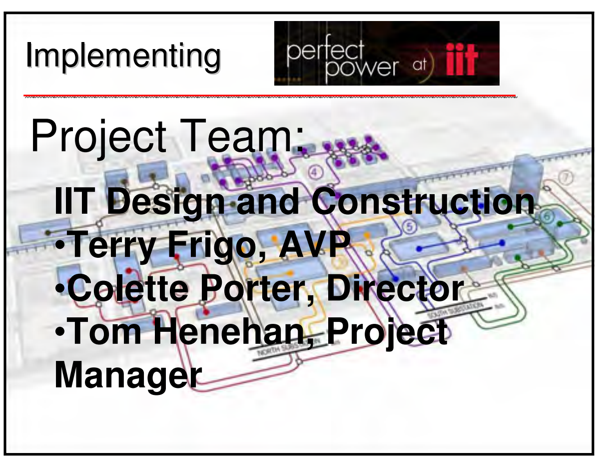
- Deploy a Zigbee sensing and control network throughout the Electrical and Computer Engineering building at IIT
- Monitor HVAC systems, measure ambient lighting levels and temperature, and control designated lighting systems within the building.


Implementing
perfect power at iit
Year One Summary
February 12, 2010


Implementing
perfect power at iit
Scope


Implementing
perfect power at iit
Scope


Implementing
perfect power at iit
Scope


Implementing
perfect power at iit
Project Team:
IIT Design and Construction
•Terry Frigo, AVP
•Colette Porter, Director
•Tom Henehan, Project Manager


Implementing
perfect power at iit
Project Team:
Bulley and Andrews
•Tim Puntillo, Vice President
•Mike Lemmons, Project Manager
•Duane Czerwonka, Superintendent

Implementing perfect power at iit

Project Team:

Aldridge Electric

•Jeff Belk, Project Manager

Implementing perfect power at iit

Project Team:

S&C Electric

•Jim Niemira, Principal Engineer

•Tim Horan, Design Engineer

•Andrew Kunze, Design Engineer

Implementing perfect power at iit

Key Issues:

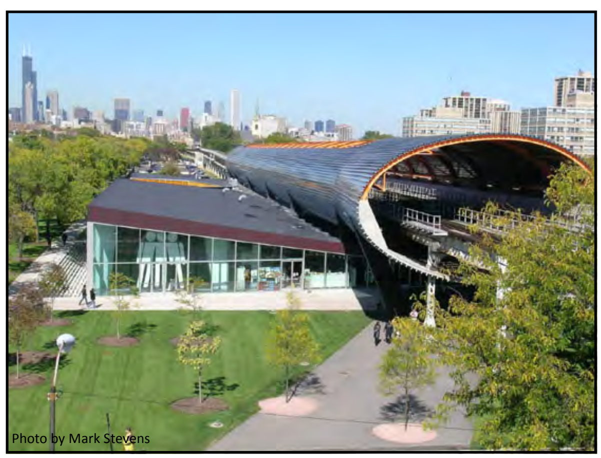
Historical Context

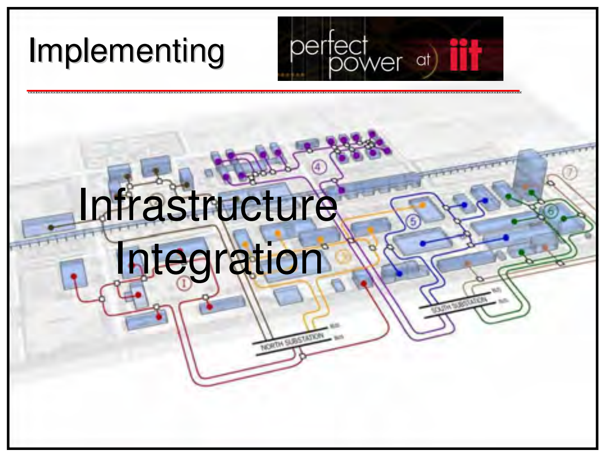
Infrastructure Integration

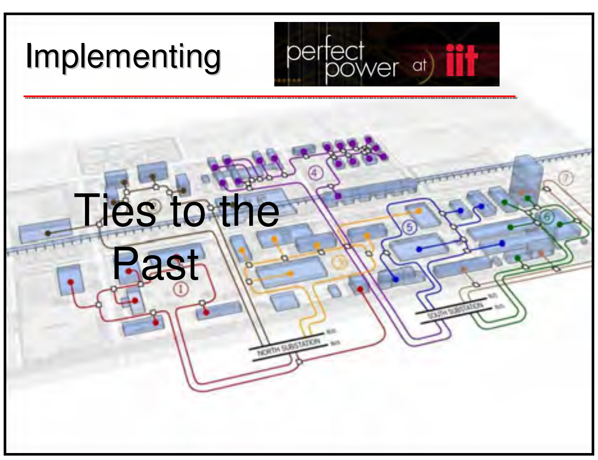
Ties to the Past

Implementing perfect power at iit

Historical Context




Implementing
perfect power at iit
Infrastructure Integration


Implementing
perfect power at iit
Ties to the Past

Implementing perfect power at iit

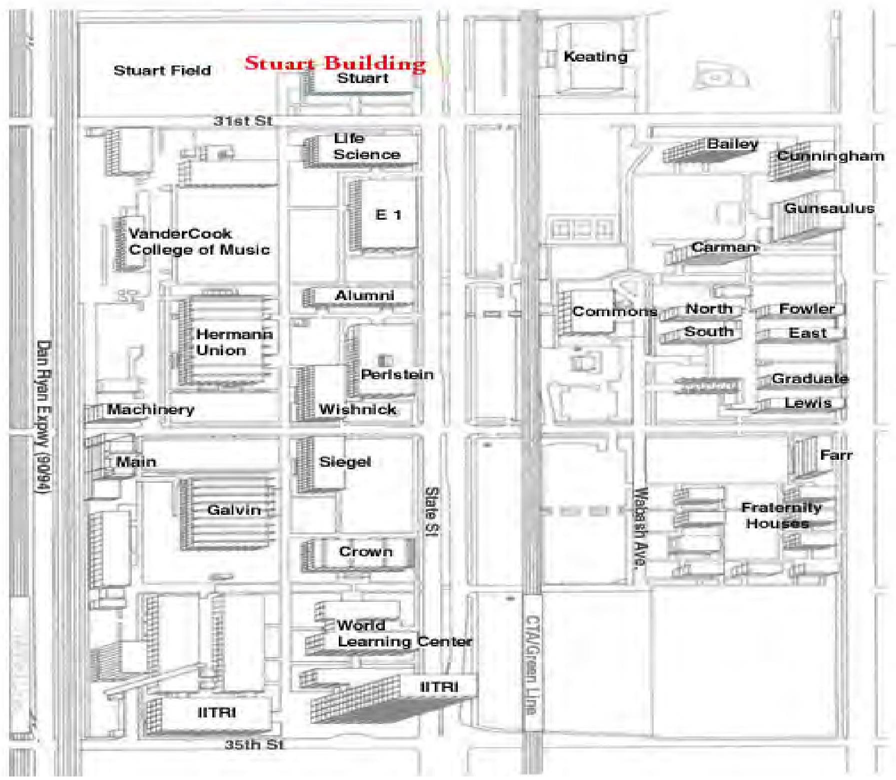
Lessons Learned:

- **Increase planning time**
- **Integrate selectively**
- **Target off-season**

Appendix 2

Report on IIT Distribution System

The IIT distribution system is a complex and intricate network with a large number of components and a variety of them. The perfect power project aims to create loops within the distribution system, but since the system needs to be radial we keep some of the relays and breakers open. In case of a fault, so that the particular segment can be isolated by the closing of the breaker and all the other loads in the loop will continue to have power. It is our effort to look at the various cable fault cases and study the impact of each failure on the distribution system.



Let us look at the statistics of the various components in the IIT distribution system.

Equipment Name	**No**
Feeder	4
Breaker	7
Cable	233
Equivalent Sources	4
Fuse	4
Interconnection	24
Loop	4
Node	407
Overhead Line Balanced	199
Relay	21
Section	435
Source Node	4
Spot Load	61
Switch	89
Synchronous Generator	2
Two-Winding Transformer	59
Meter (Relay)	4

List of Loads:

As we can see there are 61 loads in the IIT distribution system. The loads include major department buildings such as Siegel Hall, Wishnick Hall, Perlstein Hall, Hermann Hall, IITRI Tower, etc.

Equipment #	Total Thro Power (KW)	Total Thro Power (KVAR)	Total Thro Power (KVA)	Pf avg (%)
HERMANN_HALL_BLDG_1_(HH)	143	67	158	90.62
HERMANN_HALL_BLDG_2_(HH)	0	0	0	0
ENGINEERING_BLDG_1_(E1)	379	177	418	90.62
CROWN_HALL_(CR)	95	44	105	90.62
PERLSTEIN_HALL_(PH)	286	133	315	90.62
VANDERCOOK_BLDG_(A1)	95	45	105	90.62
CTA2_BLDG_(A3)	113	53	125	90.62
LIFE_SCIENCE_BLDG_(LS-CHILLERS)	0	0	0	0
LIFE_SCIENCE_BLDG_(LS-POWER)	284	132	313	90.62
CTA1_BUILDING_(A2)	133	62	147	90.62
MACHINERY_HALL_(MH)	114	53	126	90.62
COMMONS_BLDG_(MTCC)	568	265	627	90.62
KEATING_GYMNASIUM_(KH)	188	88	208	90.62
STATE_STREET_VILLAGE_1_(SSV)	90	15	91	98.61
STATE_STREET_VILLAGE_2_(SSV)	90	15	91	98.61
STATE_STREET_VILLAGE_3_(SSV)	90	15	91	98.61
BOILER_PLANT_2_(BP)	75	13	76	98.61
IITRI_ME_RESEARCH_BLDG_1_(LSR)	224	38	227	98.61
IITRI_ME_RESEARCH_BLDG_2_(LSR)	0	0	0	0
LSR_CHILLERS	1144	683	1332	85.87
3424_SOUTH_(GST)	112	19	113	98.55

IITRI_RESEARCH_TOWER_AIR_COND	621	369	722	86
IITRI_RESEARCH_TOWER_2_(RT)	150	25	152	98.61
IITRI_RESEARCH_TOWER_1_(RT)	150	25	152	98.61
3424_CENTRAL_BLDG_(GTC)	171	79	189	90.75
GALVIN_2_(GL)	102	47	113	90.74
MAIN_BLDG	86	40	94	90.74
GALVIN_CHILLERS	221	131	257	86
GALVIN_1_(GL)	86	40	94	90.74
RESIDENT_HALL_C_(RE)	51	24	56	90.74
GUNSAULUS_HALL_APTS_(GU)	102	47	112	90.74
CUNNINGHAM_HALL_APTS_(CY)	102	47	112	90.74
CARMAN_HALL_APTS_(CA)	102	47	112	90.74
RESIDENT_HALL_A_(RN)	102	47	112	90.74
FOWLER_HALL_(FO)	26	12	28	90.74
GRADUATE/LEWIS_HALL_BLDG_(RL)	128	59	141	90.74
BLDG_42	10	5	11	90.74
BLDG_46	26	12	28	90.75
BLDG_39	26	12	28	90.75
BLDG_38	51	24	56	90.74
BLDGS_37_AND_40	26	12	28	90.75
BLDG_43	51	24	56	90.74
BLDG_44	26	12	28	90.75
FARR_HALL_(FH)	34	16	38	90.74
IITRI_ENGR_RESEARCH_BLDG_(ERB)	342	158	377	90.74
IITRI_RESEARCH_TOWER_4_(RT)	340	157	375	90.74
IITRI_RESEARCH_TOWER_3_(RT)	340	157	374	90.74
FDR_3_BP_500KVA_XFMR_1	0	0	0	0
IITRI_CHEM_RESEARCH_BLDG	428	198	472	90.74
METALS_SOUTH_BLDG_(MTBS)	343	159	378	90.74
METAL_NORTH_BLDG_(MTBN)	172	79	189	90.75

3410_INST_GAS_TECH_BLDG_1_(GTN)	94	44	104	90.11
ENGINEERING_BLDG_CHILLER	1147	681	1334	86
ENGINEERING_BLDG_3_(E1)	263	100	282	93.5
ENGINEERING_BLDG_2_(E1)	263	100	281	93.5
LIFE_SCIENCE_BLDG_(LS-LIGHTING)	133	50	142	93.5
STUART_BLDG_(SB-LIGHTING)	132	50	141	93.5
STUART_BLDG_(SB-COMPUTER)	119	45	127	93.5
STUART_BLDG_(SB-POWER)	265	100	283	93.5
WISHNICK_HALL_1_(WH)	199	76	213	93.5
SIEGEL_HALL_(SH)	133	50	142	93.5
TOTAL LOAD	11386	5277	12601	

As we can see the total load in the IIT Distribution system is about 12,600 KVA, which is supplied by the 4 feeders (Substations) in the network. Using the CYME software, the power flow in the distribution network has been determined. Let us now have look at the power flow details in the feeders.

Feeder Loading Report

Substation: NORTH_SUBSTATION_1 :

Network ID	Total Load		Total Load		Generators		Generators		Total Losses		Total Losses	
792	kVA	PF (%)	kW	PF (%)	kVA	PF (%)	kW	PF (%)	kVA	PF (%)	kW	PF (%)
	2963.42	89.89	2663.72	89.89	0	0	0	0	47.05	19.84	9.34	19.84
Total	2963.42	89.89	2663.72	89.89	0	0	0	0	47.05	19.84	9.34	19.84

Substation: NORTH_SUBSTATION_2 :

Network ID	Total Load		Total Load		Generators		Generators		Total Losses		Total Losses	
CECO_NS_#2	kVA	PF (%)	kW	PF (%)	kVA	PF (%)	kW	PF (%)	kVA	PF (%)	kW	PF (%)
	2677.07	89.84	2405.06	89.84	0	0	0	0	56.59	11.43	6.47	11.43
Total	2677.07	89.84	2405.06	89.84	0	0	0	0	56.59	11.43	6.47	11.43

Substation: SOUTH_SUBSTATION_1 :

Network ID	Total Load		Total Load		Generators		Generators		Total Losses		Total Losses	
CECO_SS_#1	kVA	PF (%)	kW	PF (%)	kVA	PF (%)	kW	PF (%)	kVA	PF (%)	kW	PF (%)
	4552.13	89.88	4091.43	89.88	0	0	0	0	65.79	15.54	10.22	15.54

Total	4552.13	89.88	4091.43	89.88	0	0	0	0	65.79	15.54	10.22	15.54

Substation: SOUTH_SUBSTATION_2 :

Network ID	Total Load		Total Load		Generators		Generators		Total Losses		Total Losses	
CECO_SS_#2	kVA	PF (%)	kW	PF (%)	kVA	PF (%)	kW	PF (%)	kVA	PF (%)	kW	PF (%)
	2508.41	89.96	2256.6	89.96	0	0	0	0	128.66	10.97	14.11	10.97
Total	2508.41	89.96	2256.6	89.96	0	0	0	0	128.66	10.97	14.11	10.97

Summary

	Total Load		Total Load		Generators		Generators		Total Losses		Total Losses	
	kVA	PF (%)	kW	PF (%)	kVA	PF (%)	kW	PF (%)	kVA	PF (%)	kW	PF (%)
Total	12701.02	89.89	11416.81	89.89	0	0	0	0	297.92	13.47	40.14	13.47

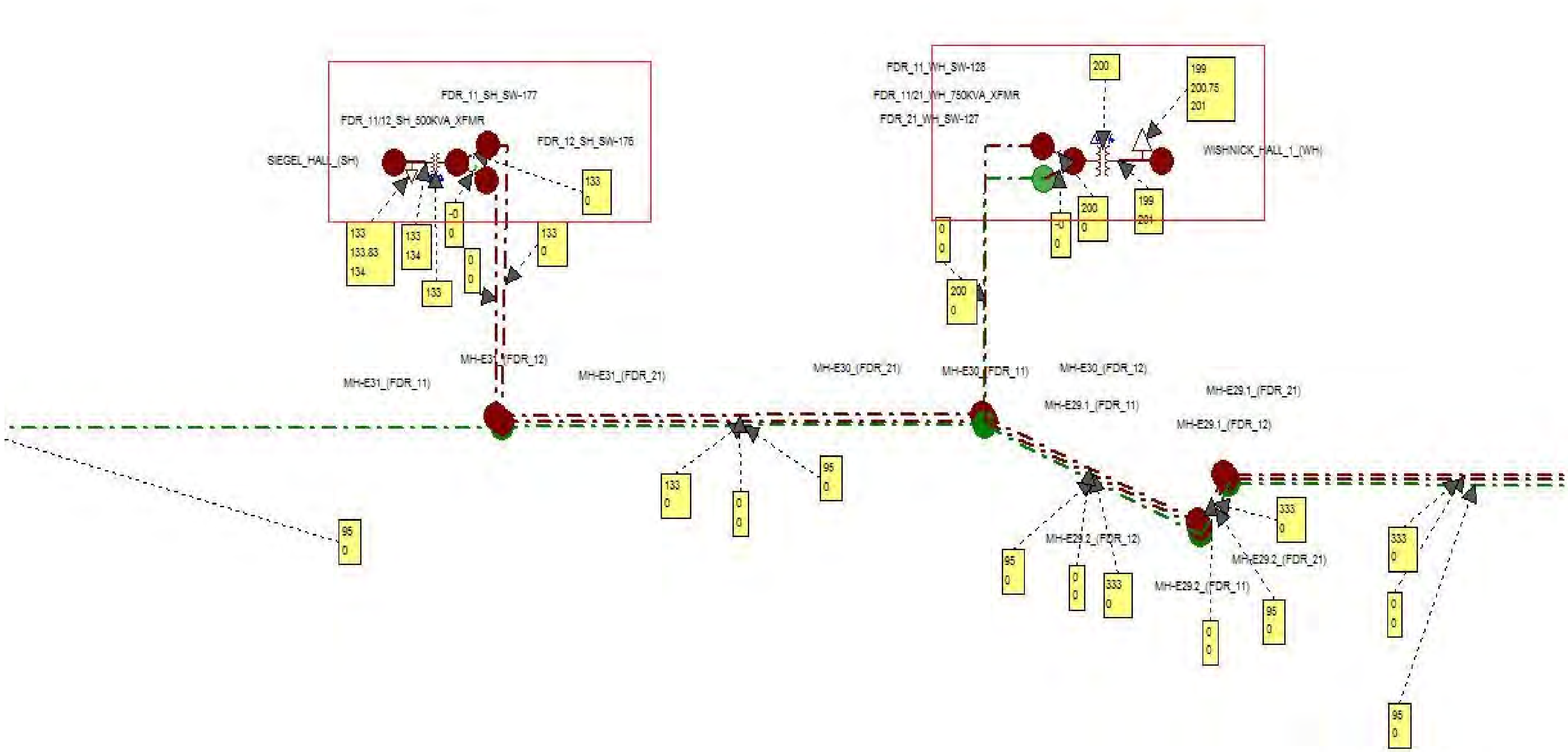
From the feeder power flow details we can see that a total load of 12.70 MW is provided by the 4 feeders which are connected to the transmission system. As we can see that the losses in the network is about 2.72 % of the total power flowing into the network. Since, the power flow was carried out on a steady state analysis the losses are less when compared to a transient analysis which would be done in the future.

Let us now look at the line flows around a particular load in a section of the of the distribution network.

Base case Line Flows in the Old IIT Power Grid :

For the sake of this report I am going to take into consideration the power flows near my department, **Siegel Hall** which will be a part of Loop 3 in the Perfect Power project of the distribution network. The load on my department is 133 kW; let us see how this load is being satisfied by the lines in the distribution system. This is a base case power flow analysis before the implementation of Perfect Power project. Let us first have a look at this section of the distribution system.

Section 1:



In the section 1, as we can see from the snapshot of the network, the power comes from the 2 feeders connected to the **North Substation**. The yellow boxes represent the following (from top)

1. Total through kW
2. Total spot load kW
3. Total kW

The red boxes represent the department buildings and the one on the left is **Siegel Hall** and the one on the right is **Wishnick Hall**. The red/green dot and dashed lines are the cable lines which connect the loads and the nodes in the distribution network.

Let us see the line flows in this section in the following table.

Connection	Equipment #	Equipment ID	Code	V	Length (ft)	Total Thro Power (KW)	Total Thro Power (KVAR)	Total Thro Power (KVA)	Pf avg (%)	Ibal (Amps)	Angle I
SH Node-SH Load	FDR_11-12	350_EPR	Cable	119.8	88.2	133	52	143	93.02	19.9	-21.59
	FDR_12-9	500_EPR	Cable	119.7	72.9	0	0	0	0	0	0
WH Node-SH Node	FDR_12-8	500_EPR	Cable	119.7	165.6	0	0	0	0	0	0
	FDR_21-12	500_EPR	Cable	119.8	164.4	95	46	106	90.17	14.7	-25.68
	FDR_11-11	350_EPR	Cable	119.8	164.8	133	52	143	93.02	19.9	-21.59
WH Node-WH Load	FDR_11-13	500_EPR	Cable	119.8	100.5	200	78	214	93.08	29.8	-21.49
	FDR_21-11	500_EPR	Cable	119.8	92.6	0	0	0	0	0	0
SH Node-CH Load	FDR_21-13	500_EPR	Cable	119.8	363	95	46	106	90.17	14.7	-25.68
WH Node-PH Node(1)	FDR_21-10	500_EPR	Cable	119.8	80.3	95	46	106	90.17	14.7	-25.68
	FDR_12-7	500_EPR	Cable	119.7	80.3	0	0	0	0	0	0
	FDR_11-10	500_EPR	Cable	119.8	79.6	333	131	357	93.06	49.7	-21.53
PH(1) Node-PH Node(2)	FDR_11-9	500_EPR	Cable	119.8	17.4	333	131	357	93.06	49.7	-21.53
	FDR_12-6	500_EPR	Cable	119.7	16.3	0	0	0	0	0	0

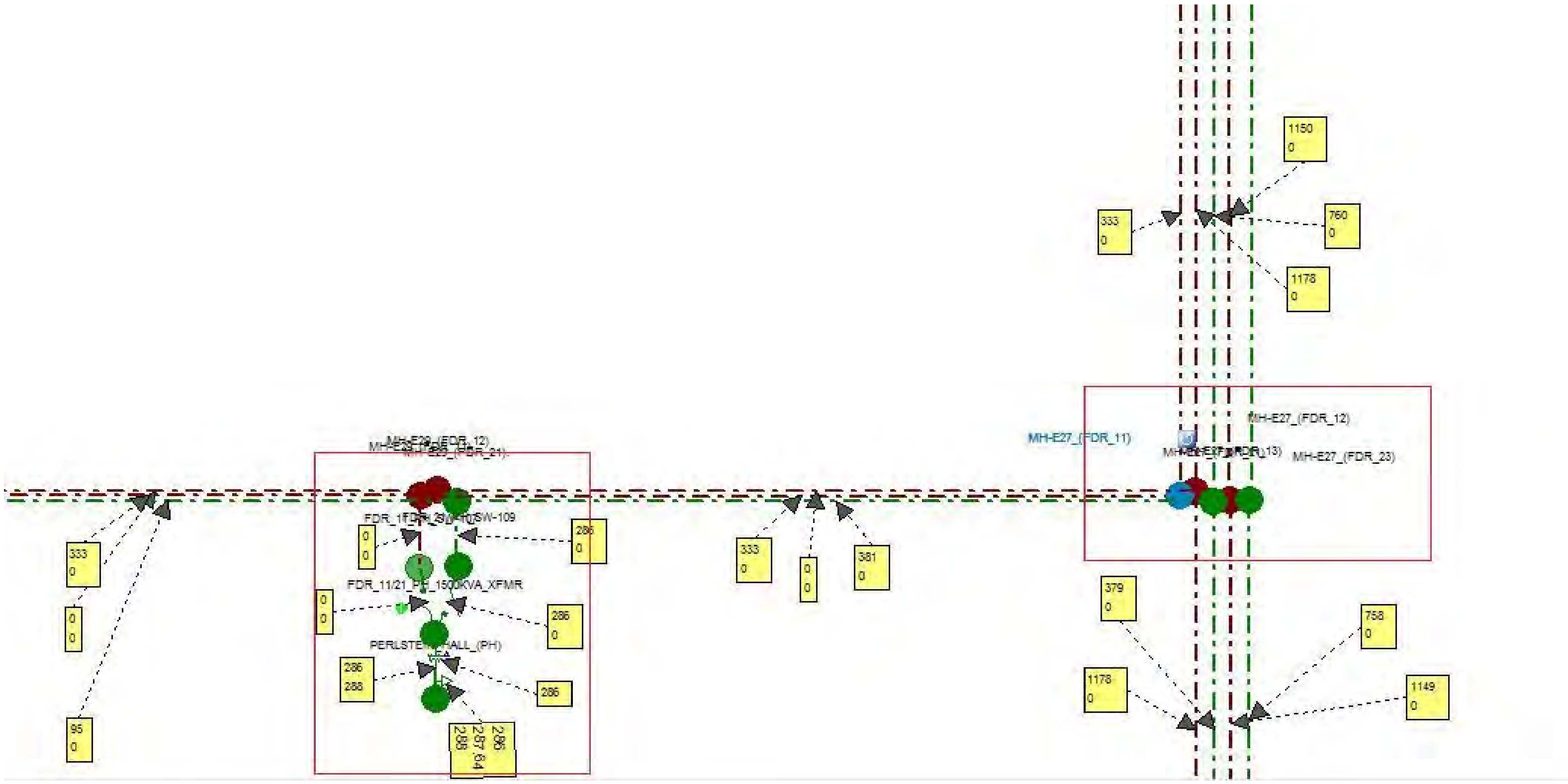
	FDR_21-9	500_EPR	Cable	119.8	17.7	95	46	106	90.17	14.7	-25.68
PH(2) Node-PH Node(3)	FDR_21-8	500_EPR	Cable	119.8	167.6	95	46	106	90.17	14.7	-25.68
	FDR_11-8	500_EPR	Cable	119.8	157.4	333	131	357	93.05	49.7	-21.53
	FDR_12-5	500_EPR	Cable	119.7	163.8	0	0	0	0	0	0

Where,

SH – Siegel Hall
WH – Wishnick Hall
PH – Perlstein Hall
CH – Crown Hall

Here, in the table the lines with the highlighted data are the lines which will be re-routing the power in case of a power failure. But, this does not prevent the loads from being blacked out in case of a failure. [Note: All the calculations are performed on steady state analysis of the system and hence the power flows show very little loss in the network.]

Section 2:



The yellow boxes represent the following (from top)

1. Total through kW
2. Total spot load kW
3. Total kW

The red boxes represent the department buildings and the one on the left is **Perlstein Hall** and the one on the right is **Memorial Hall**. The black dot and dashed lines are the cable lines which connect the loads and the nodes in the distribution network.

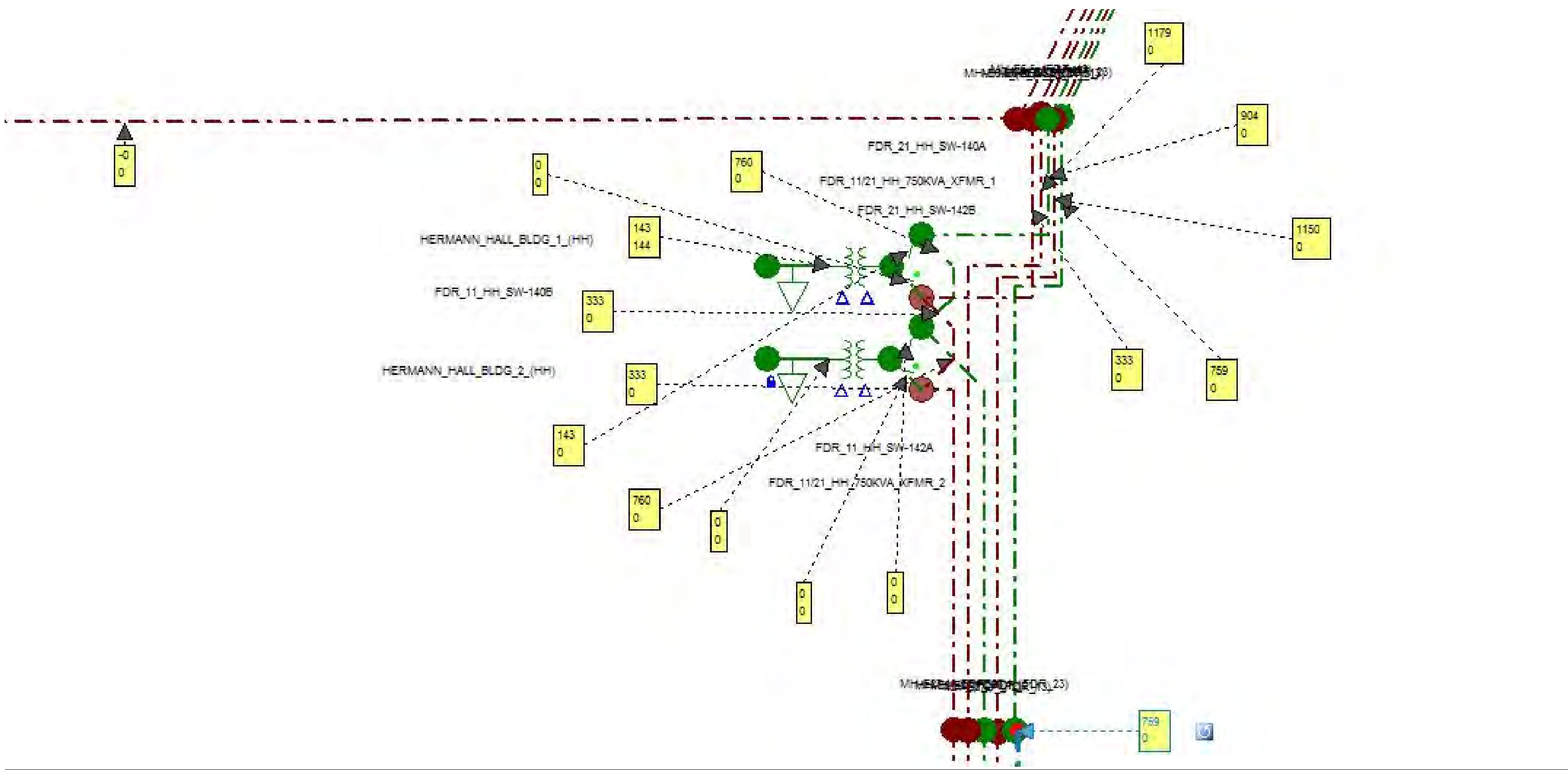
Let us see the line flows in this section in the following table.

Connection	Equipment #	Equipment ID	Code	V	Length (ft)	Total Thro Power (KW)	Total Thro Power (KVAR)	Total Thro Power (KVA)	Pf avg (%)	Ibal (Amps)	Angle I
PH Node(3)-PH Load	FDR_11-7	500_EPR	Cable	119.9	30.2	0	0	0	0	0	0
	FDR_21-7	350_EPR	Cable	119.8	18.4	286	137	317	90.16	44.1	-25.69
PH Node(3)-MH(1) Node	FDR_21-6	500_EPR	Cable	119.8	219.2	381	183	423	90.16	58.7	-25.68
	FDR_11-6	500_EPR	Cable	119.9	220	333	131	358	93.05	49.7	-21.53
	FDR_12-4	500_EPR	Cable	119.7	219.3	0	0	0	0	0	0
MH(1) Node-MH(2) Node	FDR_11-5	500_EPR	Cable	119.9	160.6	333	131	358	93.05	49.7	-21.53
	FDR_21-5	500_EPR	Cable	119.8	170.3	760	370	845	89.92	117.5	-25.98
	FDR_12-3	500_EPR	Cable	119.7	165	1178	479	1272	92.63	176.8	-22.19
	FDR_13-3	500_EPR	Cable	119.7	169.5	1150	684	1338	85.94	186	-30.8
MH(1) Node-MTCC/E1 Node	FDR_21-14	500_EPR	Cable	119.8	245.4	379	187	423	89.7	58.7	-26.28
	FDR_12-10	500_EPR	Cable	119.7	257.3	1178	479	1271	92.65	176.8	-22.19
	FDR_23-4	350_EPR	Cable	119.7	188.8	758	373	845	89.74	117.5	-26.21
	FDR_13-4	500_EPR	Cable	119.6	237.5	1149	683	1337	85.95	186	-30.8

Where,

MH (1), MH (2) – Memorial Hall
WH – Wishnick Hall
MTCC/E1 – MTCC (1 node) and Engineering 1 (3 nodes)
[Note: All the calculations are performed on steady state analysis of the system and hence the power flows show very little loss in the network.]

Section 3:



The yellow boxes represent the following (from top)

1. Total through kW
2. Total spot load kW
3. Total kW

The red boxes represent the department buildings and the one on the right is **Hermann Hall**. The black dot and dashed lines are the cable lines which connect the loads and the nodes in the distribution network.

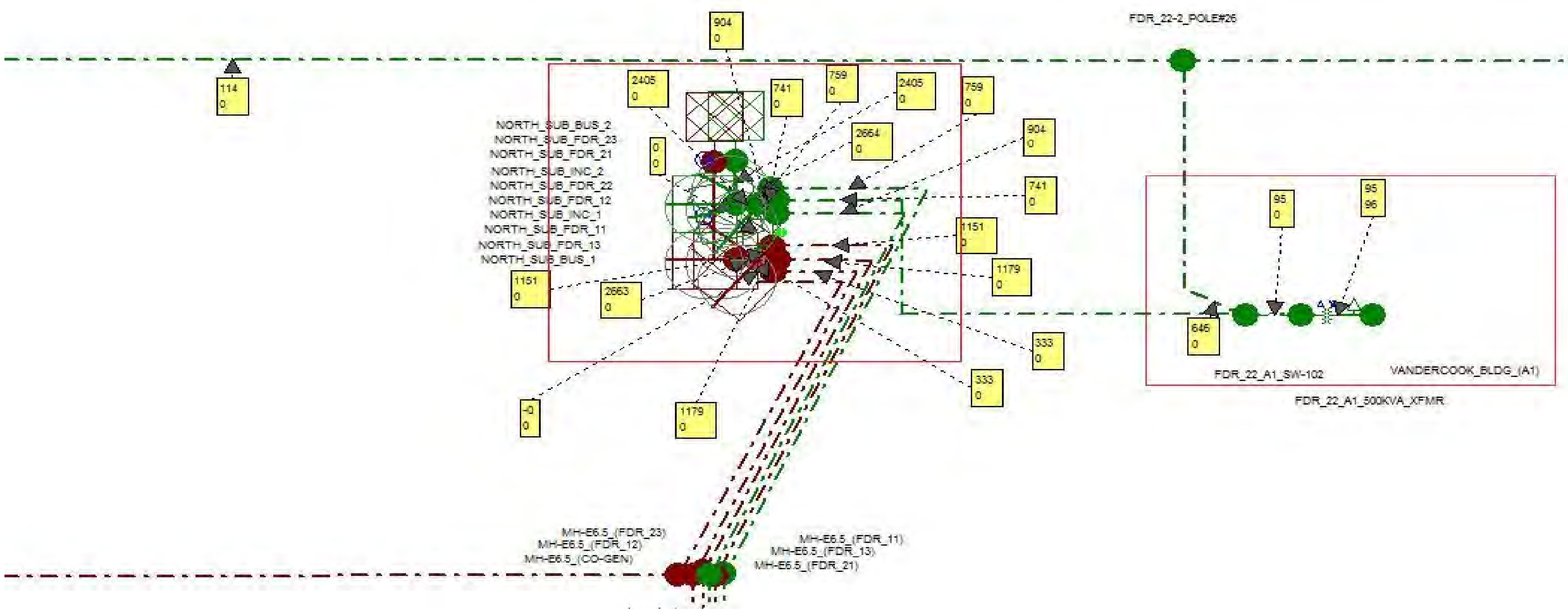
Let us see the line flows in this section in the following table.

Connection	Equipment #	Equipment ID	Code	V	Length (ft)	Total Thro Power (KW)	Total Thro Power (KVAR)	Total Thro Power (KVA)	Pf avg (%)	Ibal (Amps)	Angle I
MH(1) Node-MH(2) Node	FDR_23-3	350_EPR	Cable	119.8	170.1	759	373	845	89.74	117.5	-26.21
MH(2) Node-NSS(2) Node	FDR_23-2	350_EPR	Cable	119.8	212.6	759	373	846	89.73	117.5	-26.21
	FDR_12-2	500_EPR	Cable	119.8	221.7	1179	480	1273	92.62	176.8	-22.19
	FDR_13-2	500_EPR	Cable	119.8	216.2	1150	685	1339	85.93	186	-30.8
MH(2) Node-HH(2Red) Node	FDR_11-4	500_EPR	Cable	119.9	119.9	333	131	358	93.04	49.7	-21.53
MH(2) Node-HH(2Green) Node	FDR_21-4	500_EPR	Cable	119.9	138.6	760	370	846	89.92	117.5	-25.98
HH(2Green) Node-NSS(2) Node	FDR_21-2	500_EPR	Cable	119.9	78.7	904	439	1005	89.95	139.5	-25.93
HH(2Red) Node-NSS(2) Node	FDR_11-2	500_EPR	Cable	119.9	92.9	333	131	358	93.04	49.7	-21.53
NSS(2) Node-SSS Node	NORTH_SUB_CO-GEN_TIE_2	500_EPR_3_SETS	Cable	119.9	664.6	0	0	0	0	0	89.98
HH(2Red) Node-HH(2Red) Node	FDR_11-3	500_EPR	Cable	119.9	38.2	333	131	358	93.04	49.7	-21.53
HH(2Green) Node-HH(2Green) Node	FDR_21-3	500_EPR	Cable	119.9	38.4	760	370	846	89.91	117.5	-25.98
HH(2Green) Node-HH(1A) Node	FDR_21_HH_SW-140A	BUS_SECTION	Line	119.9	10	143	69	159	90.16	22	-25.65
HH(1A) Node-HH(2Red) Node	FDR_11_HH_SW-140B	BUS_SECTION	Line	119.9	10	0	0	0	0	0	89.97
HH(2Green) Node-HH(1B) Node	FDR_21_HH_SW-142B	BUS_SECTION	Line	119.9	10	0	0	0	0	0	89.97
HH(1B) Node-HH(2Red) Node	FDR_11_HH_SW-142A	BUS_SECTION	Line	119.9	10	0	0	0	0	0	89.97

Where,

MH (1), MH (2) – Memorial Hall
NSS (2) – North Sub Station
SSS – South Sub Station
HH (1A), HH (1B), HH (2Red), HH (2Green) – Hermann Hall
[Note: All the calculations are performed on steady state analysis of the system and hence the power flows show very little loss in the network.]

Section 4:



The yellow boxes represent the following (from top)

1. Total through kW
2. Total spot load kW
3. Total kW

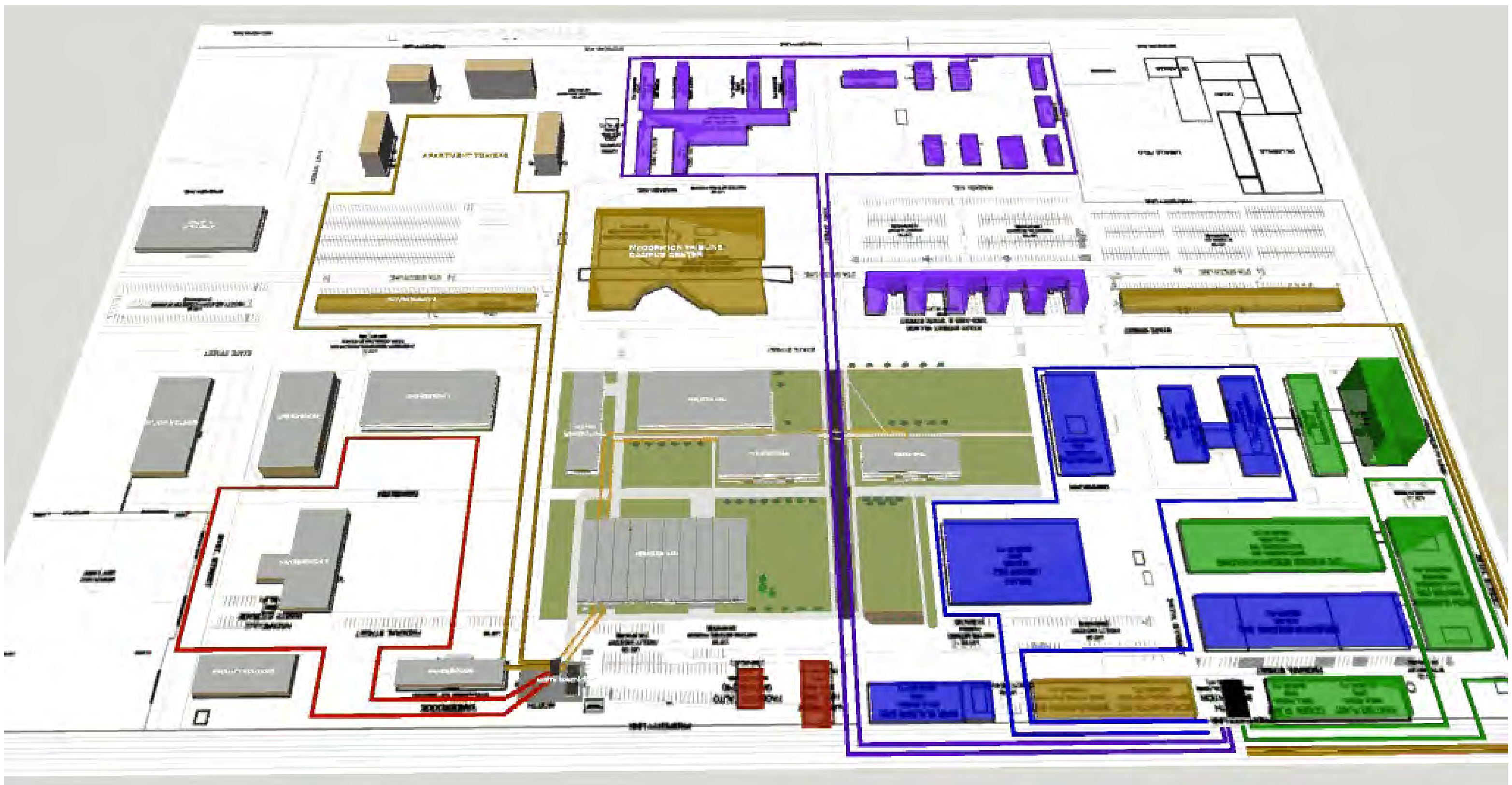
The red boxes represent the department buildings and the one on the left is the **North Sub Station** and the one on the right is the **Vander Cook School of Music**. The black dot and dashed lines are the cable lines which connect the loads and the nodes in the distribution network.
Let us see the line flows in this section in the following table.

Connection	Equipment #	Equipment ID	Code	V	Length (ft)	Total Thro Power (KW)	Total Thro Power (KVAR)	Total Thro Power (KVA)	Pf avg (%)	Ibal (Amps)	Angle I
NSS(1) Node-NSS(2) Node	NORTH_SUB_CO-GEN_TIE_3	500_EPR_3_SETS	Cable	119.9	150.5	0	0	0	0	0	89.98
	FDR_11-1	500_EPR	Cable	119.9	145.8	333	131	358	93.04	49.7	-21.53
	FDR_11-1	500_EPR	Cable	119.9	145.8	333	131	358	93.04	49.7	-21.53
	FDR_12-1	500_EPR	Cable	119.9	152.1	1179	480	1273	92.61	176.8	-22.19
	FDR_13-1	500_EPR	Cable	119.9	167.6	1151	685	1339	85.91	186	-30.8
	FDR_21-1	500_EPR	Cable	119.9	182.6	904	439	1005	89.94	139.5	-25.93
	FDR_21-2	500_EPR	Cable	119.9	78.7	904	439	1005	89.95	139.5	-25.93
	FDR_21-3	500_EPR	Cable	119.9	38.4	760	370	846	89.91	117.5	-25.98

Where,
NSS (1), NSS (2) – North Sub Station
[Note: All the calculations are performed on steady state analysis of the system and hence the power flows show very little loss in the network.]

Perfect Power Implementation:

The perfect power is a Department of Energy funded project which deals with the smart grid and its implementation at IIT. In this project, we have divided the entire distribution network into 8 micro-grids or 8 loops which will have the capability to self-heal i.e. in case of a contingency, only the load with the failure will lose power and that too will be restored in less than a minute. The smart grid/ perfect power project aims at improving the quality/reliability of the power being distributed reduce the number of outages in the campus and also to upgrade the entire system which was pretty old. Now, out of the 8 loops, I have chosen the Loop 3 in which Siegel Hall (my department) is located.



Before we go in depth on the loop 3, I would like to show you the change in the feeder loading report once the Loop3 has been implemented and how it has changes when compared to the previous case with the old system in place.

Feeder Loading Report

Substation: NORTH_SUBSTATION_1 :

Network ID	Total Load		Total Load		Total Losses		Total Losses	
CECO_NS_#1	kVA	PF (%)	kW	PF (%)	kVA	PF (%)	kW	PF (%)
	2855.52	89.07	2543.51	89.07	70	10.54	7.38	10.54
Total	2855.52	89.07	2543.51	89.07	70	10.54	7.38	10.54

Substation: NORTH_SUBSTATION_2 :

Network ID	Total Load		Total Load		Total Losses		Total Losses	
CECO_NS_#2	kVA	PF (%)	kW	PF (%)	kVA	PF (%)	kW	PF (%)
	2399.07	88.66	2127.06	88.66	83.33	8.83	7.36	8.83
Total	2399.07	88.66	2127.06	88.66	83.33	8.83	7.36	8.83

Substation: SOUTH_SUBSTATION_1 :

Network ID	Total Load	Total Load	Total Losses	Total Losses

CECO_SS_#1	kVA	PF (%)	kW	PF (%)	kVA	PF (%)	kW	PF (%)
	6226.49	88.51	5511.06	88.51	238.98	15.68	37.48	15.68
Total	6226.49	88.51	5511.06	88.51	238.98	15.68	37.48	15.68

Substation: SOUTH_SUBSTATION_2 :

Network ID	Total Load		Total Load		Total Losses		Total Losses	
CECO_SS_#2	kVA	PF (%)	kW	PF (%)	kVA	PF (%)	kW	PF (%)
	3329.93	88.54	2948.23	88.54	140.13	11.96	16.76	11.96
Total	3329.93	88.54	2948.23	88.54	140.13	11.96	16.76	11.96

Summary

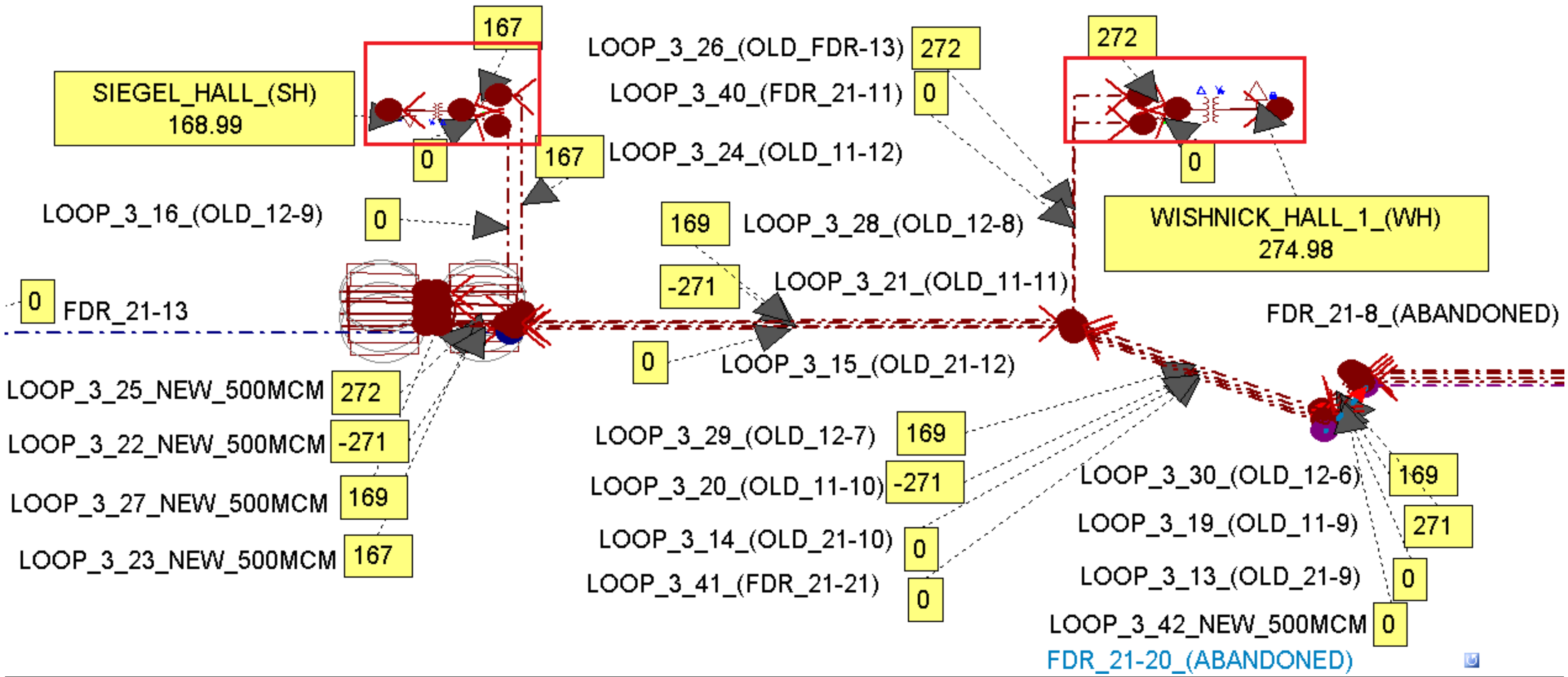
	Total Load		Total Load		Total Losses		Total Losses	
	kVA	PF (%)	kW	PF (%)	kVA	PF (%)	kW	PF (%)
Total	14810.8	88.65	13129.9	88.65	532.26	12.96	68.98	12.96

In this case, we can see that the losses have gone up because of the transformer losses. And also, how the feeder has redistributed the power with one of the loops (loop 3) having been implemented. Now let us go to the Loop 3 power flows in base case after the loop 3 has been implemented.

Base case Line Flows in the IITs Perfect Power Grid :

In this case, I am only going to look at the power flows in the Loop 3, in which Siegel Hall is located. Below is the pictorial representation of the Loop 3 being implemented at IITs main campus.

Section 1:



In the section 1, as we can see from the snapshot of the network, the power comes from the 2 feeders connected to the **North Substation**. The yellow boxes represent the following (from top)

1. Total through kW

The red boxes represent the department buildings and the one on the left is **Siegel Hall** and the one on the right is **Wishnick Hall**. The red/green dot and dashed lines are the cable lines which connect the loads and the nodes in the distribution network. Just below the Siegel Hall load, we see a serious of breakers, this is called as **'vista switch'**, in case of fault this switch will re-route the power to the other loads in the loop and will recover the load to full power within 1 minute.

Let us see the line flows in this section in the following table.

Connection	Equipment #	Equipment ID	Code	V	Length (ft)	Total Thro Power (KW)	Total Thro Power (KVAR)	Total Thro Power (KVA)	Pf avg (%)	Ibal (Amps)	Angle I
Vista Switch	LOOP_3_25_NEW_500MCM	500_EPR	Cable	119.7	186.7	272	137	305	89.3	42.4	-26.82
	LOOP_3_22_NEW_500MCM	500_EPR	Cable	119.7	35.2	-271	-137	304	89.18	42.2	153.02
	LOOP_3_27_NEW_500MCM	500_EPR	Cable	119.7	21.1	169	84	188	89.45	26.2	-26.63
	LOOP_3_23_NEW_500MCM	500_EPR	Cable	119.7	24.5	167	84	187	89.26	26.1	-26.87
Vista Switch-SH Load	LOOP_3_24_(OLD_11-12)	350_EPR	Cable	119.7	83.3	167	84	187	89.26	26.1	-26.87
	LOOP_3_16_(OLD_12-9)	500_EPR	Cable	119.8	76	0	0	0	0	0	0
WH Node-Vista Switch	LOOP_3_28_(OLD_12-8)	500_EPR	Cable	119.7	165.6	169	84	188	89.45	26.2	-26.63
	LOOP_3_21_(OLD_11-11)	350_EPR	Cable	119.7	164.8	-271	-137	304	89.18	42.2	153.02
	LOOP_3_15_(OLD_21-12)	500_EPR	Cable	119.8	164.4	0	0	0	0	0	0
(From VS)WH Node-WH Load	LOOP_3_26_(OLD_FDR-13)	500_EPR	Cable	119.7	99.4	272	137	305	89.3	42.4	-26.82
	LOOP_3_40_(FDR_21-11)	500_EPR	Cable	119.7	92.6	0	0	0	0	0	0
WH Node-PH Node(1)	LOOP_3_29_(OLD_12-7)	500_EPR	Cable	119.7	80.3	169	84	189	89.45	26.2	-26.63
	LOOP_3_20_(OLD_11-10)	500_EPR	Cable	119.7	79.6	-271	-137	304	89.18	42.2	153.02
	LOOP_3_14_(OLD_21-10)	500_EPR	Cable	119.8	80.3	0	0	0	0	0	0
	LOOP_3_41_(FDR_21-21)	500_EPR	Cable	119.7	81	0	0	0	0	0	0
PH(1) Node-PH Node(2)	LOOP_3_30_(OLD_12-6)	500_EPR	Cable	119.7	16.3	169	84	189	89.45	26.2	-26.63
	LOOP_3_19_(OLD_11-9)	500_EPR	Cable	119.7	17.4	271	137	304	89.17	42.2	-26.98
	LOOP_3_13_(OLD_21-9)	500_EPR	Cable	119.8	17.7	0	0	0	0	0	0
	LOOP_3_42_NEW_500MCM	500_EPR	Cable	119.7	17.9	0	0	0	0	0	0
SH Node-CH Load	FDR_21-13	500_EPR	Cable	119.8	363	0	0	0	0	0	0

Where,

SH – Siegel Hall

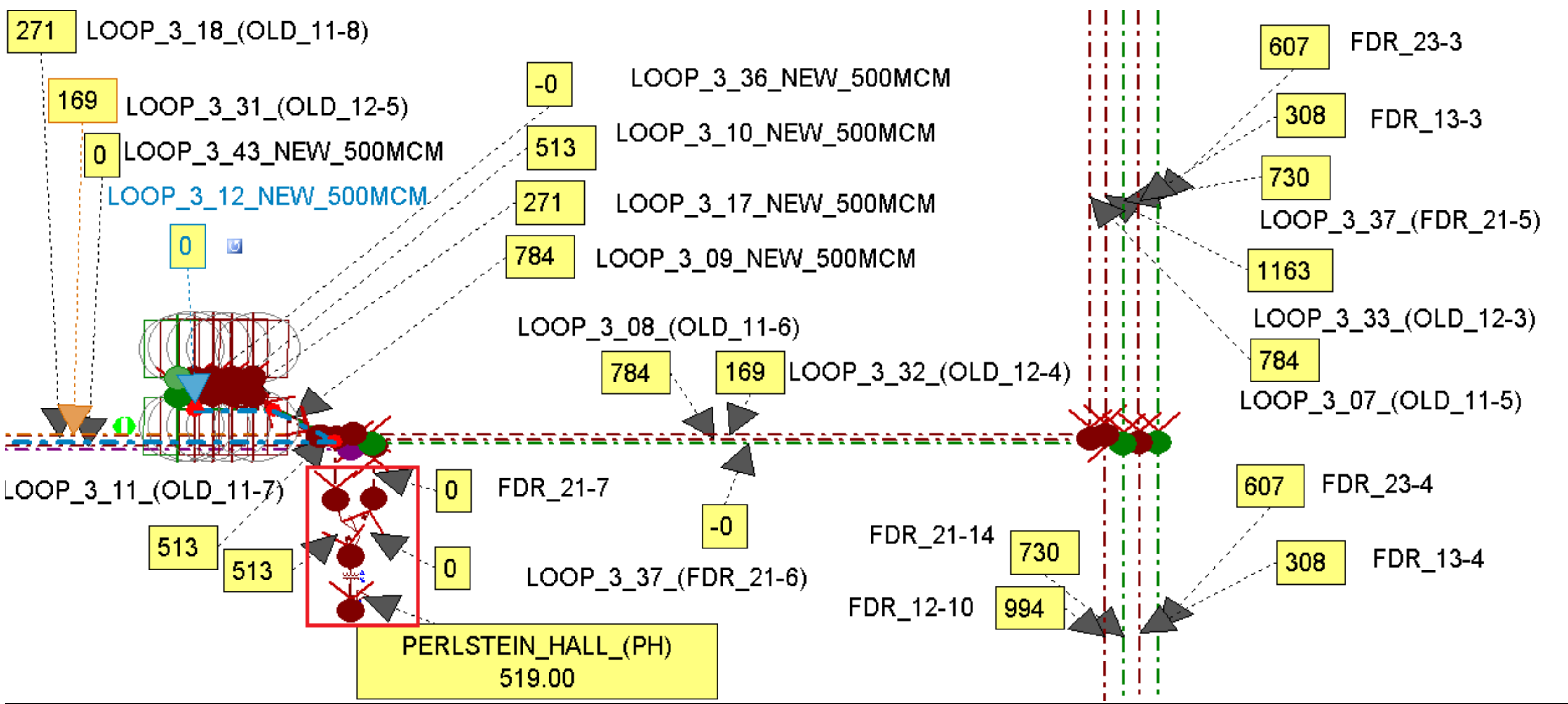
WH – Wishnick Hall

PH – Perlstein Hall
CH – Crown Hall

Here, in the table the lines with the highlighted data are the lines which will be re-routing the power in case of a power failure. The power will be re-routed using the above concept of 'vista switches'.

[Note: All the calculations are performed on steady state analysis of the system and hence the power flows show very little loss in the network.]

Section 2:



The yellow boxes represent the following (from top)

1. Total through kW

The red boxes represent the department buildings and the one on the left is **Perlstein Hall** and the one on the right is **Memorial Hall**. The black dot and dashed lines are the cable lines which connect the loads and the nodes in the distribution network.

Let us see the line flows in this section in the following table.

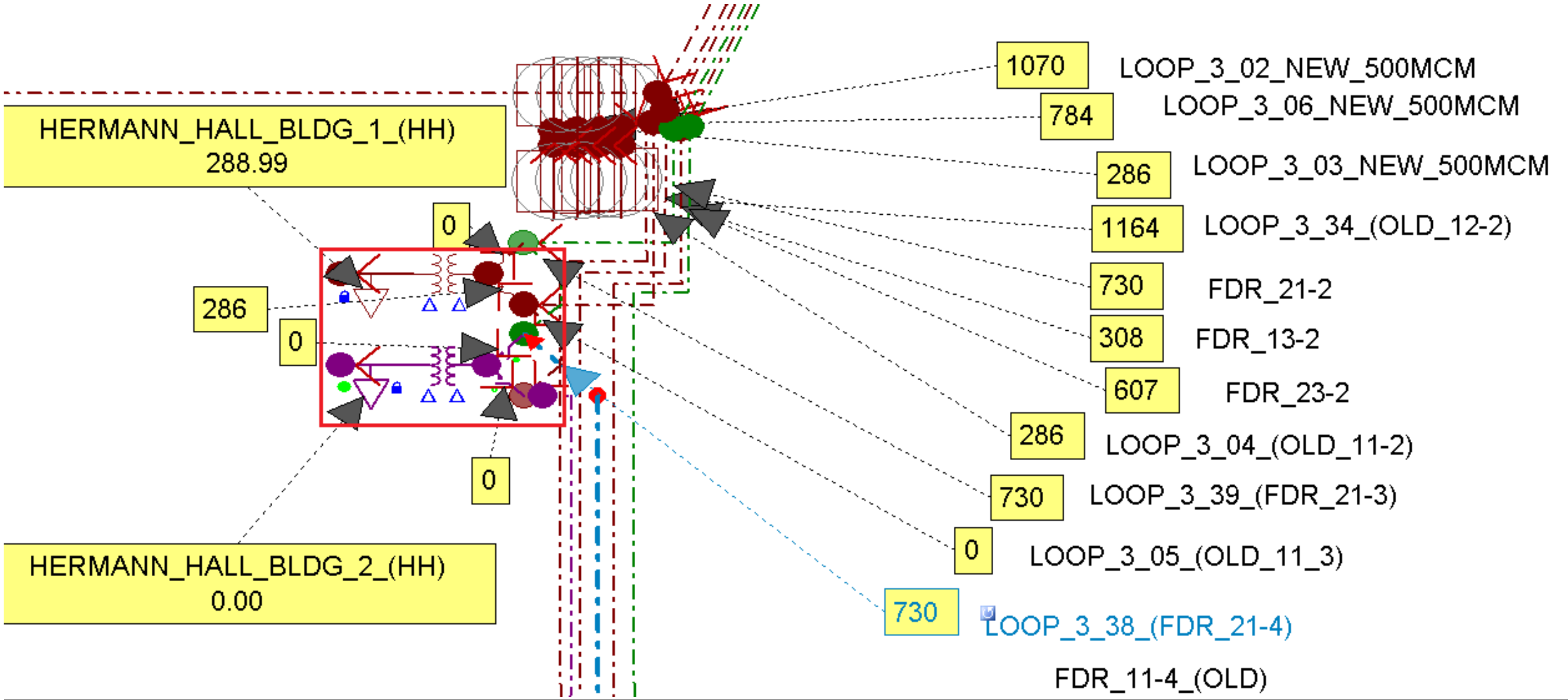
Connection	Equipment #	Equipment ID	Code	V	Length (ft)	Total Thro Power (KW)	Total Thro Power (KVAR)	Total Thro Power (KVA)	Pf avg (%)	Ibal (Amps)	Angle I
PH Node(2)-Vista Switch	LOOP_3_12_NEW_500MCM	500_EPR	Cable	119.8	205.7	0	0	0	0	0	0
PH Node(3)-Vista Switch	LOOP_3_36_NEW_500MCM	500_EPR	Cable	119.8	64.8	0	0	0	0	0	89.96
	LOOP_3_10_NEW_500MCM	500_EPR	Cable	119.7	38.9	513	261	576	89.14	80	-27.01
	LOOP_3_17_NEW_500MCM	500_EPR	Cable	119.7	33.5	271	137	304	89.17	42.2	-26.98
	LOOP_3_09_NEW_500MCM	500_EPR	Cable	119.8	28.6	784	398	879	89.15	122.3	-27
PH Node(2)-PH Node(3)	LOOP_3_31_(OLD_12-5)	500_EPR	Cable	119.7	163.8	169	84	189	89.45	26.2	-26.63
	LOOP_3_18_(OLD_11-8)	500_EPR	Cable	119.7	157.4	271	137	304	89.17	42.2	-26.98
	LOOP_3_43_NEW_500MCM	500_EPR	Cable	119.7	166.9	0	0	0	0	0	0
PH Node(3)-MH(1) Node	LOOP_3_32_(OLD_12-4)	500_EPR	Cable	119.7	219.3	169	84	189	89.45	26.2	-26.63
	LOOP_3_08_(OLD_11-6)	500_EPR	Cable	119.8	220	784	399	880	89.14	122.3	-27
	LOOP_3_37_(FDR_21-6)	500_EPR	Cable	119.8	219.2	0	0	0	0	0	89.96
MH(1) Node-MH(2) Node	FDR_23-3	350_EPR	Cable	119.8	170.1	607	315	684	88.78	95	-27.42
	FDR_13-3	500_EPR	Cable	119.9	169.5	308	149	342	89.99	47.5	-25.89
	LOOP_3_37_(FDR_21-5)	500_EPR	Cable	119.8	170.3	730	391	828	88.12	115.1	-28.24
	LOOP_3_33_(OLD_12-3)	500_EPR	Cable	119.7	165	1163	600	1309	88.87	182	-27.34
	LOOP_3_07_(OLD_11-5)	500_EPR	Cable	119.8	160.6	784	399	880	89.13	122.3	-27
PH Node(3)- PH Load	FDR_21-7	350_EPR	Cable	119.7	18.4	0	0	0	0	0	0
	LOOP_3_11_(OLD_11-7)	500_EPR	Cable	119.7	26.8	513	261	575	89.15	80	-27.01

MH(1) Node-MTCC/E1 Node	FDR_23-4	350_EPR	Cable	119.8	188.8	607	315	684	88.79	95	-27.42
	FDR_13-4	500_EPR	Cable	119.9	237.5	308	149	342	89.99	47.5	-25.89
	FDR_12-10	500_EPR	Cable	119.6	257.3	994	515	1120	88.79	155.8	-27.46
	FDR_21-14	500_EPR	Cable	119.8	245.4	730	391	828	88.13	115.1	-28.24

Where,

MH (1), MH (2) – Memorial Hall
WH – Wishnick Hall
MTCC/E1 – MTCC (1 node) and Engineering 1 (3 nodes)
[Note: All the calculations are performed on steady state analysis of the system and hence the power flows show very little loss in the network.]

Section 3:



The yellow boxes represent the following (from top)

1. Total through kW

The red boxes represent the department buildings and the one on the right is **Hermann Hall**. The black dot and dashed lines are the cable lines which connect the loads and the nodes in the distribution network.

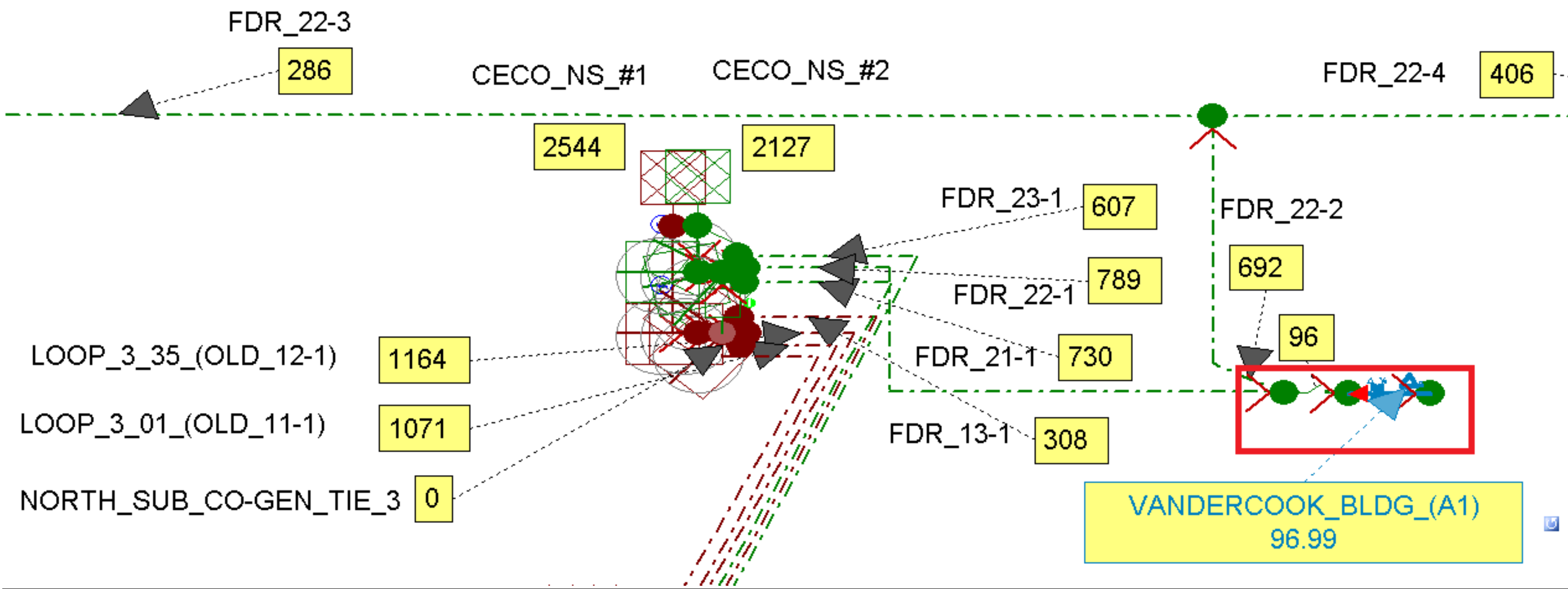
Let us see the line flows in this section in the following table.

Connection	Equipment #	Equipment ID	Code	V	Length (ft)	Total Thro Power (KW)	Total Thro Power (KVAR)	Total Thro Power (KVA)	Pf avg (%)	Ibal (Amps)	Angle I
MH(2) Node-NSS(2) Node	LOOP_3_06_NEW_500MCM	500_EPR	Cable	120	51.6	784	399	880	89.13	122.3	-27
	LOOP_3_34_(OLD_12-2)	500_EPR	Cable	120	221.7	1164	601	1310	88.85	182	-27.34
	FDR_13-2	500_EPR	Cable	120	216.2	308	149	342	89.98	47.5	-25.89
	FDR_23-2	350_EPR	Cable	120	212.6	607	315	684	88.77	95	-27.42
NSS(2) Node-Vista Switch	LOOP_3_02_NEW_500MCM	500_EPR	Cable	120	13.4	1070	545	1201	89.11	166.8	-27.02
	LOOP_3_03_NEW_500MCM	500_EPR	Cable	120	23	286	146	321	89.05	44.6	-27.1
HH(2Green) Node-NSS(2) Node	FDR_21-2	500_EPR	Cable	120	78.7	730	392	829	88.11	115.1	-28.24
HH(2Red) Node-NSS(2) Node	LOOP_3_04_(OLD_11-2)	500_EPR	Cable	120	92.9	286	146	321	89.05	44.6	-27.1
HH(2Red) Node-HH(2Red) Node	LOOP_3_39_(FDR_21-3)	500_EPR	Cable	120	38.4	730	392	829	88.12	115.1	-28.24
HH(2Green) Node-HH(2Green) Node	LOOP_3_05_(OLD_11_3)	500_EPR	Cable	120	38.2	0	0	0	0	0	0
NSS(2) Node-SSS Node	NORTH_SUB_CO-GEN_TIE_2	500_EPR_3_SETS	Cable	120	664.6	0	0	0	0	0	89.98
MH(2) Node-HH(2Green) Node	LOOP_3_38_(FDR_21-4)	500_EPR	Cable	120	138.6	730	392	828	88.12	115.1	-28.24

Where,

MH (1), MH (2) – Memorial Hall
NSS (2) – North Sub Station
SSS – South Sub Station
HH (1A), HH (1B), HH (2Red), HH (2Green) – Hermann Hall
[Note: All the calculations are performed on steady state analysis of the system and hence the power flows show very little loss in the network.]

Section 4:



The yellow boxes represent the following (from top)

1. Total through kW

The red boxes represent the department buildings and the one on the left is the **North Sub Station** and the one on the right is the **Vander Cook School of Music**. The black dot and dashed lines are the cable lines which connect the loads and the nodes in the distribution network.
Let us see the line flows in this section in the following table.

Connection	Equipment #	Equipment ID	Code	V	Length (ft)	Total Thro Power (KW)	Total Thro Power (KVAR)	Total Thro Power (KVA)	Pf avg (%)	Ibal (Amps)	Angle I
NSS(1) Node-NSS(2) Node	NORTH_SUB_CO-GEN_TIE_3	500_EPR_3_SETS	Cable	119.9	150.5	0	0	0	0	0	89.98
	FDR_13-1	500_EPR	Cable	119.9	167.6	308	149	342	89.98	47.5	-25.89
	LOOP_3_35_(OLD_12-1)	500_EPR	Cable	119.9	152.1	1164	602	1311	88.84	182	-27.34
	LOOP_3_01_(OLD_11-1)	500_EPR	Cable	119.9	145.8	1071	546	1202	89.1	166.8	-27.02
	FDR_22-1	350_EPR	Cable	119.9	188.7	789	402	885	89.11	122.9	-27
	FDR_23-1	350_EPR	Cable	119.9	185.1	607	315	684	88.77	95	-27.42
	FDR_21-1	500_EPR	Cable	119.9	182.6	730	392	829	88.1	115.1	-28.24

Where,

NSS (1), NSS (2) – North Sub Station

[Note: All the calculations are performed on steady state analysis of the system and hence the power flows show very little loss in the network.]

Open Circuit Study

A comprehensive open circuit study was conducted on each and every cable in the loop 3 (#43) and the various power flows and abnormalities were noted down. The abnormalities include overloads on a particular component or low voltage levels (low reactive power levels as well). From the above analysis, we could determine that the following components in the various feeders were being stressed in the system.

Let us look at each of the Feeders individually to check for overloads in the system.

1. CECO_SS_#1:

Feeder ID	Section ID	Equipment ID	Code	Loading A (%)	Thru Power A (kW)	Thru Power A (kVAR)	VA (%)
CECO_SS_#1	CECO_SS_#1_INC	DEFAULT	Relay	864.1	1836.3	964.8	99.95
CECO_SS_#1	FDR_9_FO_75KVA_XFMR	75KVA_2.8%	Transformer	100.8	22.7	11.7	97.14
CECO_SS_#1	FDR_9_RN_300KVA_XFMR	300KVA_5.23%	Transformer	100.2	90.4	49.4	95.84
CECO_SS_#1	FDR_9_CY_300KVA_XFMR	300KVA_5.23%	Transformer	102.3	92.3	50.6	95.48
CECO_SS_#1	FDR_9_GU_300KVA_XFMR	300KVA_5.1%	Transformer	102.4	92.4	50.5	95.62
CECO_SS_#1	FDR_9_CA_300KVA_XFMR	300KVA_5.23%	Transformer	102.4	92.4	50.7	95.61

2. CECO_SS_#2:

Feeder ID	Section ID	Equipment ID	Code	Loading A (%)	Thru Power A (kW)	Thru Power A (kVAR)	VA (%)
CECO_SS_#2	CECO_SS_#2_INC	DEFAULT	Relay	462.1	982.4	515.5	99.96
CECO_SS_#2	SOUTH_SUB_FDR_6	DEFAULT	Relay	275.6	585.7	307.3	99.94

3. CECO_NS_#2:

Feeder ID	Section ID	Equipment ID	Code	Loading A (%)	Thru Power A (kW)	Thru Power A (kVAR)	VA (%)
CECO_NS_#2	FDR_22_MH_300KVA_XFMR	300KVA_2.5%	Transformer	105.8	95.3	49	98.47

In total there are **9 components** in the system which is impacted by the open circuit in almost each and every case for loop 3. Also, the CECO_NS_#1 does not have any abnormalities in terms of overloading. Of the 9 components all of them are transformers and relays in the system.

One thing we must keep in mind is that these values are for **"peak load"**, means that all the loads are peaking at the same time whose probability is very less and will never happen realistically. Hence the overloads on the relays can be said as exaggerations but these relays must be kept under watch in real-time operations for upgrade in the future.

[Note: The values for these components are taken from the power flow analysis of the system in one of the open circuit conditions. Although the values might differ a little in each case but these components appear in almost all the open circuit study cases.]

Let us look at each of the Feeders individually to check for low voltages in the system.

1. CECO_SS_#1:

Feeder ID	Section ID	Equipment ID	Code	Loading A (%)	Thru Power A (kW)	Thru Power A (kVAR)	VA (%)
CECO_SS_#1	FDR_9_CA_300KVA_XFMR	BUS_SECTION	Line	22.3	92.2	44.7	95.61
CECO_SS_#1	FDR_9_FH_100KVA_XFMR	100KVA_3.75%	Transformer	97.1	29.2	15.4	97.06
CECO_SS_#1	FDR_9_FH_100KVA_XFMR	BUS_SECTION	Line	6.9	29.1	14.1	97.06
CECO_SS_#1	FDR_3_IITRI_RT_1000KVA_XFMR_3	1000KVA_6.2%	Transformer	76.8	230.9	124.6	96.91

CECO_SS_#1	FDR_3_IITRI_RT_1000KVA_XFMR_3	BUS_SECTION	Line	55	230.4	111.6	96.91
CECO_SS_#1	FDR_3_IITRI_RT_1000KVA_XFMR_4	1000KVA_5.78%	Transformer	88.4	265.7	144.5	96.72
CECO_SS_#1	FDR_3_IITRI_RT_1000KVA_XFMR_4	BUS_SECTION	Line	27.5	265.2	128.4	96.72
CECO_SS_#1	FDR_9_BLDG_42_30KVA_XFMR	30KVA_3%	Transformer	12.2	11	5.8	96.8
CECO_SS_#1	FDR_9_BLDG_42_30KVA_XFMR	BUS_SECTION	Line	2.6	11	5.3	96.8
CECO_SS_#1	FDR_9_RE_150KVA_XFMR	150KVA_4.18%	Transformer	99.4	44.8	23.9	96.5
CECO_SS_#1	FDR_9_RE_150KVA_XFMR	BUS_SECTION	Line	10.7	44.7	21.7	96.5
CECO_SS_#1	FDR_9_FO_75KVA_XFMR	BUS_SECTION	Line	5.4	22.7	11	97.14
CECO_SS_#1	FDR_9_RN_300KVA_XFMR	BUS_SECTION	Line	21.8	90.2	43.7	95.84
CECO_SS_#1	FDR_9_CY_300KVA_XFMR	BUS_SECTION	Line	22.3	92.1	44.6	95.48
CECO_SS_#1	FDR_9_GU_300KVA_XFMR	BUS_SECTION	Line	22.3	92.2	44.7	95.62

2. CECO_SS_#2:

Feeder ID	Section ID	Equipment ID	Code	Loading A (%)	Thru Power A (kW)	Thru Power A (kVAR)	VA (%)
CECO_SS_#2	FDR_6_LSR_CHILLERS_2000KVA_XFMR	BUS_SECTION	Line	39.3	382.6	186.6	97.22
CECO_SS_#2	FDR_8_IITRI_RT_CHILLERS	750KVA_6.1%	Transformer	92.6	208.7	114.8	96.82
CECO_SS_#2	FDR_8_IITRI_RT_CHILLERS	BUS_SECTION	Line	21.6	208.3	100.9	96.82

3. CECO_NS_#2:

Feeder ID	Section ID	Equipment ID	Code	Loading A (%)	Thru Power A (kW)	Thru Power A (kVAR)	VA (%)
CECO_NS_#2	FDR_23_KH_500KVA_XFMR	500KVA_6.5%	Transformer	70.5	105.9	56.9	97.28
CECO_NS_#2	FDR_23_KH_500KVA_XFMR	BUS_SECTION	Line	24.9	105.7	51.2	97.28

In total there are **20 components** in the system which is impacted by the open circuit in almost each and every case for loop 3. Also, the CECO_NS_#1 does not have any abnormalities in terms of overloading. Of the 20 components all of them are transformers and lines/cables in the system.

The drop in the reactive power in this case might not be too drastic but in order to create a reliable system we need to push these reactive power values to acceptable limits. Since, these values are for all peak loads in the system and realistically since it is not the case. The reduction in reactive power might me also less making these lines and transformers more reliable.

[Note: The values for these components are taken from the power flow analysis of the system in one of the open circuit conditions. Although the values might differ a little in each case but these components appear in almost all the open circuit study cases.]

Comprehensive Short Circuit Study:

The short circuit study was conducted for all the lines together and a report was generated in CYME for the most impacted sections for each case. There can be 3 cases, one being the steady state operations, the second being sun-transient and the last being the transient mode of operations. All these cases were tested with all the 4 feeders connected in service.

The above three cases could be studied for another 3 sets of input voltages to the solution. The first being the base voltage for doing the short circuit study, the second being the load flow solution voltages after a base case power flow has been run and finally the operating voltage of the network was taken for the implementation of the short circuit study.

I will be showing you the results for the Base voltage under steady state operations which was one of the cases studied from the ones discussed above.

1. Base Voltage (Steady State Operation):

Fault Current Summary

Feeder	**CECO_NS_#1**
Source Voltage	4.16 kVLL 0.00 Deg.
Parameters	
Security Factor (K)	Max. = 1.00 Min. = 0.40
Zf For Line 'LG' Fault	0.00 +j 0.00 Ohms
Zf For Line 'LLL' Fault	0.00 +j 0.00 Ohms
Generator Impedance	Steady State Impedance
MVA Base	100.00 MVA
Conductor Resistance Selection	25C

Summary

Fault Type	Section Id	Bolted (Amps)	Kmax (Amps)	KmaxZ (Amps)	Kmin (Amps)	KminZ (Amps)
Max 3 Phase Fault	LOOP_3_WH_750KVA_XFMR	43335.3	43335.3	43335.3	17334.1	17334.1
Min 3 Phase Fault	STUART_BLDG_(SB-COMPUTER)	12232.3	12232.3	12232.3	4892.9	4892.9
Max 2 Phase Fault	LOOP_3_WH_750KVA_XFMR	37529.5	37529.5	37529.5	15011.8	15011.8
Min 2 Phase Fault	STUART_BLDG_(SB-COMPUTER)	10593.5	10593.5	10593.5	4237.4	4237.4
Max 2 Phase Ground Fault	LOOP_3_WH_750KVA_XFMR	44395.5	44395.5	44395.5	17758.2	7103.3
Min 2 Phase Ground Fault	STUART_BLDG_(SB-COMPUTER)	11873.4	11873.4	11873.4	4749.4	1899.7
Max 1 Phase Ground Fault	LOOP_3_WH_750KVA_XFMR	44771.3	44771.3	44771.3	17908.5	17908.5
Min 1 Phase Ground Fault	STUART_BLDG_(SB-COMPUTER)	10828.9	10828.9	10828.9	4331.6	4331.6

Feeder **CECO_NS_#2**

Source Voltage 4.16 kVLL

Parameters

Security Factor (K) Max. = 1.00 Min. = 0.40
Zf For Line 'LG' Fault 0.00 +j 0.00 Ohms
Zf For Line 'LLL' Fault 0.00 +j 0.00 Ohms
Generator Impedance Steady State Impedance
MVA Base 100.00 MVA
Conductor Resistance Selection 25C

Summary

Fault Type	Section Id	Bolted (Amps)	Kmax (Amps)	KmaxZ (Amps)	Kmin (Amps)	KminZ (Amps)
Max 3 Phase Fault	VISTA-3B_WAY-2	98902.3	98902.3	98902.3	39560.9	39560.9
Min 3 Phase Fault	FDR_22_A3_300KVA_XFMR	10912	10912	10912	4364.8	4364.8
Max 2 Phase Fault	VISTA-3B_WAY-2	85651.9	85651.9	85651.9	34260.8	34260.8
Min 2 Phase Fault	FDR_22_A3_300KVA_XFMR	9450	9450	9450	3780	3780
Max 2 Phase Ground Fault	VISTA-3B_WAY-2	99936.1	99936.1	99936.1	39974.4	15989.8
Min 2 Phase Ground Fault	FDR_22_A3_300KVA_XFMR	10625.4	10625.4	10625.4	4250.2	1700.1
Max 1 Phase Ground Fault	FDR_23_MTCC_2000KVA_XFMR	75581.4	75581.4	75581.4	30232.6	30232.6
Min 1 Phase Ground Fault	FDR_23-16	8534.6	8534.6	8534.6	3413.8	3413.8

Feeder **CECO_SS_#1**

Source Voltage 4.16 kVLL 0.00 Deg.

Parameters

Security Factor (K) Max. = 1.00 Min. = 0.40
Zf For Line 'LG' Fault 0.00 +j 0.00 Ohms
Zf For Line 'LLL' Fault 0.00 +j 0.00 Ohms
Generator Impedance Steady State Impedance
MVA Base 100.00 MVA
Conductor Resistance Selection 25C

Summary

Fault Type	Section Id	Bolted (Amps)	Kmax (Amps)	KmaxZ (Amps)	Kmin (Amps)	KminZ (Amps)
Max 3 Phase Fault	FDR_9_BLDG_46_75KVA_XFMR	39738.1	39738.1	39738.1	15895.3	15895.3
Min 3 Phase Fault	FDR_9_BLDG_42_30KVA_XFMR	2644.2	2644.2	2644.2	1057.7	1057.7

Max 2 Phase Fault	FDR_9_BLDG_46_75KVA_XFMR	34414.2	34414.2	34414.2	13765.7	13765.7
Min 2 Phase Fault	FDR_9_BLDG_42_30KVA_XFMR	2289.9	2289.9	2289.9	916	916
Max 2 Phase Ground Fault	FDR_7_CRB_2500KVA_XFMR	40757.6	40757.6	40757.6	16303	6521.2
Min 2 Phase Ground Fault	FDR_9_BLDG_42_30KVA_XFMR	2623.4	2623.4	2623.4	1049.3	419.7
Max 1 Phase Ground Fault	FDR_7_CRB_2500KVA_XFMR	41682.4	41682.4	41682.4	16672.9	16672.9
Min 1 Phase Ground Fault	BLDG_42	2576.1	2576.1	2576.1	1030.4	1030.4

Feeder **CECO_SS_#2**

Source Voltage 4.16 kVLL 0.00 Deg.

Parameters

Security Factor (K) Max. = 1.00 Min. = 0.40

Zf For Line 'LG' Fault 0.00 +j 0.00 Ohms

Zf For Line 'LLL' Fault 0.00 +j 0.00 Ohms

Generator Impedance Steady State Impedance

MVA Base 100.00 MVA

Conductor Resistance Selection 25C

Summary

Fault Type	Section Id	Bolted (Amps)	Kmax (Amps)	KmaxZ (Amps)	Kmin (Amps)	KminZ (Amps)
Max 3 Phase Fault	FDR_3/8/21_CR_SW-175A	4457678.1	4457678.1	4457678.1	1783071.2	1783071.2
Min 3 Phase Fault	FDR_4_SSV_300KVA_XFMR_3	9681.4	9681.4	9681.4	3872.6	3872.6
Max 2 Phase Fault	FDR_3/8/21_CR_SW-175A	3860462.5	3860462.5	3860462.5	1544185	1544185

Min 2 Phase Fault	FDR_4_SSV_300KVA_XFMR_3	8384.4	8384.4	8384.4	3353.7	3353.7
Max 2 Phase Ground Fault	FDR_3/8/21_CR_SW-175A	4032827.5	4032827.5	4032827.5	1613131	645252.4
Min 2 Phase Ground Fault	BOILER_PLANT_2_(BP)	9399.7	9399.7	9399.7	3759.9	1503.9
Max 1 Phase Ground Fault	FDR_3/8/21_CR_SW-175A	2471922.8	2471922.8	2471922.8	988769.1	988769.1
Min 1 Phase Ground Fault	FDR_4_SSV_300KVA_XFMR_3	8827.1	8827.1	8827.1	3530.8	3530.8

These are the list of possible faults on all the feeders in case of a short circuit. The study of each and every line being short circuited will be done in the near future and be added to this report.

Conclusion:

- In this report I have given an overall picture of the various components in the IIT's distribution network.
- I have also listed the various loads in the network along with its demand values in terms of KW.
- After which I gave a report on the feeder details and how the power is distributed from the 2 substations in the network along with the power loss details.
- To give us an idea of how the power flows in the cables, I took a section of the network where my department (Siegel Hall) is situated and the line flows is shown in a snapshot along with a table of values.
- The perfect power project implementation was discussed briefly.
- The feeder loading report post the implementation of Loop 3 in the perfect power project is given.
- Then, the base case power flows for the Loop 3 in the above condition has been shown along with snapshots from the network.
- The open circuit study for the loop 3 was conducted using the CYME software and the components showing abnormal behavior (Low voltages and Overloads) have been listed above.
- A comprehensive short circuit study was also conducted with the help of the CYME software were the fault currents in each of the feeders have been listed with the minimum and maximum possible values listed above.

Appendix 3

IPPSC Communications Outline

Purpose
The purpose of this document is to outline the IPPSC communications requirements. Because the IPPSC will control critical functions on the IIT campus its communications are required to be reliable and secure.

Devices
The IPPSC will consist of primary supervisor software running on a server Stuart and several other agents, ether running on a server in Stuart, or located somewhere else on the campus. The other planned IPPSC modules are a Turbine Module, Building Control Module, and Solar PV Module, Distribution Module and possibly a Weather module.

Module	Proposed Locations	Summary of Primary Functions	Critical Functions
Primary Supervisory	Stuart	Sorting data, primary user interface, processing data, model building, and determination of campus, building, distribution and generation modes.	• Coordinating communications between controllers and agents. This function can be backed up with back up supervisors in the other controllers/agents.
Building Agent	Stuart	Reporting feedback temperature data, setting load reduction modes, communicates with Siemens servers which is the gateway for the building controllers.	• Coordinating building load management with turbines during outages and setting demand response modes
Turbine Agent	Turbine Controller Room	Report turbine output and efficiency information, communicate real time load capacity to HRDS and building controllers.	• Coordinate load management with building and HRDS during outage or DR event
Solar PV Agent	Siegel	Report PV output and expected output given weather conditions.	• None, could be more critical if it were to become a larger portion of on campus generation
Distribution Agent	Stuart or substations	Report distribution fault and power data, provide gateway for remotely controlling switches.	• Coordinating load management with turbines during outage

Weather	near weather station	Correlates campus weather with internet forecasts.	• none

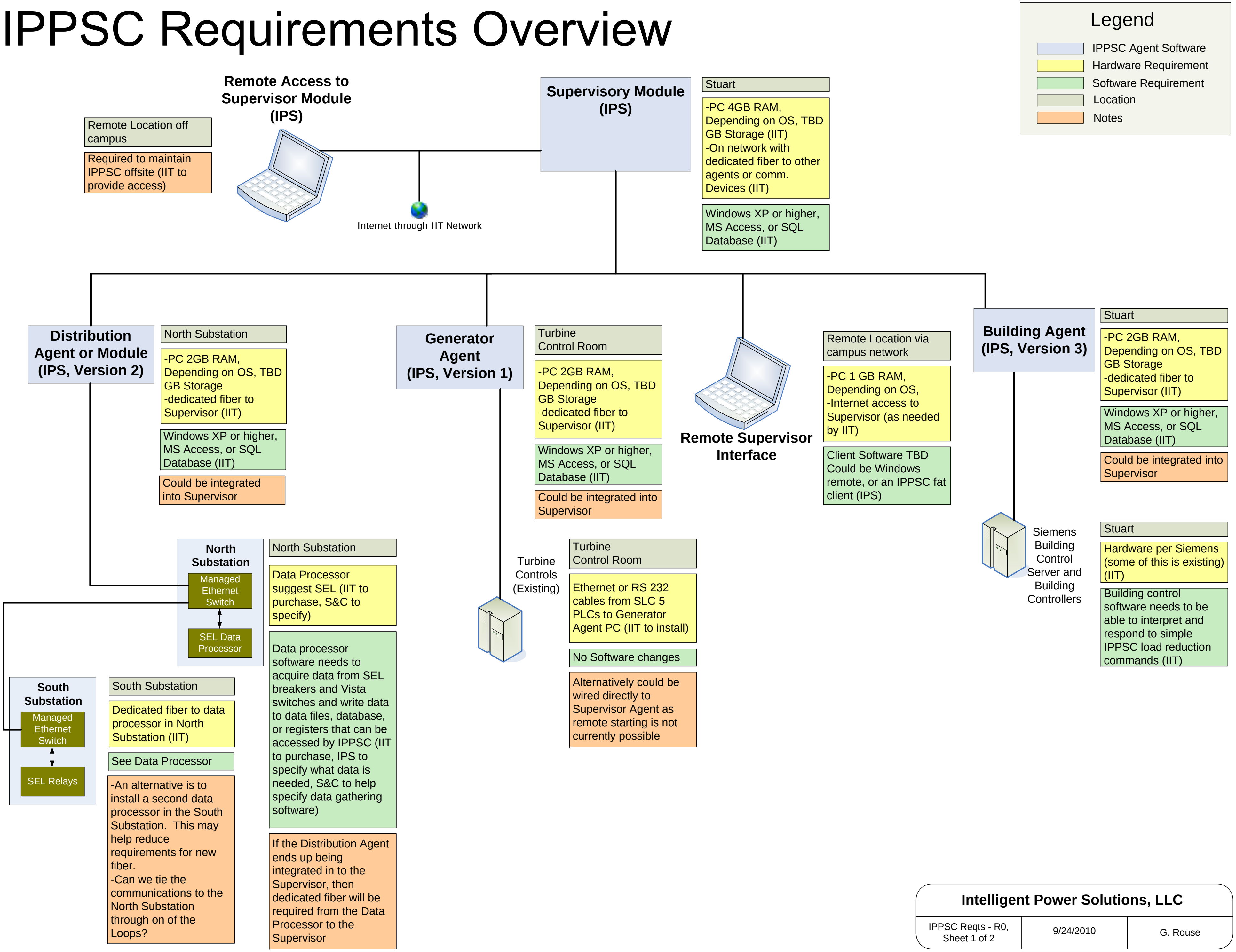
Communication Approach

The IPPSC will require dedicated lines between the Supervisor and remote agents. We are proposing to house the supervisor in one the IIT servers. The building agent and possibly the distribution agent would also reside on server in Stuart. A dedicated line is required between Stuart and Machinery Hall for remote communications to the IPPSC.

Two Siemens building servers also reside in Stuart, so housing the building agent and supervisor in Stuart will make communications easier and require less wire.

Dedicate lines are proposed to isolate the IPPSC from hackers. With a dedicated line, hacking will require physically breaking into the IPPSC system. We are assuming that the IPPSC agents operating on the IIT server can be maintained and backed up by IIT IT staff. Using dedicated lines between the slave agents and the supervisor offers a more secure communications solution.

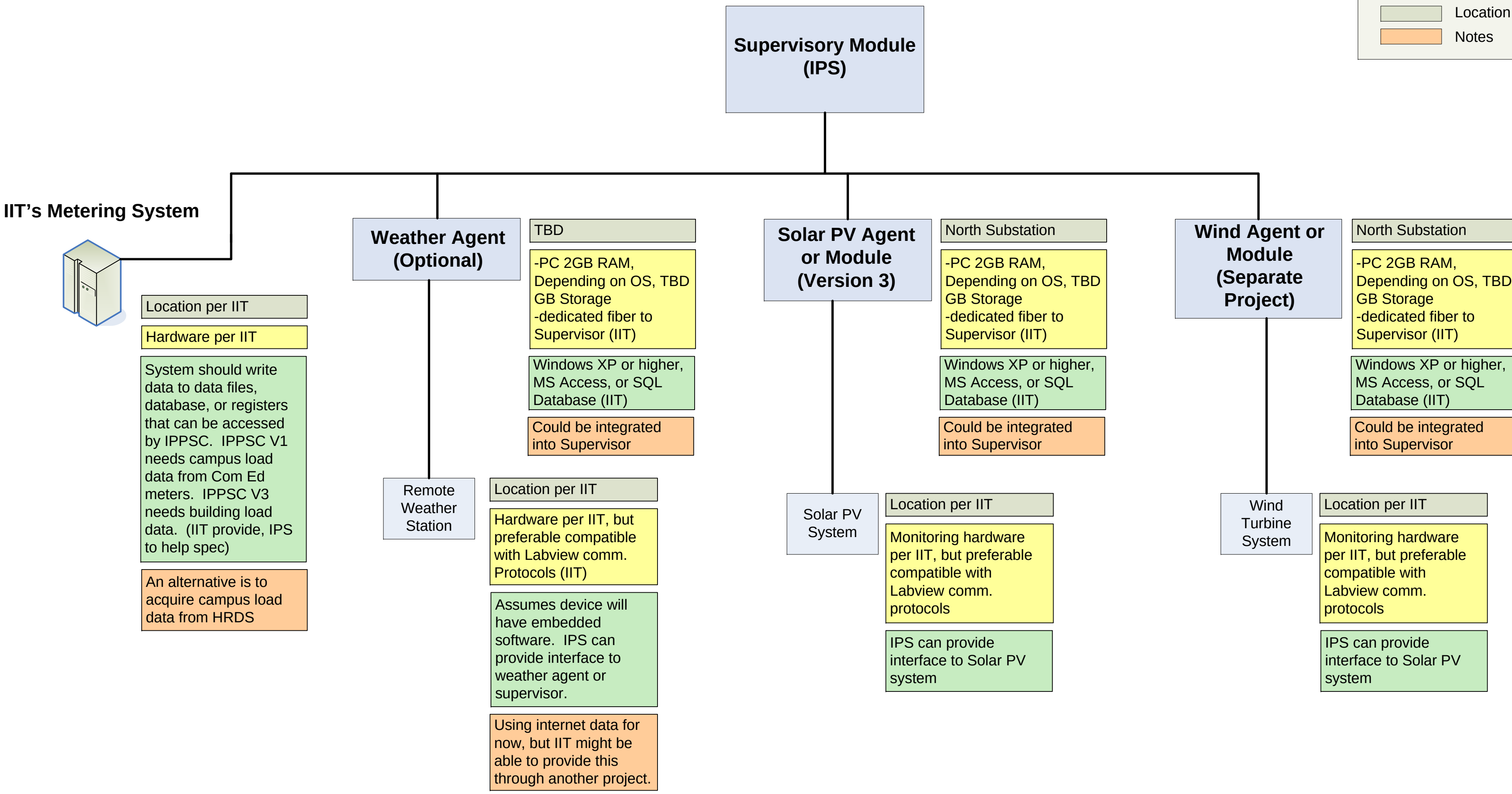
IPPSC Requirements Overview



IPPSC Requirements Overview (Cont.)

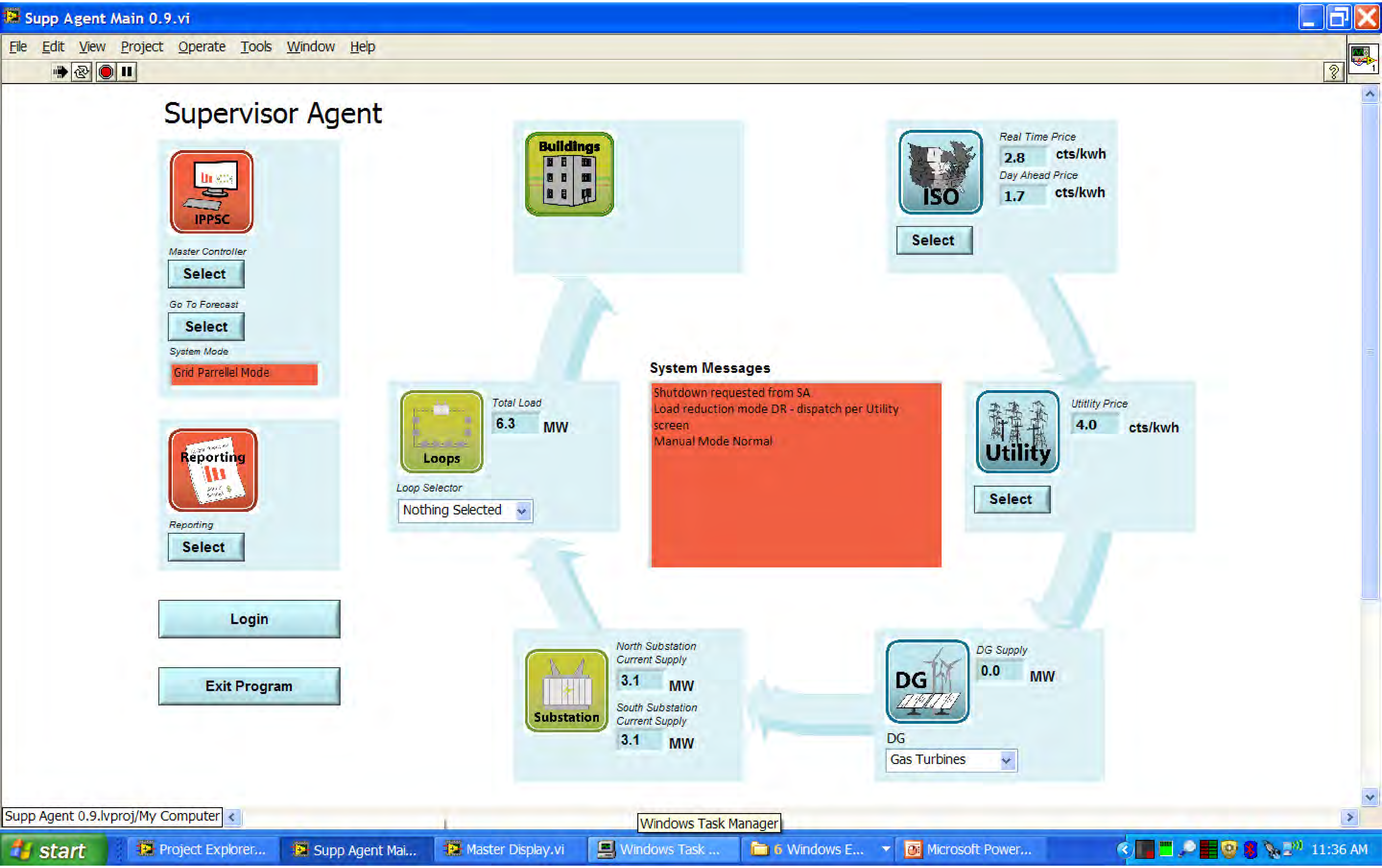
Legend

- IPPSC Agent Software
- Hardware Requirement
- Software Requirement
- Location
- Notes



Main Screen

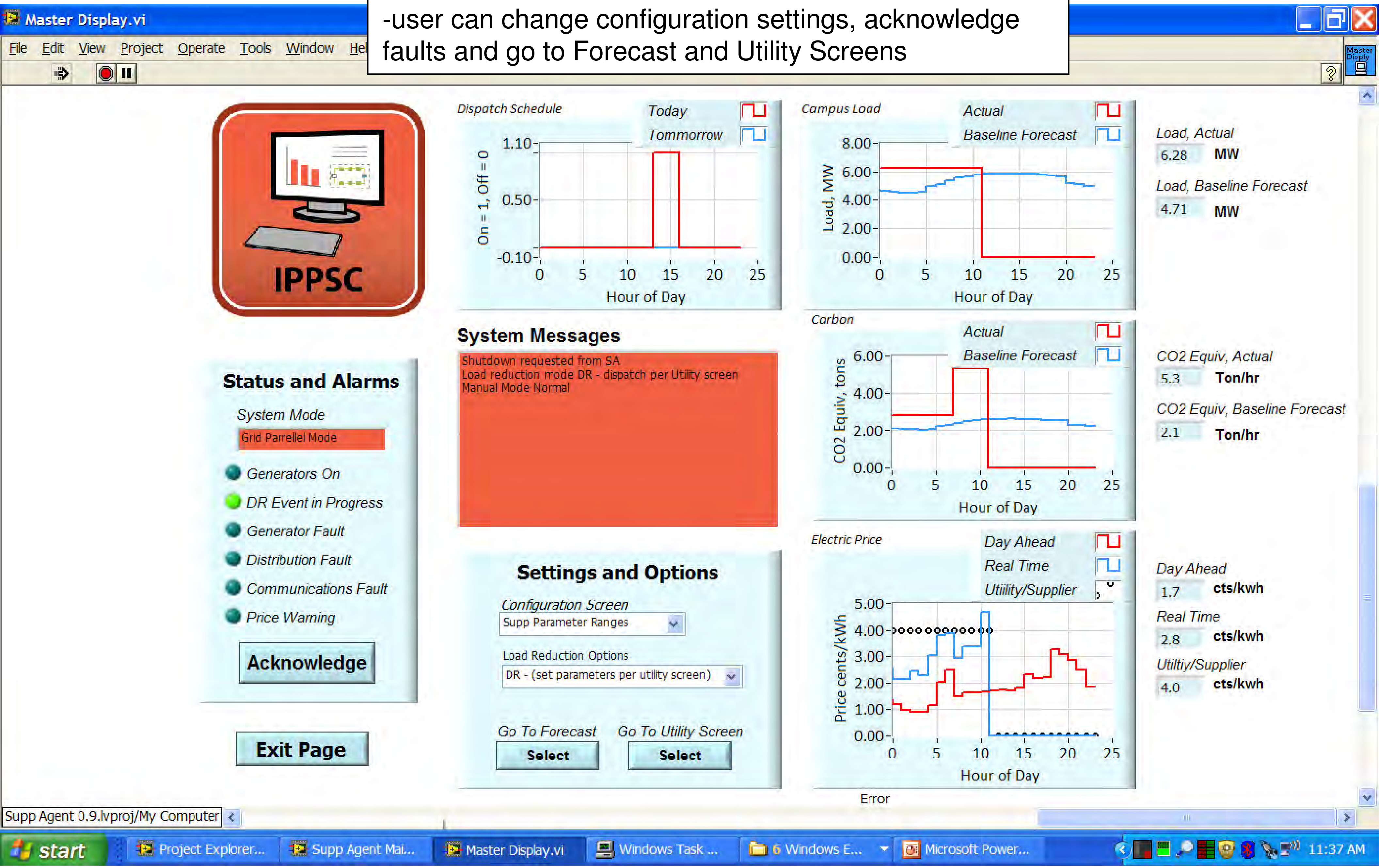
-user can select other screens to get more info and change settings



Master Controller Screen

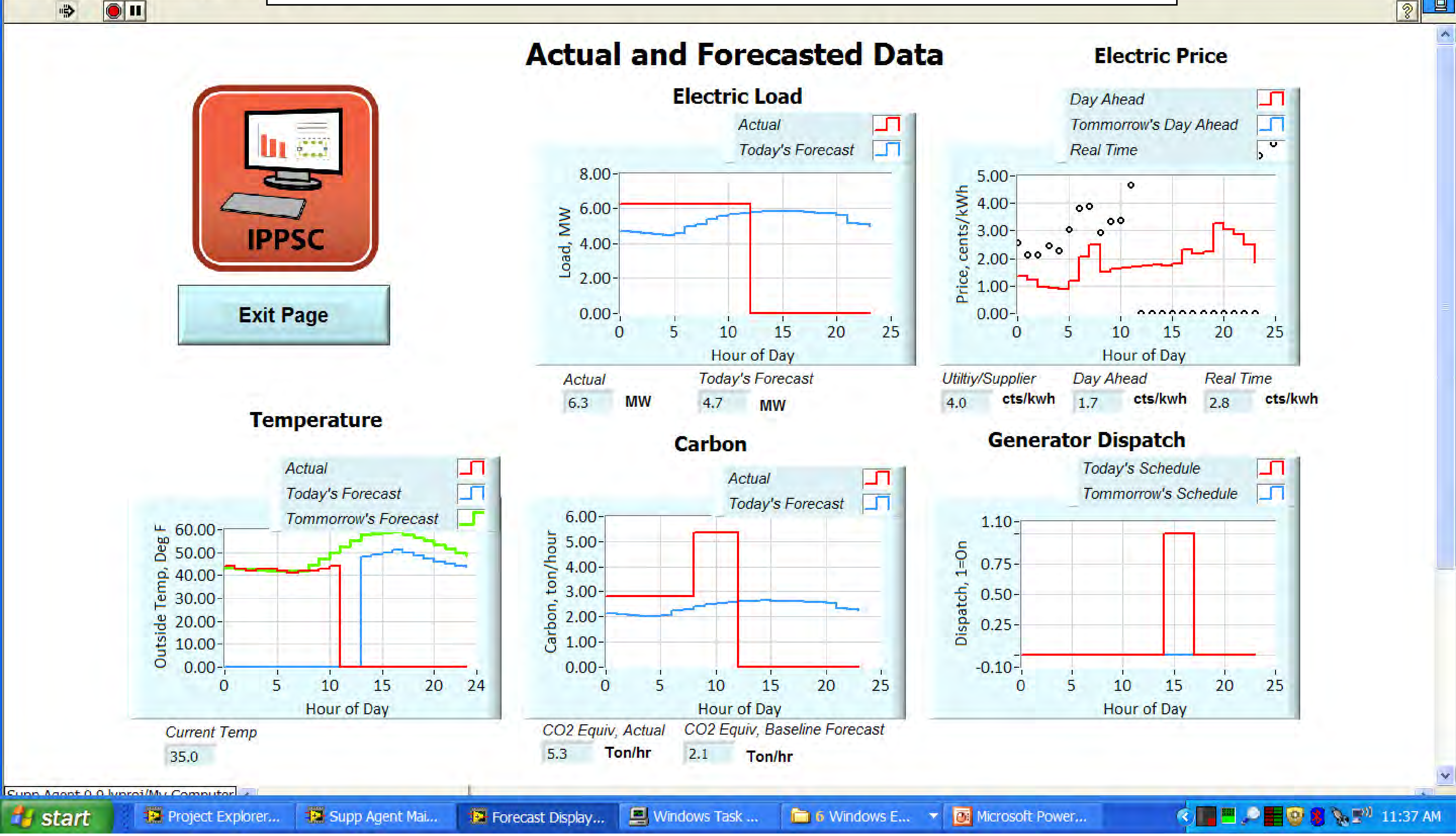
-provides overview

-user can change configuration settings, acknowledge faults and go to Forecast and Utility Screens



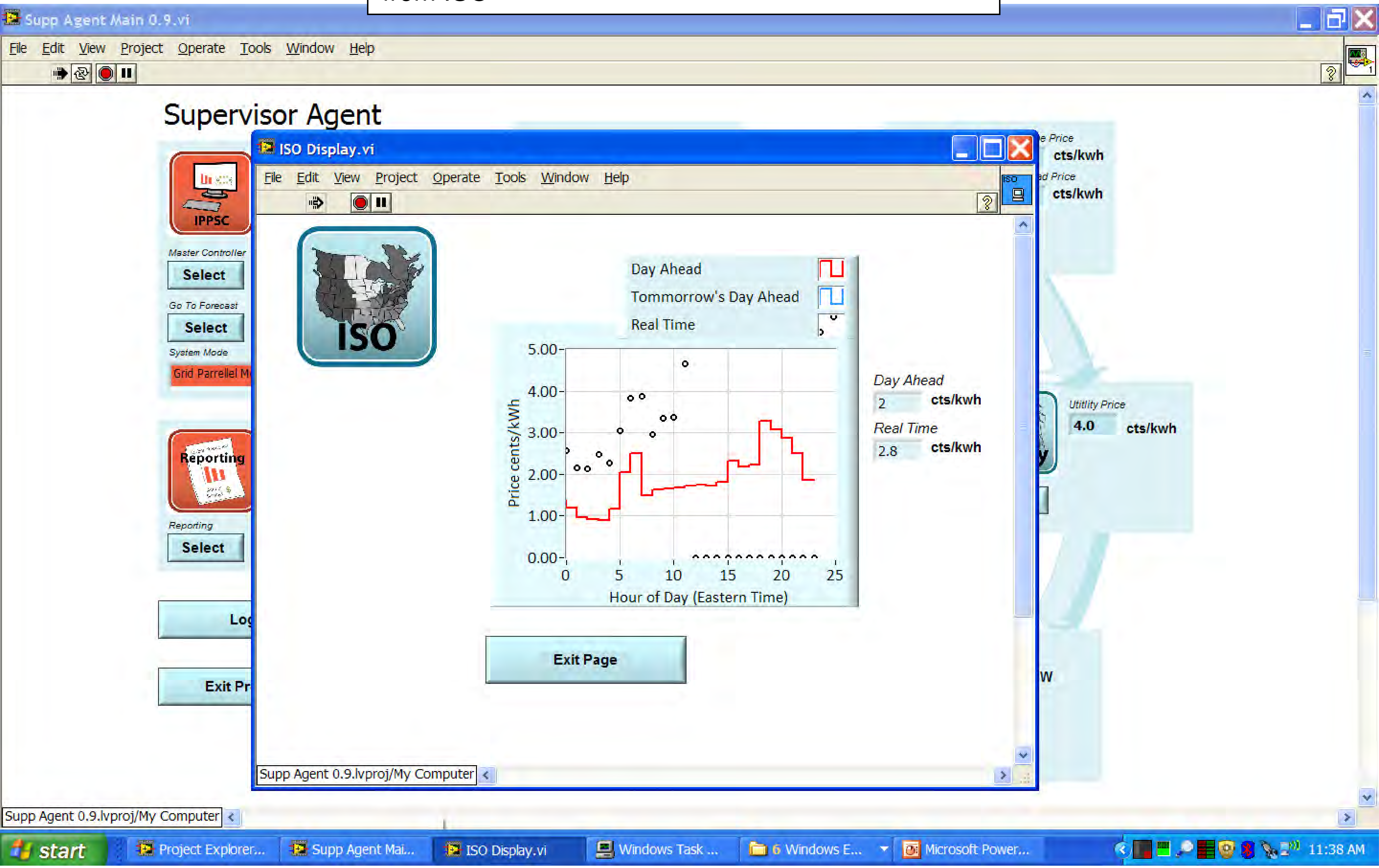
Forecast Screen

-user can monitor forecasted and actual loads, forecasted and actual carbon, forecasted and actual temperature, generator dispatch schedule and real time and day ahead prices from the ISO.



ISO Screen

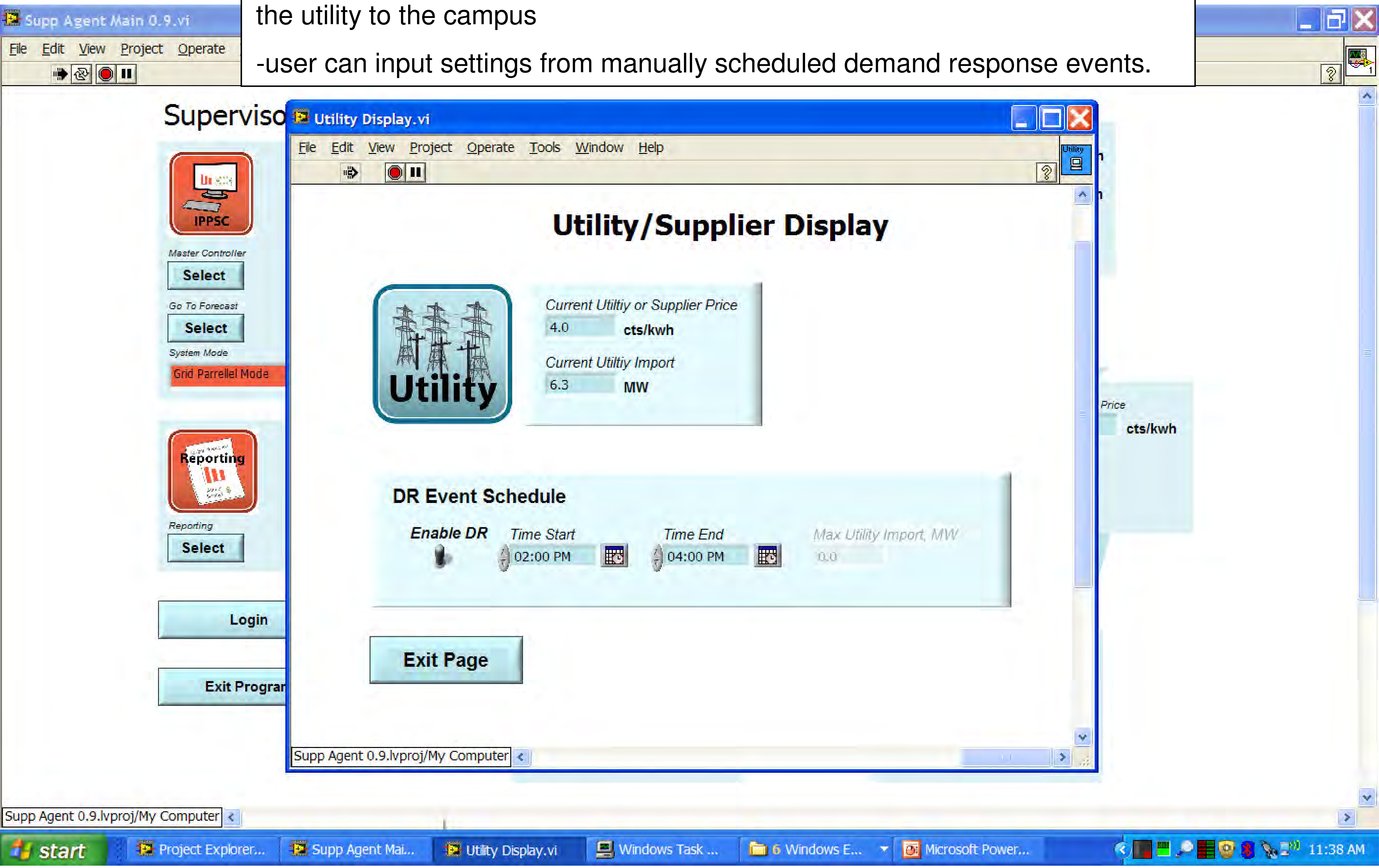
-user can monitor real time and day ahead prices from ISO



Utility Screen

-user monitor utility or third party supplier rates and the power imported from the utility to the campus

-user can input settings from manually scheduled demand response events.

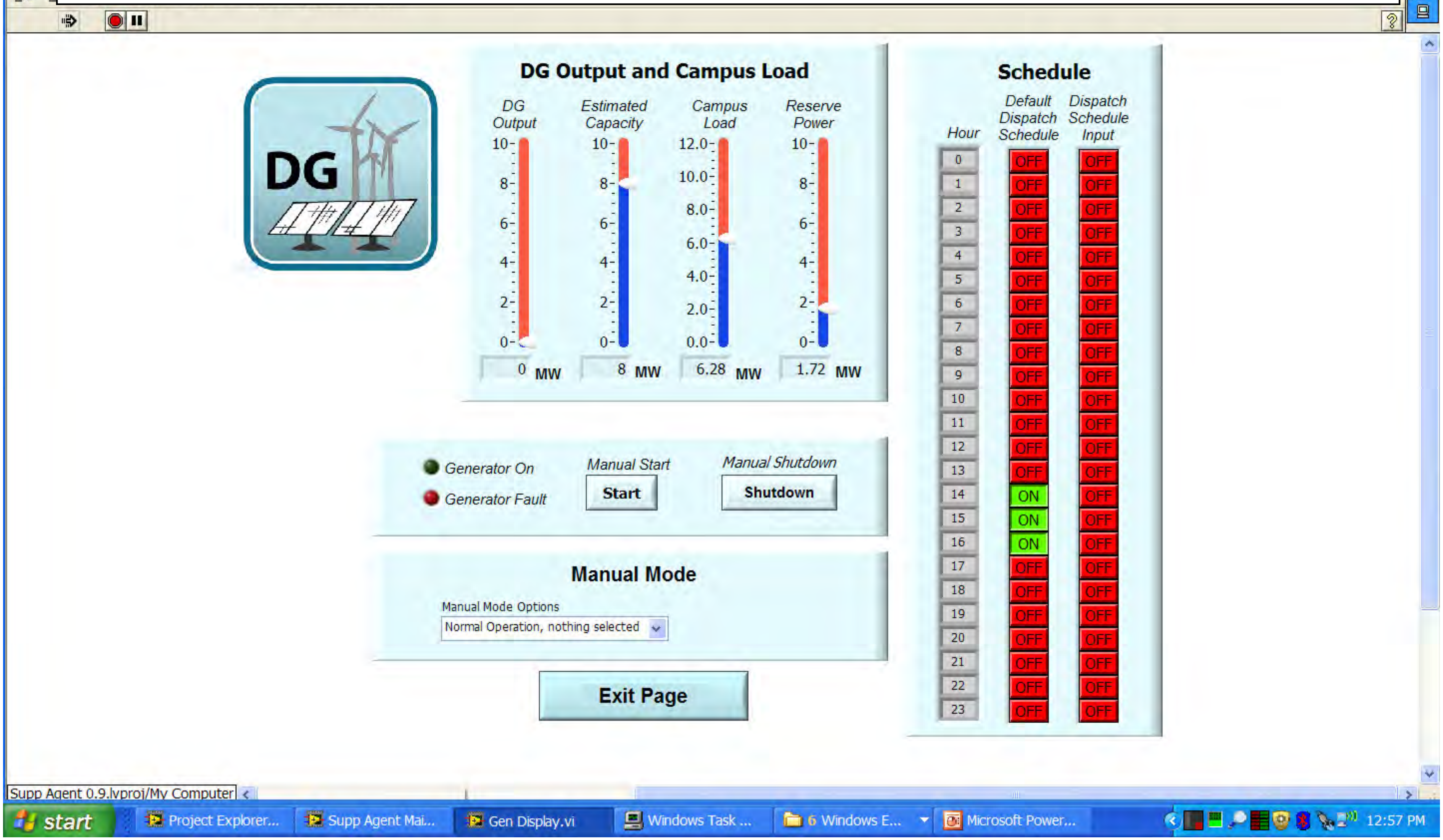


Distribution Generation Screen

-this is the screen for the gas turbines, there will be additional screens for Solar and Wind

-this screen lets the user see campus load, estimated generation capacity and estimate reserve power, and the actual turbine output.

-the user can also provide settings to manually send start and stop signals to the turbines, let IPPSC determine a dispatch schedule automatically, or override the automatic dispatch schedule by manually selecting the hours that the turbines should run.



Appendix 4

Appendix 5

EnergyToday
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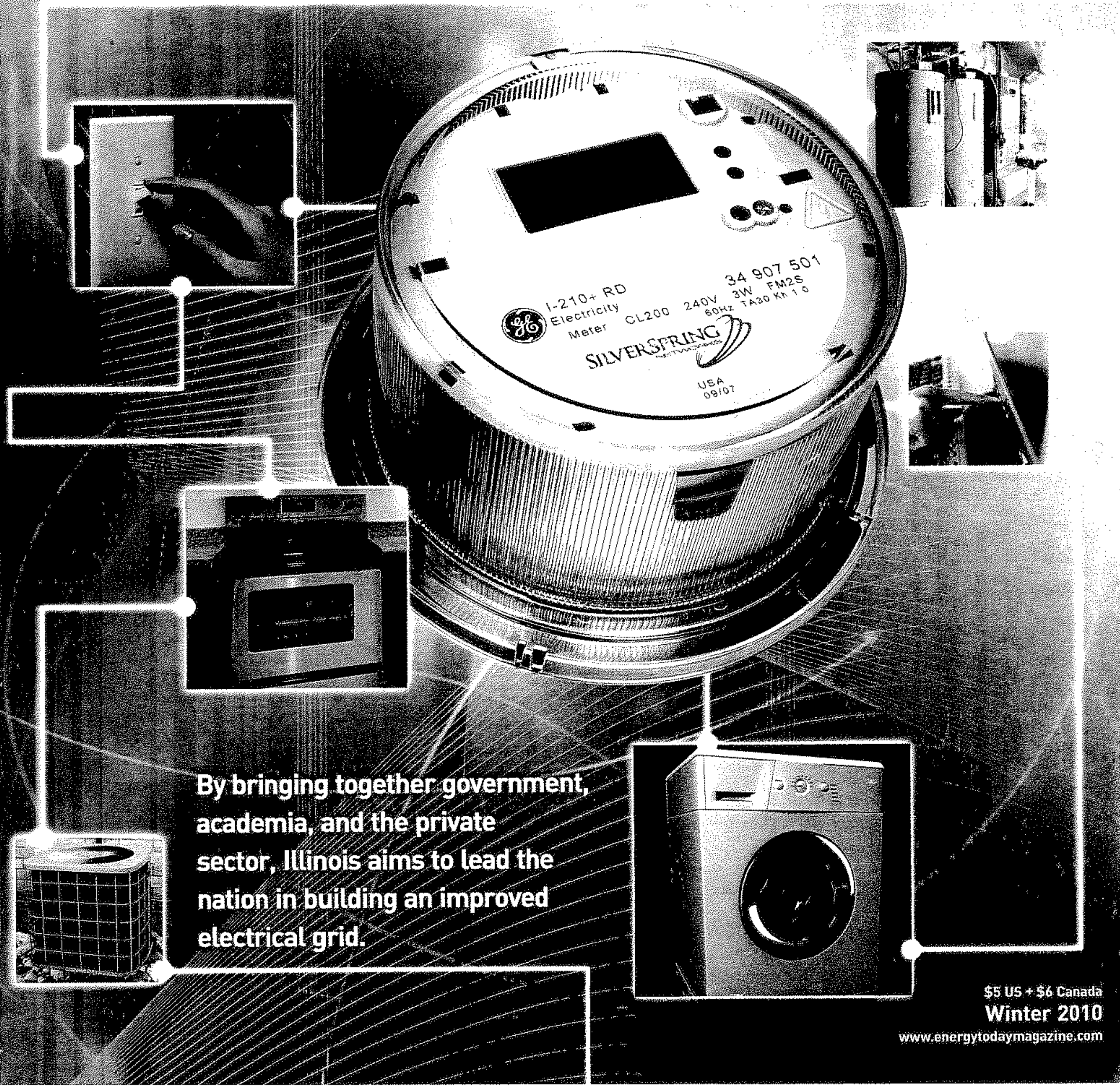
Get Smart



By bringing together government, academia, and the private sector, Illinois aims to lead the nation in building an improved electrical grid.

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funds that would be matched by state government and private entity monies. The proposal did not receive funding in the latest round of stimulus money awards, but all of the players involved say the project will go forward, albeit more slowly.

Dream big

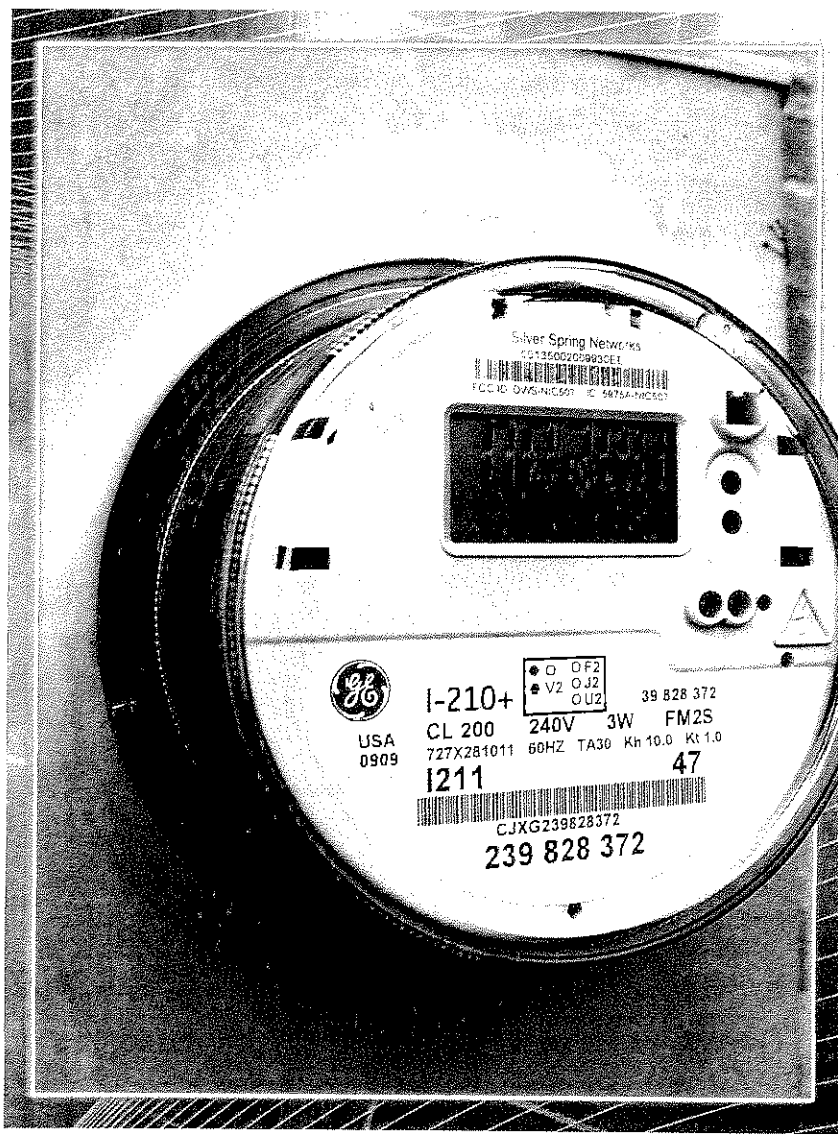
The roots of today's smart grid projects in Illinois go back to 2005, when former Motorola CEO Robert Galvin and Kurt Yeager formed the Galvin Electricity Initiative with the lofty goal of transforming the power system. Yeager, executive director, says the nonprofit aims to create new business opportunities for entrepreneurial companies to transform power the same way telecommunications has been transformed.

Prior to joining the initiative, Yeager had been head of the Electric Power Research Institute, and he asked his former colleagues to create the architecture for a more reliable system. By the end of 2006, the Perfect Power microgrid was ready to be implemented.

"Perfect Power will never fail to provide each consumer, whether it's a large business or a homeowner, exactly the quantity and quality of electricity they need. They can depend on lights, computers, and assembly lines never going down," said Yeager.

Mohammad Shahidehpour, head of IIT's electrical and computer engineering department, had met Galvin at a meeting shortly after the Northeast Blackout of 2003. Shahidehpour mentioned the difficulties IIT was having with its electrical system, and eventually, IIT was chosen as the first pilot site for Perfect Power.

"Our system was old and had grown to the point where the original design was not functional any more," said Shahidehpour. "The price of maintaining the system and our electricity bill had been increasing, primarily because the system was outdated. It's a microcosm of the national problem—IIT is essentially a small city made up of dorms, cafeterias, and faculty offices."



IIT applied for a DoE grant in 2006 and received $7 million; an additional $5 million was provided by the university and several private entities. There were three components to the project: reliability (problems are contained in a small area rather than affecting other parts of the system), self-sustained generation (use IIT's existing power plant plus renewable energy installations), and load reduction.

Shahidehpour said the increase in reliability comes from smart switches that open or close automatically in the event of a fault or disturbance, containing the problem. "We may lose one building, but it won't be like before, where we lost all 50 buildings at once," he said.

Live like the Jetsons

The load reduction is perhaps the most significant part of the project, according to Shahidehpour. It involves a new type of controller installed in a number of campus buildings that's designed to communicate with wireless sensors. The controllers receive real-time electricity pricing from the utility and turn various appliances and heating/cooling units on and off, completing "jobs" that require electricity at the least cost. IIT's goal is to reduce the university's peak load consumption by 50%.

In the home, where these controllers and sensors are eventually headed, residents will be able to specify the end-time for certain jobs, and the controller will do the rest. "The dishwasher and washing machine have jobs to be completed, but they don't have to be done simultaneously, and they don't have to be done right now," said Shahidehpour. "You might program the dishwasher to be done by 5:00 am and the washing machine to be done by 7:00 am."

If the necessary funding can be raised, residents of Oak Park, Ill. are likely to be some of the first in the country to experience the smart controllers and the Perfect Power microgrid. It's a win/win/win for residents, utilities, and the environment, said Shahidehpour.

"The residents program what they want to use and when, and these gadgets receive the real-time price of electricity and turn the appliances on and off," he said. "It's in the residents' interest because they use less electricity so they pay less, and it's in our national interest because we don't need to build as many coal units."

Shahidehpour said utilities stand to benefit through better control over peak loads and faults. Rather than customers reporting problems and utilities sending out repair crews, most issues will be solved remotely. "With the smart grid, the utility will be able to pinpoint every problem in seconds—without the need to send someone to locate the problem—and fix it," he said.

Serious savings

Indeed, Galvin Electricity Initiative's Yeager believes utilities and towns across the US would do well to become involved with these types of projects. On the utility side, it's a matter of not standing the way of progress, he said. "Oak Park and other communities want the opportunity to improve their infrastructure and don't want to be held back by the utility. They've said to me, "We want to be treated as a partner, not a prisoner.'"

For towns, there's potential for significant cost savings. Yeager said IIT saved $3 for every $1 invested in the Perfect Power microgrid installation.

"In a community, the benefits would be even larger," he said. "It's not just about the marginal savings in the electricity bill, which are important. It's about job creation, eliminating productivity losses, being in a better position to compete in a global economy, and being able to incorporate renewable energy in a way that's not possible today."

One community already seeing the benefits of an advanced power grid is Naperville, Ill., according to John Kelly, deputy director at Galvin Electricity Initiative, who played a major role in the design of the new grid at IIT.

Kelly said Naperville's municipal electrical department has been quietly working on a low-voltage smart grid for the past 15 years, implementing a similar design to the one at IIT. All of the substations have redundant feeds, and smart switches can isolate problems.

"If a squirrel bites in, it only affects a few homes. They don't have to send as many crews out; they can pinpoint it and fix it locally. They have incredible control that lets them zero in on every part of the system—if something fails, they can see it," he said.

Perhaps more importantly than the technology advances is the fact that the city achieved the changeover on a relatively small budget. "It shows that a focus on a different type of design can tremendously improve reliability," Kelly said. "Some utilities say that reliability is storm related and can't be improved. Naperville has shown that's not true."

Opening up

The main problem with projects like these is funding, say both Yeager and Kelly. "Today, new capacity always wins over efficiency because it has better financing," said Kelly.

That's why working prototypes like the one at IIT are so critical. "It attracted federal funding to accelerate it because it was viewed as a model for how you would begin to transform the power system of the country," said Yeager, adding that IIT can take 10 MW off the grid whenever necessary to help the system.

Yeager believes success stories like IIT's will help pave the way for an improved nationwide grid. "As the cost of electricity rises and the cost of building traditional infrastructure like peaking generators becomes politically unsatisfactory, I think you'll find more utilities and regulators saying that we need to open things up and begin to look at consumers not just as energy users, but as providers," he said.

For ISGC's Summy, the most important lesson learned from the IIT project concerns collaboration. "When you bring together the public, private, and academic sectors, you've put your best and brightest forward, which aligns you to create jobs—you're taking things out of the lab and putting them in the field. At the same time, you're generating benefits for consumers."

—Jill Rose

Perfect Power at IIT Celebrates Phase I Completion of Five Year Project

Chicago, Feb. 16, 2010 — Illinois Institute of Technology (IIT), Galvin Electricity Initiative, S&C Electric Company, and Intelligent Power Solutions, LLC are pleased to announce that the first phase of Perfect Power at IIT is now complete. The system consists of smart microgrids featuring a High-Reliability Distribution System (HRDS) loop design and redundant electricity and will allow IIT to eliminate costly outages, minimize power disturbances, moderate an ever-growing demand, and curb greenhouse gas emissions.

Part of a five-year project, the completion of phase one means that the first high-reliability distribution loop, serving Hermann Hall, Alumni Hall, Perlstein Hall, Wishnick Hall and Siegel Hall on IIT's Main Campus, is in operation, as is the automation of the university's north substation. The buildings included in the first phase now have automatic fault detection and distribution information that will allow for greatly improved electricity reliability. The automation of the south substation, and the installation of the high reliability distribution loops that serve other campus buildings, will be completed in the next four years of the project. Distribution systems, such as the HRDS, are critical in enabling many of the goals of the Perfect Power project and policymakers in general, such as reduction in greenhouse gases through integration of renewable energy sources and increased reliability.

The Nation's first Perfect Power System, Perfect Power at IIT, is an example of how government, utilities, businesses and municipalities can collaborate in the development and implementation of advanced power systems that are required to meet rising 21st century power demands. The project, developed by IIT, is the result of an uncommon partnership among the U.S. Department of Energy (DOE), local utility Exelon/ComEd, the entrepreneurial electricity distribution developer Intelligent Power Solutions, the Chicago-based global provider of electric power delivery solutions for the intelligent grid, S&C Electric Company, and the Galvin Electricity Initiative.

The Perfect Power System is based on a smart microgrid — a small, local, modernized version of the electricity grid that carries bulk power across the country. These microgrids focus on rapidly bringing the economic and environmental benefits of modern grid technology to consumers. They engage entrepreneurial innovators and investors to install the smart digital technology that allows the instantaneous, two-way flow of electricity and real-time pricing and demand information between utilities and consumers.

Projections indicate that the Perfect Power model at IIT will pay for itself within five years following its completion. For IIT, the Perfect Power System will generate significant savings — at least $10 million over 10 years. Following the short payback period, the university will generate money from Perfect Power through more affordable power costs, such as grid infrastructure improvements, allowing it to purchase electricity based on real-time prices rather than the traditional contracted average. IIT will also be able to sell electricity back to local energy markets and employ more efficient energy conservation efforts by integrating local power generation from clean sources.
To view a comprehensive report showcasing the design and benefits of Perfect Power, visit **http://www.iit.edu/perfect_power**.

Illinois Institute of Technology
Founded in 1890, IIT is a Ph.D.-granting university with more than 7,700 students in engineering, sciences, architecture, psychology, design, humanities, business and law. IIT's interprofessional, technology-focused curriculum is designed to advance knowledge through research and scholarship, to cultivate invention improving the human condition, and to prepare students from throughout the world for a life of professional achievement, service to society, and individual fulfillment. Visit **www.iit.edu**.

S&C Electric Company
S&C, headquartered in Chicago, IL, is applying its heritage of innovation to address challenges facing the world's power grids and thus shaping the future of reliable electricity delivery. The mission of employee-owned S&C is to continually develop new solutions for electricity delivery, fostering the improved efficiency and reliability required for the intelligent grid. Additional information about S&C is available at **www.sandc.com/sgaep**.

Galvin Electricity Initiative
The Galvin Electricity Initiative, launched by former Motorola CEO Robert W. Galvin, is leading a campaign to transform the Nation's obsolete electric power system into one that can truly meet consumers' needs in this new century. Galvin's vision — a Perfect Power System that cannot fail the end-user — includes a major technological update to the electricity grid infrastructure as well as the development of smart microgrids around the country to benefit consumers and suppliers alike. See how Galvin is turning this vision into a reality at ***www.galvinpower.org***.

NEWS | HOME AREA NETWORKS
MICHAEL KANELLOS: FEBRUARY 17, 2010

Smart Grid Tuesday: GainSpan Gets New CEO, Hara Lines Up Safeway as Customer

Hara's landing a customer a week, says CEO.

We have just begun to fight against ZigBee, GainSpan's new CEO would like you to know.

Greg Winner, an alum of Atheros, Texas Instruments and other companies, is the new CEO at **GainSpan**, which has developed an energy-efficient WiFi chip for home and building networks. Former CEO and founder Vijay Parmar, meanwhile, will head up business development.

The switch in executives is aimed at scaling up the company for the looming battle over home networks. Although ZigBee has been implemented in a number of utility trials, both Parmar and Winner say the race is far from over. Most trials, they say, are just that -- experiments to see whether home and office power consumption can be curbed by putting intelligence and communication capabilities into washing machines, lights, thermostats and other devices.

WiFi got off to a slower start in this market, but it is now gaining adherents, particularly among appliance and white good manufacturers who want to be assured that t**he networking they insert into their products will be compatible with equipment coming out from other vendors**. WiFi enjoys a broad and deep footprint: nearly every home with broadband has WiFi streaming through it already. And if a repairman wants to check on the health of a fridge, he can use an iPhone to pull information out of it; WiFi is standard on all modern smart phones.

"They (appliance makers) are pretty vocal about having more than one protocol," said Parmar.

The National Institute of Science and Technology wants to solidify standards for home networking in the next few months and has indicated that the final home standards **will likely allow for a few wireless and wired standards**. Winner predicted that NIST may concentrate on one standard for **power line networking**, which is actually not hugely popular in the U.S. but enjoys a larger market share in Europe, and then pick a few different standards for wireless, including WiFi. Another factor that may pull in WiFi's favor: the smart meter may not be a central point for communications into the home. Instead, homes may be equipped with a router that collects all of the data from a person's appliances and then feeds that data to the meter. This way, the meter, which only gets changed every few decades, can be insulated from technological and standards changes to some degree. The box will be the thing that has to be versatile and multilingual. And most people already have one of these boxes in their homes: it's called a DSL gateway.

GainSpan has to act quick, however, as the established WiFi manufacturers want to move into this market ASAP.

Naturally, ZigBee vendors disagree. The ZigBee vendors also argue that they continue to improve the performance of their technology. We've chronicled that before and will continue to do so.

Elsewhere, Hara, which makes resource management software, has inked a major deal with Safeway. The food retailer will deploy Hara's software to measure energy consumption and carbon output at 1,800 facilities, including many stores. The company came out of stealth mode last year, and has since raised $20 million and inked deals with Coca-Cola, News Corp., Brocade, and Akamai.

Around 50 companies installed energy management systems like this last year, said CEO Amit Chatterjee, citing a Groom Energy research report, and Hara got about half of the deals. This year, 250 similar deals will be signed with various vendors.

Hara is already off to a strong start, he added. The company is signing up a new customer every week. It is in negotiations with some big box retailers, as well.

"We're staring to get into each of the verticals," he added: high tech, high tech manufacturing, media, retail, etc. Hara recently nabbed a contract with **Inuit that formerly was handled by SAP**, he said. (Chatterjee came out of SAP.) Many expect companies like

Hara and Carbonetworks themselves to get snapped up by large, multinational software vendors like Oracle or IBM as the market expands.

You pronounce Hara, by the way, the same way you'd pronounce "Hurrah! The King gives each and every one of you a 16-ounce tub of Safeway Select Small Curd Cottage Cheese." That's 'hurrah' and not 'hair-a.'

Meanwhile, the Illinois Institute of Technology has completed phase one of its Perfect Power Project for microgrids. The five-year program wants to study the feasibility of campus-sized networks. And in California, Glendale Water & Power has awarded a $4.2 million contract to Utility Partners of America for smart electrical and water meters.

New Power System Completes First Phase

Thursday, 18 February 2010 09:40

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The Illinois Institute of Technology has completed Phase I of the Perfect Power System. Based on smart microgrids – smaller, local versions of the grid that carry bulk electricity across the country – Perfect Power features a High-Reliability Distribution System (HRDS) loop design and redundant electricity. The system will allow IIT to eliminate costly outages, minimize power disturbances, moderate an ever-growing electric demand, and curb greenhouse gas emissions. Distribution systems, such as the HRDS, are critical in enabling many of the goals of the Perfect Power project and policymakers in general, such as reduction in greenhouse gases through integration of renewable energy sources and increased reliability.

IIT, which initially developed the project, is partnered with the U.S. Department of Energy, local utility Exelon/ComEd, electricity distribution developer Intelligent Power Solutions, S&C Electric Company, and the Galvin Electricity Initiative. The Perfect Power System is expected to take five years to complete.

Phase I's high-reliability distribution loop serves Hermann Hall, Alumni Hall, Perlstein Hall, Wishnick Hall and Siegel Hall on IIT's main campus. These buildings now have automatic fault detection and distribution information that allows for greatly improved electricity reliability. Phase 1 also provides automation of the north substation. The automation of the south substation, and the installation of high reliability distribution loops that serve other campus buildings, will be completed in the next four years of the project.

Projections indicate that IIT's Perfect Power model will pay for itself within five years following its completion. The system will save IIT an estimated $10 million in over 10 years. After the project pays for itself, the university will generate revenue from Perfect Power through more affordable power costs, such as grid infrastructure improvements, allowing it to purchase electricity based on real-time prices rather than the traditional contracted average. IIT will also be able to sell electricity back to local energy markets and employ more efficient energy conservation efforts by integrating local power generation from clean sources, including solar.

Written on Thursday, 18 February 2010 09:40 by **Smartmeters**

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Microgrids: Utility vs. Private Ownership

By Jeff St. John Feb. 24, 2010, 7:15am PDT No Comments
0 _ 28

Microgrids — office parks, college campuses or communities that can generate their own power and disconnect and reconnect from the grid at large at a moment's notice — could be integral building blocks of the smart grid. That's why Dave Pacyna, senior vice president of Siemens Energy's North American transmission and distribution division, sees microgrids as a natural step in utilities' smart grid plans.

Most microgrids of the future won't be making and storing enough power to be grid-independent all of the time. Instead, microgrids will maintain a constant and complex relationship with the utility — buying power at some times, selling it back at others, either disconnecting from the grid to avoid a power outage or reconnecting to help the grid balance its way through instabilities, depending on the circumstances. So a central question for the future of microgrids is what will the relationship be with utilities — will it be utilities, or their customers, that pay for them and control them?

"I don't think it's even close to being baked out yet, as to what those relationships will look like," Pacyna said in a recent interview. But Siemens, a major player in the smart grid, does appear to be making some bets. For example, the German engineering giant is working with BPL Global to link up its utility-controlled distributed generation and demand response devices in homes and other buildings in a microgrid-like fashion — and BPL is "fully focused on the theory that all of their capabilities are basically designed to be utility-sponsored and utility-driven," he said.

Some of the first working examples of a microgrid have been installed by American Electric Power, which wants to own and operate them to help communities prone to loss of grid power and avoid building new transmission lines. And most of the microgrid projects currently underway are being led by utilities.

On the other hand, Siemens is also working with Viridity Energy, a startup that makes software to manage microgrids and has projects underway in New York and Philadelphia. Viridity Energy's CEO, Audrey Zibelman, places herself firmly on the customer side of the microgrid debate.

Zibelman's idea of an effective microgrid is based on the premise that the customer owns the resource and maximizes its value by selling self-generated power — or "negawatts" of reduced power demand — into more and more markets that have traditionally been the domain of utilities and their big power plant partners. The more money microgrids can make that way, the faster they'll be built, and that should help the utilities with grid stability and integrating distributed generation sources like rooftop solar panels into their renewable energy goals.

But not if the utilities get in the way. "I think the model for the industry can't be one that says it's exclusively the utility's domain to develop these microgrids," she said in a February interview. "I just don't see where utilities that want to operate microgrids for stability will be as aware of the economic benefits to the customer." To be sure, it's not that she's advocating an adversarial relationship between utilities and their microgrid customers, but instead likens the relationship to telecom customers, as in, "They don't want the telephone company to tell them what kind of cell phone they can buy."

Indeed, the evolving relationship between utilities and their customers could be likened to the changes that have come to the telecommunications industry since the breakup of Ma Bell. The Galvin Electricity Initiative, which is leading a Department of Energy grant-backed microgrid project at Chicago's Illinois Institute of Technology, sees microgrids as a path toward what it calls a "consumer-driven electric power system," one in which every customer has full access to open markets for power that's priced dynamically, and every community has the right to an electricity distribution system that meets its needs.

In some cases, microgrids are being planned alongside communities' efforts to gain energy independence from their utility. Take Marin County, which has created Marin Clean Energy, a "community choice aggregation" (CCA) public power entity allowed under California law to buy and sell electricity from wholesale power markets on behalf of residents in place of their local utility, in this case Pacific Gas & Electric. Marin County is also hosting a microgrid demonstration project linking five municipal buildings, featuring software from Boulder, Colo.-based Infotility and backing from DOE and Pacific Northwest National Laboratory.

The idea, according to Infotility, is to scale up the microgrid model to eventually "enable utilities and communities to manage distributed renewable energy supplies such as solar and wind as conventional grid assets, as a foundation and reliable part of their energy portfolio" — a future that sounds pretty close to that envisioned by smart grid proponents. But in this instance, utility-community conflict is already built in — PG&E is the sole backer of a California ballot measure that would amend the state's constitution to require a difficult to obtain two-thirds vote for citizens to form a CCA, a move that has drawn the ire of backers of public power, including the Galvin Electricity Initiative's executive director, Kurt Yaeger.

Image courtesy of NREL Solar Decathlon 2009's photostream Flickr Creative Commons.

Smart Grid

: American Electric Power, CERTS, Infotility, Marin Clean Energy, microgrid, Siemens, Viridity

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Smart grid: Perfect Power at IIT completes phase I construction

Chicago, February 23, 2010 — Illinois Institute of Technology, Galvin Electricity Initiative, S&C Electric Company, and Intelligent Power Solutions, LLC said the first phase of Perfect Power at IIT is now complete.

The system consists of smart microgrids featuring a High-Reliability Distribution System loop design and redundant electricity and will allow IIT to eliminate costly outages, minimize power disturbances, moderate an ever-growing demand and curb greenhouse gas emissions.

Click here for more smart grid news

Part of a five-year project, the completion of phase one means that the first high-reliability distribution loop, serving Hermann Hall, Alumni Hall, Perlstein Hall, Wishnick Hall and Siegel Hall on IIT's Main Campus, is in operation, as is the automation of the university's north substation.

The buildings included in the first phase now have automatic fault detection and distribution information that will allow for greatly improved electricity reliability.

The automation of the south substation, and the installation of the high reliability distribution loops that serve other campus buildings, will be completed in the next four years of the project.

Distribution systems, such as the HRDS, are critical in enabling many of the goals of the Perfect Power project and policymakers in general, such as reduction in greenhouse gases through integration of renewable energy sources and increased reliability.

The Nation's first Perfect Power System, Perfect Power at IIT, is an example of how government, utilities, businesses and municipalities can collaborate in the development and implementation of advanced power systems that are required to meet rising 21st century power demands.

The project, developed by IIT, is the result of an uncommon partnership among the U.S. Department of Energy (DOE), local utility Exelon/ComEd, the entrepreneurial electricity distribution developer Intelligent Power Solutions, the Chicago-based global provider of electric power delivery solutions for the intelligent grid, S&C Electric Company, and the Galvin Electricity Initiative.

The Perfect Power System is based on a smart microgrid — a small, local, modernized version of the electricity grid that carries bulk power across the country.

These microgrids focus on rapidly bringing the economic and environmental benefits of modern grid technology to consumers. They engage entrepreneurial innovators and investors to install the smart digital technology that allows the instantaneous, two-way flow of electricity and real-time pricing and demand information between utilities and consumers.

Projections indicate that the Perfect Power model at IIT will pay for itself within five years following its completion.

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U.S. awards $100M in smart grid training grants

Rick Merritt
4/8/2010 3:14 PM EDT

SAN JOSE, Calif. — The U.S. Department of Energy has awarded a total of nearly $100 million in grants to train an estimated 30,000 workers in smart grid technologies. The awards go out to a diverse group of 54 colleges, universities and companies for programs to train electricians, line workers, technicians, system operators, power systems engineers, cyber security specialists and transmission planners. The grants will fund training and the development of program materials in a variety of areas. They span topics including existing electric transmission and distribution systems as well as future intelligent grid systems including smart meters, phasor measurement sensors and advanced communication networks.

The utility Florida Power and Light, Pennsylvania State University and Illinois Institute of Technology were among the largest winners with grants of about $5 million each. IIT will create a smart grid training center that could train 49,000 people over three years with local and distance-learning courses.

IIT is already championing a handful of major smart grid projects including the high profile Perfect Power initiative building a so-called microgrid. It is also working on three DoE funded projects on wind energy including and effort to build a 1.5 megawatt win research facility.

General Electric was the only smart-grid systems vendor to win an award. It snagged $649,000 to help fund a $1.2 million smart grid center of excellence where it aims to train 260 engineers and software developers each year.

GE formed a smart grid business unit a year ago to pull together work over the last several years in the field. "We know the smart grid has taken off, and it's not just a U.S. phenomenon," said Luke Clemente, general manager for smart grid at GE who said he sees significant business coming in China, Europe, India and elsewhere.

The DoE posted a full list of the grant winners online.

At least two surveys estimate as many as 47 percent of today's power engineers—about 14,500 people--will be eligible for retirement or leave the industry in the next five years.

"We're not cranking out enough grads to fill the pipeline," said Wanda Reder, president of the IEEE Power and Energy Society. "We assumed we would need double that many people to handle new technologies coming on line in smart grids and renewable energy sources," she said.

"This is a great opportunity for workers to upgrade their skills and earn more, or for laid off workers from other industries to start fresh in a new and growing field," said U.S. Secretary of Energy Steven Chu in a prepared statement.


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Perfect Power System Proves Worth

June 1, 2010

By Mike Larson

[Page 1 of 2] Text size: A A

The new Perfect Power smart-grid electrical system that the Illinois Institute of Technology is installing on its Chicago campus could be the blueprint for a new microgrid power-distribution system that would revitalize the aging electrical grid in the U.S.

Photo Courtesy of IIT

The Illinois Institute of Technology, shown here in an aerial view, is paying $12 million for its Perfect Power smart-grid electrical system.

Related Links:
- Spotlight on Power
- FutureGen Awaits OK

Officials from the Galvin Electricity Initiative, which developed the Perfect Power concept, say the system going in at IIT is the country's first Perfect Power system and one of just nine "renewable and distributed systems integration" prototypes funded by the U.S. Dept. of Energy. DOE is paying $7 million of the system's $12-million cost. IIT is paying the other $5 million.

System Will Eliminate Outages, Boost Efficiency Installing Perfect Power will stop the three unexpected power outages it averages per year, which cost the university a total of $500,000 in ruined experiments, restarting costs and lost productivity.

The new system's efficiency will also give IIT plenty of electrical capacity to support the school's future growth, while eliminating the need to build a $5-million third substation on campus. When the system reaches full operation in 2013, its computerized controls will also save the university money by automatically purchasing electricity when rates are cheapest.

The IIT plans to eventually add more on-site auxiliary generating capacity that will enable it to sell electricity back to the grid.

The savings from eliminating outages, not having to build a third substation, using electricity more efficiently, buying electricity when rates are lower, and eventually selling campus-generated electricity back to the grid are expected to add up to a five-year payback and estimates that net earnings from the system range from $10 million to $20 million over the next decade.

IIT is Demonstration and Research Site The Perfect Power concept was created by the Galvin Electricity Initiative, a nonprofit group founded by Robert Galvin, retired chairman of Motorola Inc. The group's aim is to change the way the country generates and delivers electricity.

IIT, the Galvin Electricity Initiative, S&C Electric and local utility Commonwealth Edison, all of Chicago, are working together to develop and build the Perfect Power system that will enable IIT to minimize power outages and meet its growing need for reliable, lower-cost electricity.

Aldridge Electric Inc. of Libertyville, Ill., is doing the first two years' installation projects. Contracts for later installation work have not yet been let.

In addition to helping IIT meet its need for reliable, efficient and economical power, the university's Perfect Power system will serve as a laboratory for research on microgrids and will demonstrate how the system could be used nationwide to help improve the U.S. power grid.

"One of IIT's goals is to show that this technology can be applied at the community scale," Galvin says. "What we do here on the campus could be repeated in cities across the country. It could become the blueprint for how to fix the U.S. electrical grid system."

Smart Technology Makes it Work The Perfect Power system is a smart microgrid that serves a local area through dual electrical loops that are controlled by smart meters, advanced electronically operated switches and a master controller that all communicate electronically. The full system also includes local auxiliary power sources that store electricity or kick in instantly if the main power feed from the utility fails.

The local Perfect Power grid divides the university campus into seven loops, each serving a number of buildings. Each loop has the ability to feed electricity to its buildings from at least two directions, so that if there's an outage anywhere

Dodge Reports

Below is a brief listing of Projects Bidding in Midwest. Click on any project to get Dodge Report, Plans and Specifications.

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Blog: Midwest Musings

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along one line, power can be delivered uninterrupted through the other one. The advanced switchgear for each loop receives continuous feedback about the loop's condition and passes it to the master controller.

Information from all of the loops is fed to the master controller. The brain of the system, the master controller is a computer that instantly evaluates mountains of information, then in milliseconds decides whether the system is working properly, how much electricity is being demanded and where the demand is coming from.

If it detects a problem, the controller can reroute power, or allocate it to higher-priority needs, or turn on on-site back-up generating systems. In addition, it can be programmed to evaluate current power prices from the utility, adjust for expected weather or to allow for a myriad of other conditions.

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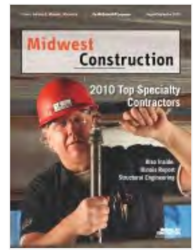

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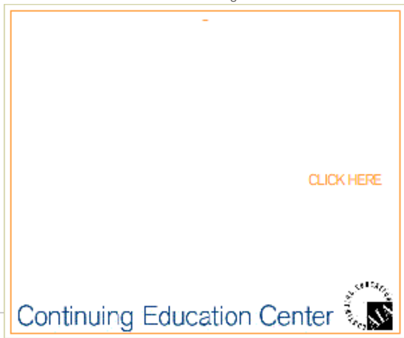

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Perfect Power Implementation, Education, and Research at IIT

Friday, October 1, 2010: 9:30 AM

Trustee Room (Illinois Institute of Technology)

Description: The Perfect Power project has several goals in three categories: technical, financial and leadership. The technical goals include the demonstration of the key capabilities of Perfect Power with respect to reliability, demand response load reduction, energy efficiency load reduction and integration of renewable sources. The financial goals include the deferral of major capital costs, the reduction of energy and outage costs, as well as the influx of ancillary services' revenues. The leadership goals include the reduction of the university's carbon footprint, the creation of a living laboratory and the opportunity to lead Smart Grid development through the Perfect Power project.

Sponsor: Energy

Chair: Mohammed Shahidehpour
Email: ms@iit.edu

9:30 AM	Perfect Power Implementation at Illinois Institute of Technology Joseph Clair
10:00 AM	Autonomous Agents for Advanced Distribution Automation In Perfect Power Systems Alex Flueck
10:30 AM	Update on IIT Microgrid Master Controller Greg Rouse
11:00 AM	Application of Zigbee Wireless In Smart Grid Chi Zhou
11:30 AM	Illinois Institute of Technology Smart Grid Education and Workforce Training Center Melissa Gordon

See more of this Group/Topical: 2010 Midwest Regional Conference

<< Previous Session | Next Session >>

Appendix 6

Talk 4: 11:15-11:50 am

Smart Grid: A New Paradigm of Power Delivery

Mohammad Shahidehpour
Department of Electrical and Computer Engineering
Illinois Institute of Technology, Chicago, IL

This presentation will highlight some of the key issues in the smart grid design and applications. Smart grid represents a vision for a digital upgrade of electric power transmission and distribution. It optimizes the grid operations, enhances the grid security, and opens up new markets for the utilization of sustainable energy production. Smart grid is an aggregate term for a set of related technologies for electric power systems rather than a name for a specific technology with a generally agreed on specification. The key to a smart grid is using the Internet protocol on home devices to shuttle information back and forth between the electric utility and customers. A smart meter installed at consumer premise measures, monitors, and helps manage how much energy is used. With a smart two-way communications mechanism between a power consumer and its provider, both parties can get far more control over electric power consumption, cost, outages, and security.

The development of a prototype model of smart grid which is funded by the U.S. Department of Energy and being implemented at the Illinois Institute of Technology will be discussed. The global IEEE activities for promoting smart grid technologies will also be discussed. At the end of the presentation, a short video on smart grid, which is produced by the IEEE Power and Energy Society, will be exhibited.

CHICAGO COUNCIL ON SCIENCE AND TECHNOLOGY

Feb 18, 2010

Storing Alternative Energies

Filed under: Programs - C²ST — Jillian @ 3:26 pm

Policy Perspectives – Notes on Storing Alternative Energies

Speakers:

Dr. Mohammad Shahidehpour, Bodine Distinguished Professor and Chair, Electrical and Computer Engineering Department, Illinois Institute of Technology

Dr. Michael R. Wasielewski, Director, Argonne-Northwestern Solar Energy Research Center

Jeff Chamberlain, Senior Account Manager, Office of Technology Transfer, Argonne National Laboratory

As we near the end of the 21st century's first decade, it has become painfully clear that the current forms of energy storage currently in use are obsolete and inadequate. With the world's demand for energy growing ever steadily, the need for innovative, economical, and environmentally sound ways of storing and distributing power is at the forefront of today's energy research.

Join C²ST and a panel of experts as they discuss state-of-the-art solar, battery, and Smart Grid technologies that might one day redefine our understanding of energy use and storage.

Location: Illinois Institute of Technology, McCormick Tribune Campus Center, 3201 S. State Street

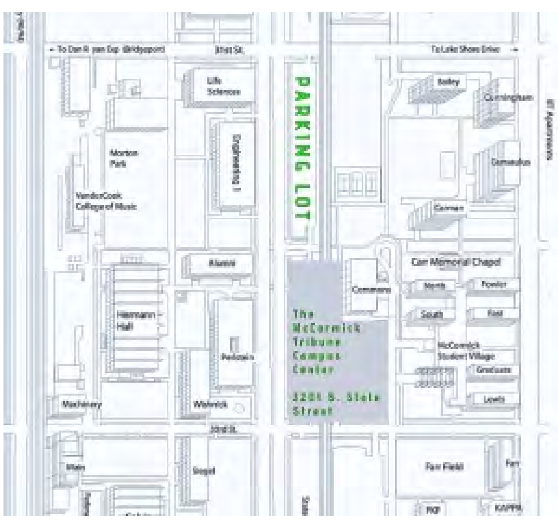
5:00 p.m. Registration and Reception

6:00 p.m. Presentation & Panel Discussion

$10 advance registration, $15 at the door.

$5 for students, but please email info@c2st.org for the promo code.

Parking is $4.



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A Programação Técnica está pronta e pode ser consultada no link PROGRAMAÇÃO, ao lado. Lá você encontra data, local e horário de apresentação de cada um dos 203 trabalhos que serão apresentados nas 45 Sessões Técnicas.

Nossos palestrantes convidados, nacionais e internacionais, já confirmaram suas presenças, e os títulos de suas apresentações são os seguintes:

- Previsão de Potência Eólica no Curto Prazo e Impacto na Operação de um Sistema Interligado
  Prof. Vladimiro Miranda (INESC / Universidade do Porto, Portugal)

- Desafios de Controle em Sistemas de Potência Modernos
  Dr. Nelson Martins (CEPEL)

- Smart Grid: A New Paradigm for Power Delivery
  Prof. Seyed Mohammad Shahidehpour (Illinois Institute of Technology, Chicago, IL, USA)

- Lightning Protection Topics as Applied to High-Voltage Transmission Lines
  Prof. Vladimir Rakov (University of Florida, Gainesville, FL, USA)

- Aplicações de Tecnologias de Medição Fasorial Sincronizada: Experiências do Projeto MedFasee
  Prof. Ildemar Cassana Decker (Universidade Federal de Santa Catarina, UFSC)

O jantar de confraternização será na Maison Pomme D'Or.

Nossa Comissão Organizadora está realizando todo esforço possível para que nossos convidados e todos os participantes do SBSE/2010 possam desfrutar de um bom clima de hospitalidade, e um Simpósio bem organizado, fraterno e principalmente sólido no seu aspecto técnico.

Esperamos encontrar todos vocês aqui em Belém dentro dos próximos dias !

FEDERAL ENERGY REGULATORY COMMISSION
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JUNE 2, 2010

Location: Commission Meeting Room

8:00	**Richard O'Neill, FERC** Welcome and Introduction
	Session A: Unit Commitment Models in ISO Markets
8:20	**Andy Ott, PJM** Unit Commitment in PJM
	Mark Rothleder, California ISO Unit Commitment in the CAISO Market
	Rana Mukerji, NYISO NYISO Day Ahead Unit Commitment Design
10:20	**Break**
	Session B: Experience, Challenges, and Future Directions in Unit Commitment
10:30	**Art Cohen and Chien-Ning Yu, ABB** Unit Commitment in Energy Markets: Recent Experience and Future Directions
	William Hogan, Harvard Scarcity Pricing and Locational Operations Reserve Demand Curve
11:40	**Lunch**
12:40	**Boris Gisin and James David, PowerGEM** Practical Security Constrained Unit Commitment Implementation Challenges
	Boris Gisin and Qun Gu, PowerGEM PJM Perfect Dispatch
1:40	**Break**
	Session C: Advances in Hardware and Software
1:50	**Jeremy Bloom and John Gregory, IBM** How Advances in Algorithms and Processors Will Impact Power System Markets and Operations
	Alkis Vazacopoulos, FICO Solving Hard Mixed Integer Programming Problems
	Session D: New Designs and Advanced Unit Commitment Models
3:00	**Kory Hedman, Arizona State University** **Co-Author: Shmuel Oren, University of California, Berkeley** Co-optimization of Network Topology in Future Unit Commitment Models
	Tongxin Zheng, ISO-NE **Co-Authors: Eugene Litvinov, Jinye Zhao, ISO-NE** Risk-based Approach to Reliability Unit Commitment
4:15	**Break**
	Session E: Test Model Data Sets
4:30	**Richard O'Neill and Eric Krall, FERC** Test Model Data Sets
	Avnaesh Jayantilal, Areva T&D and Jim Waight, Siemens IEC Working Group 16 Activities
5:30	**Richard O'Neill, FERC** Day 1 Conclusion

JUNE 3, 2010

Location: Commission Meeting Room

8:00	**Richard O'Neill, FERC** Day 2 Welcome
	Session F: Special Topics
8:05	**Li Zhang and Paul Gribik, Midwest ISO** Extended LMP
	Gary Stern, Southern California Edison **Co-Authors: Joseph Yan, Peter Luh** What Objective Function Should be Used in ISO and RTO Unit-Commitment Models – A Market Participant Point of View
9:15	**Break**
	Session G: Variable Energy Resources and DR in Unit Commitment Models
9:25	**Erik Ela, NREL** Advanced Unit Commitment with High Penetrations of Variable Generation: Research at the National Renewable Energy Laboratory
	Ali Koc, IBM Modeling Intermittent Resources and Storage for Generation Planning
	Marija Ilić, Carnegie Mellon Integrating Large-Scale Wind Power in Coordination with Price Responsive Demand
	Dhiman Chatterjee, Midwest ISO Efficient Ramp Provisioning for Net Load Following with Variable Energy Resources
	Mark Rothleder and Udi Helman, California ISO Stochastic Simulation of Unit Commitment and Dispatch Under a 20% RPS in California
11:45	**Break**
	Session H: Modeling Uncertainty and Flexibility in Unit Commitment Models
11:55	**David Sun, Alstom** Modeling Resource Operational Flexibility in Unit Commitment
12:30	**Lunch**
1:20	**Jianhui Wang and Audun Botterud, Argonne National Laboratory** Stochastic Unit Commitment Modeling: Implementation and Market Implications
	Mohammad Shahidehpour, Illinois Institute of Technology Stochastic Security-Constrained Unit Commitment in a Volatile Environment
	Pablo Ruiz, CRA Comparison of Stochastic and Reserve Methods for Uncertainty Management
3:05	**Break**
3:15	**Xing Wang, Areva T&D** Smart Dispatch for Electricity Markets
	Session I: Forecasting for Market Operations
3:50	**Audun Botterud, Argonne National Laboratory** Wind Power Forecasting in Electricity Market Operations
	Victor M. Zavala, Emil Constantinescu, and Mihai Anitescu, Argonne National Laboratory Economic Impacts of Advanced Weather Forecasting on Unit Commitment
	Conclusion and Next Steps
5:00	**Richard O'Neill, FERC**

Keynote Address

Reliability of Restructured Electric Power Systems — What is the Impact of Smart Grid?

The optimal operation of electric power system is impacted by the unbundling of generation and transmission, enhanced monitoring of the transmission system by phasor measurement units, integration of renewable energy, real-time pricing and demand response, and applications of smart grid for managing the distributed control of power systems. This presentation will highlight some of the key issues with the operational reliability of restructured power systems and discuss the role of recent innovations and, in particular, the significance of smart grid design and applications on the power system operation and control. A smart grid represents a vision for digital upgrades of electric power transmission and distribution. The key to the smart grid utilization is the Internet protocol for shuttling a myriad of information back and forth between the electric utility sector and its customers. The distributed nature of restructured power systems and the new applications of monitoring and control techniques introduce a different set of indices for measuring the reliability of electric power systems. The presentation expands on the effect of renewable generation on the
security of restructured power systems. The presentation will also discuss the development of a microgrid which is funded by the U.S. Department of Energy and implemented at the Illinois Institute of Technology. The global IEEE activities for promoting the smart grid technologies will also be discussed.

Speaker's Biography

Professor Mohammad Shahidehpour
Department of Electrical and Computer Engineering
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Appendix 7

Frequency Agility in a ZigBee Network for Smart Grid Application

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***Abstract*— Smart grid is an intelligent power generation, distribution and control system. ZigBee, as wireless mesh networking scheme low in cost, power, data rate, and complexity, is ideal for smart grid applications. Unfortunately, almost all ZigBee channels are overlapped with wireless local area networks (WLAN) based on 802.11 specifications, resulting in significant service degradations in interference scenarios. We propose a frequency agility-based interference avoidance algorithm, which utilizes Energy Detection (ED) and active scan to perform smart channel selection. This algorithm can detect interference and adaptively switch nodes to "safe" channels to dynamically avoid WLAN interference. Our proposed scheme was empirically evaluated in terms of the packet error rate (PER) using a ZigBee and Wifi coexistence testbed, and the results were compared with our analytical results. The measurement results show the algorithm efficiently mitigates the effect of WiFi interference upon ZigBee networks.**

***Index Terms*-- ZigBee, WLAN, Smart Grid, frequency agility, Energy Detection, Active Scan, PER**

I. INTRODUCTION

The smart grid is an intelligent power generation, distribution and control system. It seeks to maximize energy efficiency and foster greater adoption of renewable energy sources such as solar power. In order to maximize energy efficiency, a smart grid needs to perform energy usage monitoring, net metering, and demand response. All of these tasks demand the collection and analysis of real-time data, along with the control of energy devices for energy reduction and demand response.

The IIT Perfect Power project is a five-year project sponsored by the United States Government Department of Energy (DoE), which aims to implement smart grid in IIT main campus. The objective is to improve energy efficiency throughout the campus by reducing electricity consumption by up to 11 million kWh (20% reduction) and reducing natural gas consumption by nearly 1 million terms (10% reduction) per year. The major research work includes advanced distribution automation and recovery system, buried cable fault detection and mitigation, intelligent perfect power system controller, and advanced wireless sensor networks for data collection and automatic control.

ZigBee is a wireless mesh networking scheme based on the IEEE 802.15.4 standard. ZigBee is low in cost, power, data rate, and complexity, and easy for deployment and implementation. These features, along with its usage of unlicensed spectrum and its advantage of it being a standardized rather than proprietary protocol, makes it the most suitable wireless technology to monitor, collect, and analyze data on energy usage in real time for smart grid application. IIT perfect power adopts ZigBee to implement energy usage monitoring, net metering, and demand response. The research aspects include the design and development of interference avoidance techniques, self-forming and self-healing cluster-tree ZigBee systems, energy-efficient contention-free MAC layers access protocol and installation plan of ZigBee routers and energy-efficient routing algorithm.

The ubiquitous IEEE 802.11 Wireless Local Area Networks (WLAN) or WiFi in residential, commercial and business buildings within shares the same license-free 2.4GHz Industrial, Scientific and Medical (ISM) frequency band with ZigBee. For different purpose, ZigBee and WiFi need to build and collocated with each other in most situations as shown in Figure 1. Almost all ZigBee channels are overlapped with WiFi, whose transmission power is far stronger than ZigBee resulting in significant performance degradation. Therefore, we need to evaluate the performance of ZigBee with the coexistence with WiFi to guide the practical implementation of ZigBee for both residential and business environments for smart grid applications.

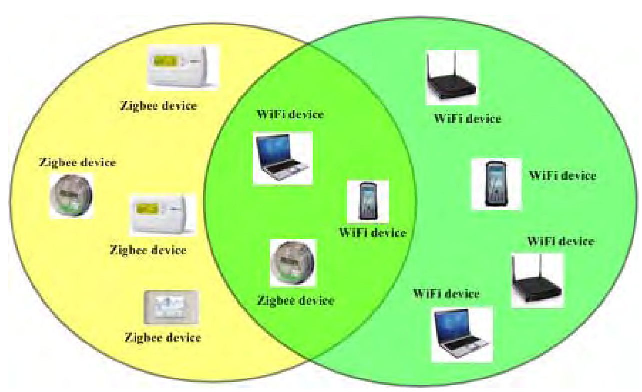

Fig. 1. ZigBee and WiFi collocated

Studies have been performed to examine the performance of ZigMee in the presence of WiFi interference. Several works have developed theoretical models to examine ZigBee and Wifi coexistence. In [1], the impact of 802.11 interference on IEEE 802.15.4 is analyzed in terms of the Bit error rate (BER). In [2], the Packet Error Rate (PER) is obtained from BER and collision time by means of an analytical model and simulation. The PER of ZigBee as a result of WLAN and Bluetooth interference is obtained in [3], and the results show that WLAN is a much greater interferer than Bluetooth. The interaction between ZigBee and IEEE 802.11g is empirically evaluated in terms of throughput in [4], with results indicating that ZigBee does not affect IEEE 802.11g significantly; however the effect on the throughput of ZigBee is significant when the spectrum of the chosen channels of operation coincide.

All coexistence performance evaluations prove that ZigBee can be significantly interfered by WiFi under heavy WiFi traffic conditions. An effective interference mitigation scheme is therefore required in order to guarantee ZigBee reliability. Won et al [5] proposed an adaptive channel allocation scheme for ZigBee and WiFi coexistence, which let ZigBee adopt multiple channels in a PAN; however ZigBee specifies that each PAN uses only one channel and it can only be set by coordinator which is full function device. End devices are reduced function devices which have no ability to change the channel. An adaptive, interference-aware multi-channel clustering algorithm is proposed in [6], but such as scheme will be plagued by significant delays in real-word deployments. According to empirical data in [7], frequency agility is an efficient method to mitigate interference, but they do not provide a detailed explanation.

In this paper, we propose a frequency agility-based interference mitigation algorithm for ZigBee networks. All the devices within the PAN use the same frequency channel, with the coordinator taking responsibility for channel switching decisions. A NACK counter and energy detection are used to detect the presence of significant levels of interference within the current channel. Once interference is detected, the coordinator instructs all the routers to perform an energy detection scan on channels from high priority to low priority in the network and pass the information to network. The coordinator select the channel with the lower noise levels and then requests an active channel scan to see whether there are other ZigBee networks present in that channel. If it's a clear channel all nodes in the PAN change to the channel, otherwise coordinator choose the other low noise channel according to the energy detection results. This distributed, smart channel selection algorithm enables ZigBee networks to dynamically avoid interference from neighboring WiFi networks.

The rest of paper is organized as follows. A thorough evaluation of ZigBee and WiFi coexistence performance is presented in Section II. Our frequency agility-based interference mitigation scheme is proposed in Section III, and in Section IV, we empirically evaluate the performance of proposed scheme in a ZigBee testbed. Finally, the paper is concluded in Section V.

II. Performance of ZigBee and WiFi Coexistence

To measure the performance of ZigBee under WiFi, we calculate the bit error rate (BER) and packet error rate (PER) in accordance with the analytical model in [3], while corresponding measurement have been done in both residential and laboratory experiments.

We assume the signal transmission in an additive white Gaussian noise (AWGN) channel, with blind transmissions for both IEEE 802.15.4 and IEEE 802.11b, meaning that they will both persist in transmission whether the channel is available or busy. In addition, retransmissions are not taken into account.

Zigbee utilizes Offset Quadrature Phase-Shift Keying (OQPSK) modulation within the 2.4 Ghz band, and according to [8], WiFi signals can be considered as partial band jamming noise for ZigBee. The BER can be calculated using the following equation [3]:

$$BER = Q(\sqrt{2SINR}) \quad (1)$$

where SINR is signal to interference plus noise ratio.

In view of the fact that ZigBee and WiFi networks are mostly deployed in the indoor environments, a simplified indoor path loss model [8] is used to calculate path loss (L_p):

$$L_p(d) = \begin{cases} 20\log_{10}(\frac{4\pi d}{\lambda}) & , \quad d \le d_0 \\ 20\log_{10}(\frac{4\pi d}{\lambda}) + 10n\log_{10}\frac{d}{d_0}, & d > d_0 \end{cases} \quad (2)$$

where d_0 is a break point. The path loss exponent n equals to 3.3 and d_0 is 8 meter [2].

The PER is calculated based on BER and collision time [3]. The Collision time model is shown in Fig. 2, and we define T_Z and T_W as inter-arrival time between two ZigBee WiFi data packets separately. In accordance with the assumption of blind transmission, the contention window is not changed by the occurrence of a busy status. Both ZigBee and WiFi adopt the Carrier Sense Multiple Access

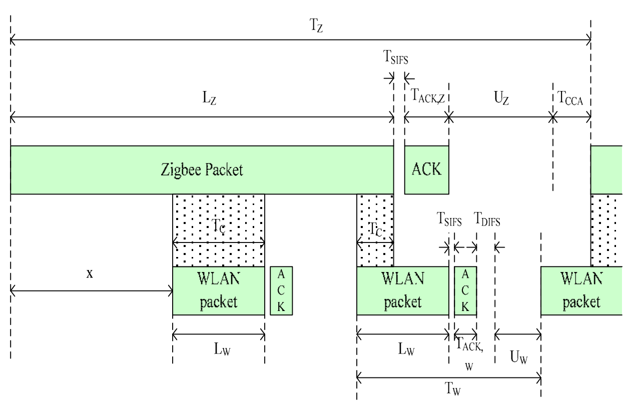

Fig. 2. IEEE 802.11b and IEEE 802.15.4 Interference Model [2]

with Collision Avoidance (CSMA/CA) scheme. U_z and U_w are random values within minimum contention window, and we set them equal to half of the IEEE 802.15.4 and IEEE 802.11 minimum contention windows respectively. ZigBee only detects the availability of channel twice by operating Clear Channel Assessment (CCA) after back off time U_z. From Figure 2, we get:

$$T_Z = L_Z + T_{SIFS,Z} + T_{ACK,Z} + U_Z + T_{CCA} \quad (3)$$

$$T_W = L_W + T_{SIFS,W} + T_{ACK,W} + DIFS + U_W \quad (4)$$

The average collision time can be calculated by following equation, where x is the time offset between WLAN packets and ZigBee packets. To simplify the model, x is assumed to be uniformly distributed in [0, T_W):

$$T_c = \frac{\int_0^{L_z} T_c(x)dx}{L_z} \quad (5)$$

The PER of ZigBee (IEEE 802.15.4) under IEEE 802.11b interference can be expressed as:

$$PER = 1 - [(1-P_b)^{N_z - \lceil T_c/b \rceil} \times (1-P_b^I)^{\lceil T_c/b \rceil}] \quad (6)$$

where P_b is bit error ratio without IEEE 802.11 interference and P^I_b is bit error ratio with IEEE 802.11 interference, N_z is the number of the bits in a ZigBee packet and b is duration of a bit transmission.

Theoretical analysis results indicate that ZigBee may be severely interfered by WiFi and that a “Safe Distance and Offset Frequency” can be identified to guide the ZigBee deployment. We analytically and empirically determined that a separation of 8 meters between ZigBee and WiFi is the safe distance that can guarantee reliability ZigBee communication regardless of the offset frequency, while 8MHz is a “safe” offset frequency(i.e., the interference is negligible) even when the distance is just 2 meters. Moreover, our results confirm that in general, ZigBee provides satisfactory service in the residential environments, as very rare are all WiFi channels occupied, and the total traffic is not large enough to prevent ZigBee transmissions. The deployment of ZigBee networks within the safe distance and offset boundaries guarantees operation with negligible interference effects.

III. Interference Avoidance Scheme—Frequency Agility

Based on our studies into IEEE 802.15.4 and IEEE 802.11b coexistence, we observe that if ZigBee devices can detect interference, find “safe channels” and migrate the entire PAN to a clear channel, performance will be significantly improved. The proposed solution should require minimal adjustments to the existing IEEE 802.15.4 standard in order to facilitate easy adoption. In addition to these requirements, any proposed solution must be simple in order to avoid a performance penalty and reduce the usage of system resources. Considering these factors, we propose a frequency agility algorithm for IEEE 802.15.4 cluster-tree networks which combines the star and mesh topologies, achieving both high levels of reliability and scalability, and energy-efficient operations.

The primary elements of our scheme are interference detection and smart channel selection. Each sender node utilizes a NACK counter to record number of failed transmission and detects interference by energy detection. If the channel is available, the sender transmits the packet successfully before the NACK counter reaches the threshold value. If NACK exceeds threshold value, the coordinator instructs all the routers in the PAN to perform an energy detection scan of all the available channels in accordance with the channel classification table for that network. The Coordinator selects the channel with the least interference channel based on the feedback from all the energy detection scans. Once the channel is determined, all routers perform an active scan to ensure no other ZigBee PAN currently occupy this channel. The final step is the migration of all the PAN devices to this “safe” channel.

A. *Interference Detection Scheme*

Since ZigBee is an energy efficient mesh networking scheme, energy-saving interference detection is very important. From a large number of test results, it has been observed that ZigBee provides reliable service in residential environments, but it experiences significant interference in the laboratory environments due to heavy traffic. In order to extend device battery lifetime there is no need to call interference mitigation functions unless absolutely necessary.

Some interference detection schemes have been studied for sensor network including [8], [5] and [6]. In [8], Zhou et al present a radio interference detection protocol (RID) to detect run-time radio interference among sensor nodes. Unfortunately their work cannot be directly applied to our scenario, as the interference we consider is from a different air interface scheme, rather than considering interferers within the same access network scheme. An interference detection scheme based on the energy detection (ED) scan results and received signal strength indication (RSSI) is proposed in [5]. Kong argued in [6] that RSSI is not an accurate measure of interference, as the RSSI values of ZigBee frames at a distance within 0.3m can be really high. Kim [9] proposed an ACK/NACK-based interference detection scheme which utilizes ACK/NACK reports to detect interference. The sender sends beacon frame to receiver and counts the number of NACK, if the value exceeds the threshold the interference detected. However ZigBee standard [10] defines that once the beacon frame is sent, all the reachable devices within the communication range will reply to the beacon request. It’s big waste of energy for ZigBee such a low power and energy efficient device.

We improve on these schemes and propose a NACK-based interference detection scheme in ZigBee network. In order to minimize redundant procedures, regular packet transmissions are utilized to detect interference. Due to

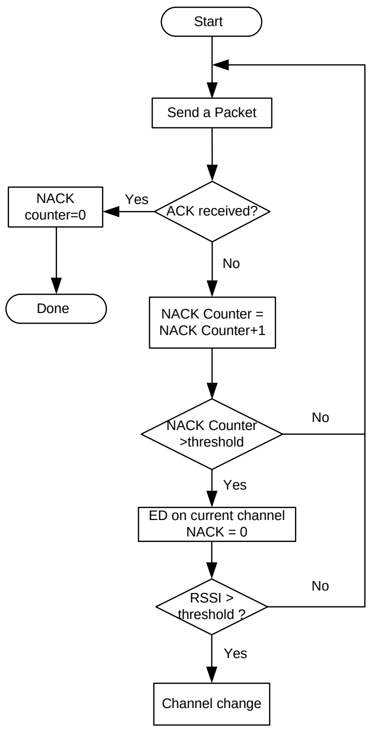

Fig.4. Flowchart of interference detection

ZigBee's low duty cycle which only requires a few milliseconds to transmit packets [11], node can successfully deliver the packet during the retransmission in most situations. It is efficient in terms of packet transmission and network battery life to use regular packet rather than signaling dedicated to do interference detection (such as dedicated beacons or periodic packet transmissions). When ACK is not received within the specified timer value the NACK counter incremented by one and the sender retransmits the packet. If the NACK counter exceeds the threshold value, the sender node stops retransmission and do the energy detection to make sure it's interference lead to transmission failure. Once energy detection result RSSI exceeds threshold, it means interference detected and node report it to coordinator. Then the coordinator calls corresponding interference avoidance scheme and initiates migration to a safe channel. The flowchart of interference detection is shown in Fig.4. Our proposed scheme emphasizes simplicity and efficiency, with low network overheads.

B. Interference avoidance

Once coordinator received interference detected report, interference avoidance scheme will be initiated as soon as possible. In [12], authors suggest to let more interfered or lower priority PAN change to another channel by beacon request. The coordinator determines which channel they switch to based on the reply of beacon request. This scheme only can be applied to interference from other ZigBee PAN. A pseudorandom-based interference avoidance scheme is proposed in [6]. All devices move to the same next channel base on the pseudorandom sequence predefined to avoid interference. It means it doesn't consider interference source and state of other channel just chooses a channel randomly does the interference detection again. Obviously, this scheme increases the delay and energy consumption.

Our interference avoidance scheme utilizes energy detection and active scans to determine which channel is appropriate for all the devices to change to. IEEE 802.11 uses 2.4 GHz frequency band and there are 13 overlapping 22 MHz wide frequency channels defined. There are only three non-overlapping channels, namely channels 1, 6, and 11 in the US and channels 1, 7 and 13 in Europe. ZigBee utilizes sixteen 2MHz wide frequency channels located in the ISM band. Our test bed experiments show that when the offset frequency is larger than 8MHz, the interference from IEEE 802.11b is negligible. When the offset frequency is less than 3MHz, ZigBee experiences significant levels of interference. Our results are in line with similar research such as [9].

In order to improve the detection time and power efficiency of our protocol, we divide all ZigBee channels into three classes based on offset frequency. As seen in Fig. 5, Class 1 consists of channels 15, 20, 25, 26 which offset frequency is larger than 12 MHz; class 2 is made up of channels 11, 14, 16, 19, 21, 24 which offset frequency is larger than 7 MHz and smaller than 12 MHz; while class 3 consists of channels 12, 13, 17, 18, 22 and 23 respectively which offset frequency is smaller than 3 MHz. Class 1 has highest priority and class 3 has the lowest priority. Upon receipt of an interference detection report, the coordinator sends an energy detection scan request to all routers in the PAN to check the status of channels from high priority to low priority till an available channel is found. In the cluster-tree ZigBee network, all routers doing the energy detection can avoid hidden terminal problem to some extent. In comparison to having all the devices in the PAN performing an energy detection scan, our algorithm minimizes the complexity of decision algorithm and is more energy efficient.

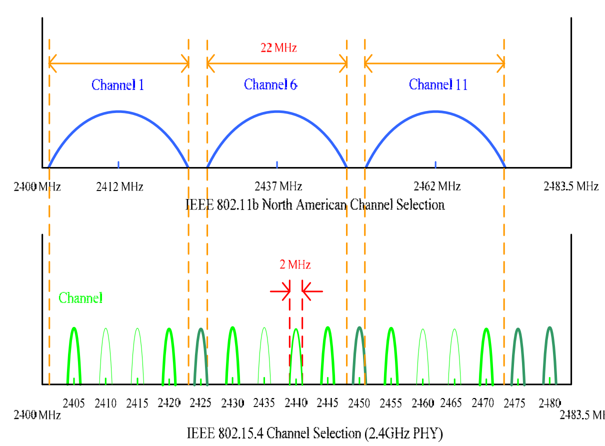

Fig. 5. ZigBee and WiFi channels in the 2.4 GHz band

Upon completion of the energy detection scan, all routers in PAN commence an active scan on the proposed migration channel selected by the coordinator. They send out a Beacon Request to determine if any other ZigBee or 802.15.4 PAN's are currently active in that channel within hearing range of the radio. If a PAN ID conflict is detected, the coordinator selects a new channel and unique PAN. The decision algorithm is detailed in Fig. 6.

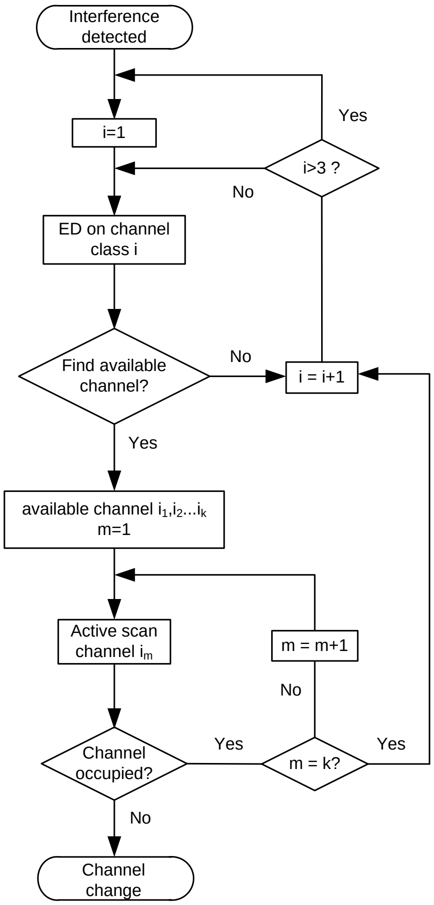

Fig.6. Flowchart of the Interference Avoidance

IV. Test Result and Performance Evaluation

The proposed algorithm is implemented in real world to evaluate the performance of ZigBee under the WiFi interference. The testbed consisted of a pair of 2.4 GHz Meshnetics ZigBit development kit, WiSpy WiFi analyzer, two laptops and a Linksys Wireless G WiFi router as shown in Fig. 7.

Wireless Router is used to build up WLAN named OWIL using channel 1, two laptops connected to OWIL network. Large files are transmitted between these two laptops through router which is intended to create the heavy traffic. The ZigBee channel was configured as channel 11, 12, 14, 15 which offset frequencies are 7MHz, 2MHz, 8MHz, and 13MHz respectively to WiFi channel 1. The PER was calculated as:

PER = (Number of failed messages / Number of attempted measurements)*100 (7)

Fig.7. Testbed equipment

PER of ZigBee under WiFi interference is shown in Fig.8. where the distance between the WiFi router and ZigBee receiver is only 1 meters. The graph demonstrates PER is pretty high when the offset frequency is smaller than 8MHz. When the offset frequency is larger than 8MHz, performance of ZigBee improved dramatically. Especially when ZigBee is operated in channel 15 (offset frequency 13MHz) which belongs to class 1, the PER is zero in large number of experiments.

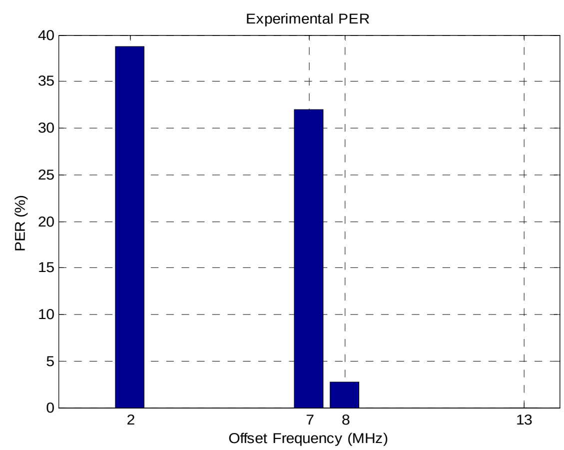

Fig.8. PER VS. Offset Frequency

Link Quality Indicator (LQI), as a character which indicates the strength or quality of received packet, is also obtained in measurement. The range of LQI value is from 0 to 255 and PER decreases as LQI increases. The LQI measurement is performed for each received packet. Thus if the packet lost, transceiver consider LQI as 0. Here we analyzed the LQI which obtained by a large number of packets transmitted in experiment. Fig.9. illustrate relationship between average LQI and offset frequency. It shows for ZigBee channels which offset frequency is small with WiFi, the link quality is weak and transmission packet strength is much lower. For those offset frequency larger than 8MHz channels, LQI is larger than 220 which means PER expected to be close to 0 [13].

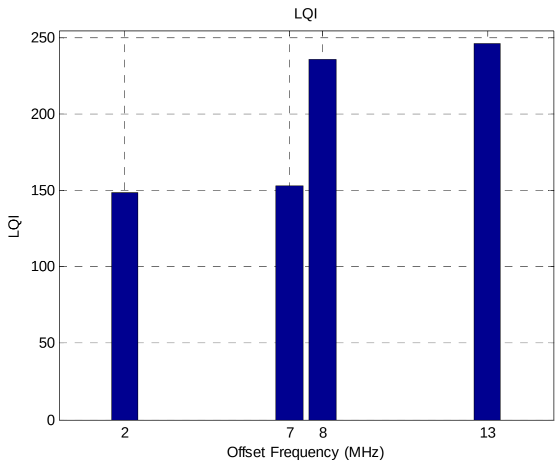

Fig.9. LQI VS. Offset Frequency

V. Conclusion

ZigBee as a new attractive wireless network can be used in several applications such as sensor interconnecting, monitoring and automating different systems in home, hospitals, manufactories and agriculture. Features like low cost, easy extension, reliability, flexibility, security, low power consumption and so on make it suitable to be deployed in smart grid. However it shares the frequency band with WiFi which is widely spread in world. Therefore, efficient interference avoidance is a key scheme to ensure the performance of ZigBee with WiFi present. In this paper, we propose frequency agility interference avoidance algorithm including interference detection and smart channel selection. NACK-based interference detection and energy detection as an energy saving and accurate interference detection scheme is adopted. Classified channels' energy detection in sequence is an intelligent method to find available channel as soon as possible. Active scan makes sure the channel is not occupied by other ZigBee PAN. From the implementation in real world, proposed scheme has been validated that it can efficiently avoid interference from WiFi.

VI. Acknowledgement

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VIII. Biographies

Peizhong Yi received her B.S. degree in Telecommunication from Xi'dian University, Xi'an, China, in 2007, and her M.S. degree in Electrical Engineering from Illinois Institute of Technology (IIT), Chicago, Illinois, in 2009. She is now a Ph.D. student at Computer Engineering Department in IIT. She is also an IEEE student member. Her Ph.D. research concentrated on design interference avoidance techniques of ZigBee, design and develop self-forming and self-healing cluster-tree ZigBee systems, and deploy ZigBee wireless network in Perfect Power project.

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Chi Zhou received two B.S. degrees in both Automation and Business Administration from Tsinghua University, China, in 1997. She received the M.S. and Ph.D. degrees in Electrical and Computer Engineering from Northwestern University in 2000 and 2002, respectively. Between 2002 and 2006, she worked in Florida International University as assistant professor. Since 2006, she has served as an assistant Professor in the Department of Electrical and Computer Engineering, Illinois Institute of Technology. Her primary research interests include wireless sensor networks for smart grid application, scheduling for OFMA/MIMO systems, network coding for wireless mesh networks, and integration of optical and wireless networks.

A Perfect Power Demonstration System

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***Abstract*—Energy efficiency, power system reliability and the environmental impact of fossil fuel plants are all drivers for more intelligent or smart grids. We discuss a Perfect Power System, a smart micro grid with system redundancy, and implement a test bed to demonstrate smart grid concepts such as demand response, onsite generation, automated lighting system control, and ambient temperature control. We conclude that the integration of Zigbee modules in building control systems will enable greater levels of building energy management, reduce energy consumption and potentially result in significant cost savings.**

***Index Terms*—Smart grid, micro grid, Perfect Power System, Zigbee.**

I. Introduction

ENERGY efficiency, reliability and environmental impact of power supply systems are issues of global concern. The typical efficiency of a fossil fuel plant is about 35%, while up to 5% of the generated power is lost during transmission, making a case for distributed power generation. An increasing proportion of loads on the grid are digital devices which are extremely sensitive to even brief power fluctuations and outages. Although the United States power grid functions with a reliability rate of 99.97%, it has been estimated that power outages and interruptions result in at least $150 billion in losses annually [1]. In addition, fossil fuel power plants in the United States produce 40% of the national carbon emissions linked with global warming [2]. It is evident that the financial effects of power grid inefficiencies and outages, as well as their environmental concerns, provide significant impetus for change.

The smart grid concept specifies the addition of intelligence and two-way digital communication to the power grid to significantly improve system reliability and security, achieve real-time fine-grained feedback on network performance, outage conditions and pricing. It facilitates rapid outage detection, real-time pricing feedback to end-users, and facilitates demand response schemes to enable user appliances to be turned on/off automatically.

Smart grids facilitate energy efficiency by means of smart meters located within customer sites, which provide users with real-time power pricing data to enable informed decision-making. They also enable greater incorporation of renewable energy sources such as wind and solar power into the grid, thereby reducing the dependence on fossil-fuel power generation, and reducing greenhouse gas emission.

System reliability is significantly improved via embedded sensors distributed throughout major nodes within the power system. These sensors enable rapid fault detection and isolation via bidirectional digital communication links. They also provide granular system health data that can be used for rapid system analysis, fault preemption and trending. By distributing power generation and enabling consumers to also supply energy to the network, system reliability is significantly improved as alternative power sources can supply the grid when there is an outage in utility power. System efficiency also increases as line losses due to long distance transmission are eliminated.

The smart grid concept has also been extended to smaller smart grid networks known as smart microgrids. A smart micro grid is a localized smart grid covering specific geographical regions such as suburban neighborhoods or university campuses, and incorporating local or onsite power generation.

We begin by introducing the Perfect Power concept in section II. In section III we discuss the Zigbee networking standard and its applicability to Building Automation Systems. Section IV details the IIT Perfect Power Demonstration System, specifically on the deployment of a test bed to demonstrate smart grid applications such as demand response and on-site power generation, ambient temperature control, ambient lighting system control and load distribution. We conclude with section V where we discuss Perfect Power implementation and future research directions.

II. The IIT Perfect Power Project

The United States power grid has remained essentially unchanged since the 1960's. The primary control elements were designed and developed before digital computing became widespread. Energy efficiency, environmental concerns, network security and customer flexibility were not taken into consideration when the initial design specifications for the power grid were developed, precipitating the issues detailed earlier. A Perfect power system resolves these problems via the integration of redundancy and onsite power generation to the smart grid to guarantee uninterrupted, high quality power to consumers at all times.

The Illinois Institute of Technology is pioneering a smart or micro grid concept termed a "Perfect Power System." The goal of such a system is to satisfy customer energy demand in terms of quality and quantity 100% of the time [3]. A Perfect Power system incorporates smart micro-grid concepts such as onsite generation and bidirectional electricity and data flows, combining them with a reliable, self-healing, redundant power delivery system. The primary goals of a perfect power system are:

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- Reliability
- Efficiency
- Cleanliness
- Security

In order to achieve these objectives, the system utilizes the following mechanisms:

A. Demand Response

Real-time power pricing (RTP) data is obtained from the utility and is incorporated into the system management algorithm, enabling load actuation on the basis of total system capacity or pricing data.

B. Onsite Power generation

An on-campus gas turbine can be used to provide power to the campus in outage scenarios, during peak rate time periods, or to generate power which can be sold back to the utility company. Solar power and other renewable energy sources will also be incorporated into the campus grid, facilitating load distribution across multiple power sources.

C. Energy efficiency

A campus-wide wireless sensor network will be deployed within each building to monitor environmental data such as temperature, lighting levels, room occupancy, humidity, and smoke. Other sensors will be connected to actuators to control heating, ventilation and air-conditioning (HVAC) systems, lighting or security alarm systems on the basis of received sensor data and system thresholds.

D. Smart Metering

Real-time power usage throughout the campus will be obtained via smart metering devices. These devices will facilitate rapid decision-making, fault detection and system trend identification.

III. ZIGBEE AND BUILDING AUTOMATION SYSTEMS

A. Building Automation Systems

Building Automation systems provide centralized and automated management of building HVAC systems, lighting controls, fire and security systems. They are used to reduce energy costs, improve energy efficiency and facilitate off-site building management [4][5][6]. The primary requirements for Building Automation applications are low cost, ease of installation and flexibility/reconfigurability.

B. The Zigbee Standard

Zigbee devices are ideal for these applications because they are wireless, cheap, and robust. The cabling and installation costs for wired devices frequently exceed the cost of the device itself. The use of building elements with embedded Zigbee radios therefore results in significant cost savings over the lifetime of the building. Zigbee end devices are battery-powered and can run for several years before battery replacement, resulting in low maintenance costs. Wireless nodes also provide flexibility, easy re-deployment and reconfiguration. These are very important features in buildings which are often re-partitioned and modified to meet differing occupant requirements.

The robust nature of Zigbee networks also makes them ideal for hostile environments where node failures may be common [7]. Their mesh networking topology, self-healing and route repair features enable routing around failed nodes, facilitating robust network architecture. Zigbee's spread spectrum modulation scheme and channel change features also help mitigate the effect of interference.

The integration of Zigbee radios with light switches, occupancy sensors, temperature sensors, smoke detectors, and ventilation actuators facilitates fine-grained measurement and control of all the building systems resulting in significant energy savings, greater comfort, safety and security for building occupants [8].

Zigbee is the wireless communication technology selected for data collection and communication throughout the IIT Perfect Power System. It is a low rate, low power, wireless personal area networking scheme [4] based on the physical (PHY) and medium access control (MAC) layers of the IEEE 802.15.4 standard. It is designed for short distance communication at a maximum data rate of 250 kbps.

Its design objectives were simplicity, extremely low-power consumption and low cost. The low cost requirements were met by making the system as simple as possible, while the low power consumption requirements were achieved by means of the selected modulation scheme and very low system duty cycles. At typical Zigbee node has a duty cycle of less than 5%, thereby guaranteeing a life-span of up to 5 years on a pair of AA batteries. Typical Zigbee applications such as environmental sensing or smart metering only require periodic data transmission and reception, permitting the radio to sleep the majority of the time.

The Zigbee standard makes use of the IEEE 802.15.4 protocol and simply adds networking and application layer stacks on top of the PHY and MAC layers of 802.15.4 protocol. Three frequency bands are defined for the Zigbee, namely 868 MHz (Europe), 915 MHz (US) and the 2.4 GHz Industrial, Scientific and Medical (ISM) band for global use. The Zigbee standard uses Binary Phase shift Keying (BPSK) modulation in the 868 and 915 MHz bands, while Offset-Quadrature Phase shift Keying (O-QPSK) is used in the 2.4 GHz ISM band. All the operating frequencies defined for 802.15.4 are unlicensed, leading to lower device and deployment costs, but making them vulnerable to other devices using the ISM band such as 802.11b/g Wireless Local Area Networks (WLAN's), baby monitors, microwave ovens etc.

Frequency	Region	Modulation Scheme	Bit rate (kbps)	Channels	Channel spacing
868 MHz	Europe	BPSK	20	1	N/A
915 MHz	Americ a and Asia	BPSK	40	10	2 MHz
2.4 GHz	Global	O-QPSK	250	16	5 MHz

Fig. 1. Zigbee Frequency and Channel Allocation

A Zigbee network consists of two major device categories, full function devices (FFDs) and reduced function Devices (RFDs) [9]. FFDs can perform network establishment, routing, and management, while RFDs only support a subset of the Zigbee device functions, making them simpler and thereby reducing their cost. A Zigbee network is made up of a Zigbee Coordinator (ZC), one or more Zigbee Routers (ZRs), and multiple End Devices (EDs). A FFD can act in any of the 3 roles, while end devices tend to be RFDs. The Zigbee Coordinator is responsible for network startup and management. Zigbee Routers are identical to Coordinator nodes but cannot perform network establishment or management functions. They are used to route traffic between the network coordinator and End devices. Routers and coordinators can communicate with all the devices on the network and are connected to mains power supplies, as they can not go to sleep without adversely affecting the ability to route traffic through the network. EDs can only communicate with routers, and are incapable of peer to peer communication. They tend to be battery-powered devices, and spend most of the time in sleep mode. They periodically awake, check for any messages buffered for them at their parent router, read their attached sensors, transmit the measured data, and return to sleep mode.

IV. THE PERFECT POWER SYSTEM TEST BED

In order to demonstrate the Perfect Power concept to stakeholders and visitors, a table-top demonstration was created at the Optical Wireless Integration Lab of the Electrical and Computer Engineering department at IIT. Its objective is to display the suitability of Zigbee control and sensor nodes for building automation within the Perfect Power project. Our goal was the development of an automatic real-time utility data collection and power control system using Zigbee. Two-way communication was used to forward readings from end nodes to a Data Collection and Control Center (DCCC), and to pass control messages from the DCCC to the end nodes. Each end node is able to relay or forward the collected data to the DCCC via distributed Zigbee routing nodes. The Zigbee Coordinator aggregates all the received data for display and processing, and transmits control signals to the end nodes according to the selected power management strategy.

The following equipment was used to create the Perfect Power Demonstration system:

- 4 Meshnetics Meshbean2 Zigbee motes
- 1 Laptop serving as the DCCC
- A Peryton Zigbee Protocol Analyzer
- 1 Power supply source switching module
- 1 Parallax Passive Infrared (PIR) sensor
- A Panasonic AQH2213 solid state relay
- 3 DC fans
- 1 Desk lamp

Fig. 2. Perfect Power Demonstration System

A Meshnetics Meshbean2 Zigbee mote was selected for the Zigbee devices around which we built our system. It combines an ATMEL 1281V low power microcontroller with 8K of RAM and 128kB of flash memory, an ATMEL RF230 Zigbee radio, onboard light and temperature sensors in a single battery powered- module with a USB interface. Its I/O interfaces permitted us to add our own sensors and actuator circuits to extend its capabilities.

Fig. 3. Meshnetics Meshbean2 Zigbee mote

5V input rated PIR sensors and relay modules were selected to enable easy interfacing with the Zigbee modules. The Panasonic AQH2213 solid state relay enables control of 110V AC loads rated at most 0.9 amps using a 5V input signal, providing a safe and convenient means of controlling the desk lamp. A Perytons 802.15.4 Protocol Analyzer was used during application development to troubleshoot Zigbee protocol messages between the coordinator and end devices.

The following tasks were accomplished to deploy our Perfect Power System demonstration system:

- Zigbee Sensor Node software development
- DCCC software development
- Hardware module development and interfacing

A. *Zigbee Module Software Development*

We have successfully coded and configured 4 Meshnetics Meshbean2 Zigbee Nodes using the C language based BitCloud Zigbee stack. The nodes are configured to automatically establish a Mesh/Star network configuration consisting of one (1) coordinator module and four (4) end devices. The coordinator and end devices are controlled and monitored using a MATLAB-based GUI, with each end device also serves as a router to its peers. The four end nodes have been coded to provide support the following features:

Sensing:

- Ambient temperature measurement

- Ambient light levels measurement
- Radio frequency interference levels
- Room occupancy (using an external PIR sensor)

Control:

- Each end node can control a maximum of 3 external DC or AC loads, such as lamp and fans.

B. DCCC Software Development

The DCCC serves as the system controller, receiving input from the various sensors along with real time power pricing. It is responsible for data analysis; load scheduling, fault detection/management, data logging and display. Its goal is efficient energy management, monitoring and controlling building loads to achieve cost savings and eliminating resource waste.

The DCCC was developed in MATLAB and utilizes a GUI- front end. It communicates directly with the Zigbee Network coordinator and provides the following functions:

- The display of received sensor data (temperature, light levels, room occupancy etc)
- Remote control of Zigbee modules
- User configuration of timing, pricing and sensor data threshold values
- Control of externally connected loads on the basis of user determined price thresholds, time of day and sensor readings
- Lighting control based on room occupancy and other variables.

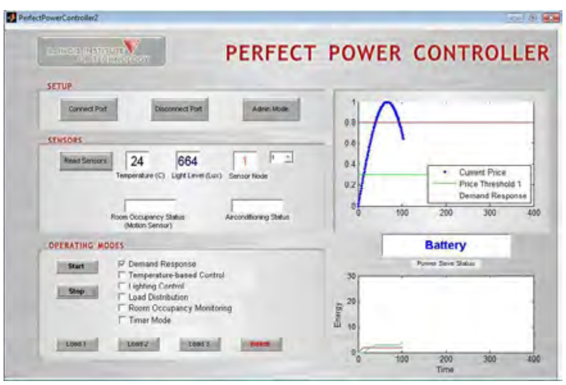

Fig. 4. Perfect Power Controller Demonstration GUI

C. Hardware Interfacing

We have developed 3 hardware modules to interface with the Zigbee nodes to enable the following:

- Power source switching of a load between AC and DC power sources
- Light control based on room occupancy and ambient light level sensing
- Load actuation based on temperature sensing or real time power pricing

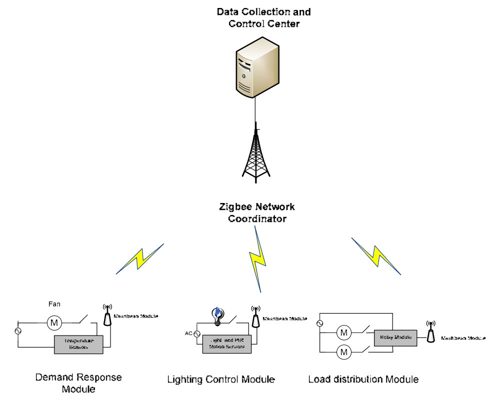

Fig. 5. Network Architecture

V. DEMONSTRATION MODES

A. Demand Response

Demand response is a mechanism whereby users can reduce their power consumption in response to utility power supply constraints or RTP. It facilitates reductions in peak power consumption throughout the grid, improving grid reliability and forestalling power outages. Combined with RTP data, it enables consumers to reduce their energy usage costs by actively managing their electrical loads. Demand response requires the presence of a communications link between actuators connected to consumer loads and the utility. These actuators enable the utility to send control signals to remotely switch these loads on/off or to inform the local management system to do so.

To demonstrate this, we designed a module consisting of the following elements:

- An AC rectification circuit
- Load driver circuit
- 5V Relay
- Meshbean2 Zigbee mote

Fig. 6. Perfect Power Controller Demonstration GUI

The Zigbee module controls the relay, enabling the load to be switched between the rectified 12V DC supply (representing the Utility supply) and an attached 9V battery (representing onsite generation).

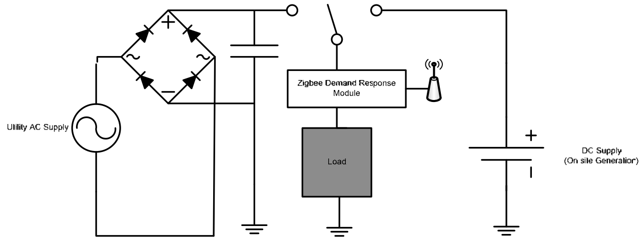

Fig. 7. Demand Response actuation module

In a full scale deployment the onsite power supply will be either a gas turbine or solar power, while the loads will include HVAC systems or other building loads. The load in our test bed was a 12V fan and load actuation was performed on the basis of current power pricing levels.

Two threshold pricing points are input by the user via the GUI. The lower threshold determines the price point at which the load will be switched to/from mains supply to battery power (onsite generation), while the upper threshold determines the price point at which the load will be switched off (load shedding). A simulated RTP stream is generated in the DCCC, while periodic messages are exchanged with the Zigbee demand response module. Whenever a threshold is crossed, a control message is sent to the remote Zigbee module to perform the relevant action. With this scheme, thresholds can be varied to establish a ceiling on how much power will be drawn from the utility during a specified time period. Figure 5 provides a graphical representation of the power usage mix between mains supply and the battery supply. The flat periods represent load shedding intervals. More/less onsite power can be used by adjusting the price thresholds for used for triggering.

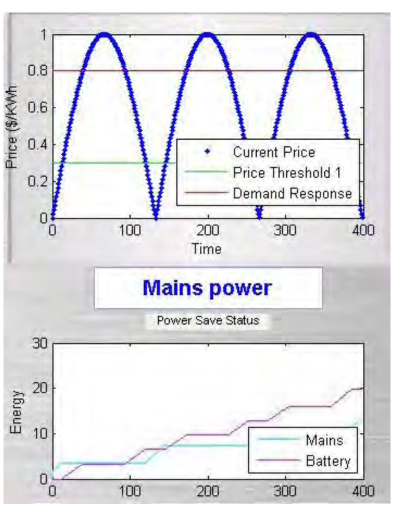

Fig. 8. Price vs energy source usage in Demand Response mode

The system also facilitates load distribution. Rather than simultaneous usage of all loads, their actuation can be scheduled in a way to maintain a constant level of total energy usage while reducing utility charges. Loads can be automatically scheduled for off peak periods to and this feature was demonstrated using the Load distribution module, which enables 2 loads to be independently switched on/off based on scheduling decisions by the DCCC.

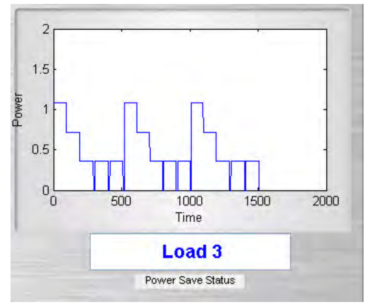

Fig. 9. Load Distribution mode screenshot

B. *Lighting Control*

Lighting is the second largest consumer of electrical energy within a building, so efficient control and energy management promises significant cost savings. We combined a Zigbee node, a passive infra-red (PIR) motion sensor, light sensor and a solid state relay circuit within a single module. The PIR sensor is tuned to infrared heat given off by a human being, enabling occupancy sensing, while the onboard light sensor of the Meshbean2 Module was used for ambient light level measurements. A solid state relay circuit built around the Panasonic AQH2213 was used to control an attached table lamp.

The ambient light threshold for a room is configured into the DCCC, and the Zigbee Light control module reads its attached sensors every 2 seconds, providing the DCCC with the light levels and room occupancy status. If the lighting level falls below the user-determined threshold, Zigbee module triggers the solid state relay, turning on the table lamp. If room occupancy is detected, the lamp is also triggered. The light can also be remote triggered from the DCCC at will.

Using ambient light levels, room occupancy and time as system inputs to the DCCC, we are able to remotely control the lighting levels in a room in an efficient manner. This application can be extended throughout an entire building to facilitate centralized lighting control and monitoring. It also provides the opportunity to customize lighting levels according to time of day, room occupancy and ambient light levels. This information can also be used for maintenance purposes, indicating lighting equipment failures.

Fig. 10. System configuration panel

C. Ambient Temperature Sensing and Control

Ambient temperature sensing was performed using the onboard LM73CIMK temperature sensor of the Meshbean2 Zigbee mote. Periodic measurements were taken from the remote Zigbee devices, and load actuation was performed on the basis of the user configured temperature threshold values. The demand response module was utilized to demonstrate this capability, and its attached load (a fan in this case) is automatically triggered whenever the ambient temperature threshold is exceeded. The readings from different points within a building can be combined to obtain a detailed picture of building temperature distributions, which can then be used for highly–accurate and automated building environment control.

VI. Conclusion

We demonstrated how Zigbee devices can be leveraged to enhance building automation systems, and permit granular control of electrical and HVAC systems for smart grid applications. Future work involves deploying a Zigbee sensor network throughout Siegel Hall, the Electrical and Computer Engineer building at IIT. We will deploy a Zigbee Data Collection and Control Center to monitor and control HVAC systems, measure ambient lighting levels and temperature, and control designated lighting systems within the building. Our scope of work also includes interference mitigation schemes, so that the Zigbee network can operate with satisfactory performance even when significant interference sources, including WiFi, microwave ovens and Bluetooth devices are present.

The final goal is to replicate such a system throughout the IIT campus, enabling building automation to even room levels, and achieving unprecedented levels of control. The Perfect Power systems is based on a hierarchical model whereby efficient energy management is performed at the building level, and then aggregated over a large area, and such a scheme will save millions of dollars per year on heating and cooling, as well resulting in a greener campus.

VII. Acknowledgement

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IX. Biographies

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Florida International University as assistant professor. Since 2006, she has served as an Assistant Professor in the Department of Electrical and Computer Engineering, Illinois Institute of Technology. Her primary research interests include wireless sensor networks for smart grid application, scheduling for OFMA/MIMO systems, network coding for wireless mesh networks, and integration of optical and wireless networks.

Modeling Load Redistribution Attacks in Power Systems

Yanling Yuan, Zuyi Li, *Senior Member, IEEE,* Kui Ren, *Member, IEEE*

***Abstract* — State estimation is a key element in today's power systems for reliable system operation and control. State estimation collects information from a large number of meter measurements and analyzes it in a centralized manner at the control center. Existing state estimation approaches are traditionally assumed to be able to tolerate and detect random bad measurements. They were, however, recently shown to be vulnerable to intentional false data injection attacks. This paper fully develops the concept of load redistribution (LR) attacks, a special type of false data injection attacks, and analyzes their damage to power system operation in different time steps with different attacking resource limitations. Based on damaging effect analyses, we differentiate two attacking goals from the adversary's perspective, i.e., immediate attacking goal and delayed attacking goal. For the immediate attacking goal, this paper identifies the most damaging attacking vector through a max-min attacker-defender model. Then, the criterion of determining effective protection strategies is explained. The effectiveness of the proposed model is tested on a 14-bus system. To the author's best knowledge, this is the first work of its kind, which quantitatively analyzes the damage of the false data injection attacks to power system operation and security. Our analysis hence provides an in-depth insight on effective attack prevention with limited protection resource budget.**

***Index Terms* — state estimation, false data injection attacks, load redistribution attacks, immediate LR attacks, delayed LR attacks, effective protection strategy.**

NOMENCLATURE

Indices

d	Load index.
g	Generator index.
l	Transmission line index.

Constants

c_g	Generation cost (in \$/MWh) of generator g.
cs_d	Load shedding cost (in \$/MWh) of load d.
D_d	Actual value of load d (in MW).
KD	Bus-load incidence matrix. $\mathbf{KD}_{\bullet d}$ is the d^{th} column of matrix **KD**.
KP	Bus-generator incidence matrix. $\mathbf{KP}_{\bullet g}$ is the g^{th} column of matrix **KP**.
M	Sufficient large positive constant.
$P_g^{\max}, P_g^{\min}$	Maximum and minimum generation output (in MW) of generator g.
$PL_l^{\max}$	Transmission capacity (in MW) of line l.
R	Attack resources.
SF	Shifting factor matrix.
ε	Sufficient small positive constant.
τ	Upper bound of $\Delta D_d / D_d$ for each load d.

Variables

ΔD_d	Attack on the measurement (in MW) of load d.
P_g	Generation output (in MW) of generator g.
PL_l	Power flow (in MW) of transmission line l.
ΔPL_l	Attack on the power flow measurement (in MW) of transmission line l.
S_d	Load shedding (in MW) of load d.
$\underline{\alpha}_l, \overline{\alpha}_l$	Lagrange multipliers associated with the lower and upper bounds for the power flow of line l.
$\underline{\beta}_l, \overline{\beta}_l$	Lagrange multipliers associated with the lower and upper bounds for the generation output of generator g.
$\delta_{D,d}, \delta_{D+,d}, \delta_{D-,d}$	Indicators. $\delta_{D,d} = 1$ if the measurement of load d is attacked, i.e., $\Delta D_d \neq 0$; $\delta_{D+,d} = 1$ indicating $\Delta D_d > 0$; $\delta_{D-,d} = 1$ indicating $\Delta D_d < 0$.
$\delta_{PL,l}, \delta_{PL+,l}, \delta_{PL-,l}$	Indicators. $\delta_{PL,l} = 1$ if the power flow measurement of line l is attacked, i.e., $\Delta PL_l \neq 0$; $\delta_{PL+,l} = 1$ indicating $\Delta PL_l > 0$; $\delta_{PL-,l} = 1$ indicating $\Delta PL_l < 0$.
$\underline{\gamma}_d, \overline{\gamma}_d$	Lagrange multipliers associated with the lower and upper bounds for the load shedding of load d.
λ	Lagrange multiplier associated with the power balance equation for the system.
μ_l	Lagrange multiplier associated with the power flow equation for line l.
$\omega_{\underline{\alpha},l}, \omega_{\overline{\alpha},l}$	Additional binary variables to represent the complementary slackness conditions for the power flow constraints of line l.
$\omega_{\underline{\beta},g}, \omega_{\overline{\beta},g}$	Additional binary variables to represent the complementary slackness conditions for the generation output constraints of generator g.
$\omega_{\underline{\gamma},d}, \omega_{\overline{\gamma},d}$	Additional binary variables to represent the complementary slackness conditions for the load shedding constraints of load d.

Note that a variable in bold without index represents the vector form of that variable.

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I. INTRODUCTION

ELECTRIC power systems, as the driving force of the modern society, are critical to any country's economy and security. The physical vulnerability of electric power systems to natural disasters and sabotage has long been recognized [1].

Recent works have addressed the vulnerability analysis of the power systems under physical terrorist attacks [2]-[8]. Effective defense or protective measures are determined by identifying the critical components in power systems whose outages may cause the maximum disruption to the systems.

The development of smart grid has brought in tremendous economic benefits and advanced communication and control capabilities to the electricity industry. In the meantime, the so-called cyber-vulnerability has caused more and more concerns. Supervisory Control and Data Acquisition (SCADA) systems, which transmit measurements, status information, and circuit-breaker signals to and from Remote Terminal Units (RTUs), are susceptible to cyber security attacks due to their reliance on communication and network technologies. It was shown recently that an attacker could corrupt the measurement data that SCADA systems collect through RTUs, heterogeneous communication networks, or control center office LANs [9]. As the information source of the control center, SCADA systems, once being attacked, may affect the outcome of state estimation and further mislead the operation and control functions of Energy Management System (EMS), possibly resulting in catastrophic consequences. False data injection attacks [10], one type of cyber attacks against state estimation through SCADA systems, are getting more attention as smart grid develops. This attack cooperatively manipulates the measurements taken at several meters, and thus distorts the outcome of the state estimation. A key observation in [10] is that a false data injection attack vector $\boldsymbol{a}$ is totally undetectable if it is a linear combination of the column vectors of the Jacobin matrix $\mathbf{H}$, which is a function of the power network configuration. This injected attack can successfully bypass bad data detection since it does not affect the measurement residual $\mathbf{r}$ while the existing bad data checking techniques are all based on the measurement residual. This attack can be easily constructed if an attacker gains access to the $\mathbf{H}$ matrix. Furthermore, this attack can manipulate the state estimation outcome in an arbitrary and predicted way, and potentially cause serious consequences. It is thus critical to protect the power systems from false data injection attacks.

In fact, it has long been known in the power systems community that certain errors are undetectable by residual analysis [11], [12]. This can be viewed as a fundamental limitation on the ability of the state estimation to handle cooperative attacks. Some work has been done to limit the effect of false data injection attack on power system state estimation. Ref. [13] introduced a Bayesian framework, which is based on the belief that power system state usually changes from one to the next gradually unless a contingency has occurred. With some prior information on the actual state, the effect of false data injection attack is effectively limited from infinity to some finite range. A new L_∞ norm detector is then introduced instead of the more standard L_2 norm based detectors by taking advantage of the inherent sparsity of the attack vector. However, the actual state of the system is usually hard to predict since a power system could undergo rapid load changes even without the occurrence of a contingency. Also, as shown in [13], under the most damaging false data injection attack, the error of state estimation can still jump to a level that may be high enough to endanger the reliable operation of power systems. Some other work focused on the protection strategy to false data injection attacks. Ref. [9] introduced two security indices for each measurement: attack vector sparsity and attack vector magnitude. The security indices of a measurement evaluate how many, and by how much other measurements need to be corrupted in coordination with this measurement to avoid the triggering of alarms. It was shown that larger measurement redundancy seems to give higher security in terms of attack vector magnitude. Unfortunately, no relationship exists between redundancy and security in terms of attack vector sparsity. Moreover, Ref. [9] intended to establish protection strategy on measurements with low security indices. However, this protection motivation can only protect the system from those attacks that need less effort to implement.

It is well known that state estimation is used to make the best estimate on the state of the power system in system monitoring. Based on the estimated state, security-constrained economic dispatch (SCED) then intends to minimize the total system operation cost through the redispatch of generation output. If the estimated state is contaminated due to bad data injection attack, false SCED solution may lead the system to an uneconomic operating state that could be accompanied with immediate load shedding, or even to an insecure operating state that could cause wider load shedding in a delayed time without immediate corrective actions. This paper first studies the damaging effect of the load redistribution attack on power system operation and control. In this paper, the damaging effect is economically quantified based on the system operation cost from the result of a false SCED. For simplicity, SCED only considers power flow equations and power transmission constraints under base case, and the operation cost only includes generation cost and load shedding cost. In this paper, the most damaging attack is identified under posited attacking resources. A specific protection strategy is designed and deployed to mitigate the most damaging effect.

The contributions of this paper are summarized as follows.

1) This paper defines a special kind of false data injection attacks – load redistribution attacks (LR attacks), in which only load bus injection measurements and line power flow measurements are attackable elements. LR attacks are realistic false data injection attacks with limited access to specific meters.

2) This paper analyzes the damaging effects of LR attacks. Since LR attacks can successfully bypass the bad data detection and manipulate the state estimation outcome, SCED based on the false estimated state would lead the system into a false secure and optimal operating state. The damage of LR attacks is described in two time steps. Accordingly, this paper differentiates two different attacking goals from the adversary's perspective, i.e., immediate attacking goal and delayed attacking goal.

3) This paper proposes a bi-level model in order to find the most damaging LR attack with the immediate attacking goal. The goal of the attack is to maximize the system operation cost under the logical assumption that the control center will implement feasible corrective actions to minimize the operation cost based on the false state estimation.

4) This paper describes the theory and criterion of protecting the system from the damage of a specific LR attack considering the existence of stochastic measurement error. With this protection criterion, effective protection strategies can then be designed to defeat the attacker's attempt.

The remainder of this paper is organized as follows. Section II introduces LR attacks and analyzes their damages to power system operation through a simple two-bus system example. Section III presents the bi-level formulation for LR attacks with immediate attacking goal and describes the proposed solution algorithm to the formulation. Section IV introduces the criterion of effective protection strategies for a specific LR attack. Section V presents and analyzes the numerical results. Section VI draws relevant conclusions and presents future work. In the appendix, the deduction of the effective protection criterion is explained in detail.

II. Load Redistribution Attacks

In practical power systems, the attack on some measurements will easily expose itself and the attacked measurements will be denied as an effective measurement for state estimation. Considering the practical situations in power system state estimation, we make a few assumptions in this paper: 1) Generator output measurement cannot be attacked. This is because this attack can be easily detected and corrected through the direct communication between control center and power plant control room. 2) The bus injection measurement of zero injection buses in the network cannot be attacked. Zero injection buses are those having neither generation nor load connected. In state estimation, zero injection may be interpreted as an exact measurement of the bus injection power. 3) Load measurements are attackable. Since in power systems, load is constantly changing and load meters are widely distributed. However, since short-term load forecasting provides an approximate estimation of the load, attack that causes load measurements to deviate far from their true values will be under suspicion. In this paper, we suppose that the attack magnitude for a load measurement does not exceed τ=50% of its true load value. Note that τ value is a constant preset by the control center based on historical data. In smart grid environment, τ may be varying for different types of load. 4) Power flow measurement for transmission lines can be attacked without being suspected. With the above assumptions, the effect of LR attacks is actually load redistribution, i.e., increasing load at some buses and reducing loads at other buses while maintaining the total load unchanged. Only load bus power injection measurements and line power flow measurements are attackable in LR attacks.

As a special case of false data injection attacks, LR attacks will mislead the state estimation process without being detected by any of the existing techniques for bad data detection. False SCED solution may harm power systems in two time steps. First, it may lead the system into a non-optimal generation dispatch; load shedding, which is originally unnecessary, may happen at the worst case. Second, it may lead the system into an insecure operating state, i.e., power flow on some transmission lines may actually exceed their transmission capacity. Without immediate corrective actions, the outage of these overloaded lines will cause more widely load shedding in a delayed time. The damaging effect of an LR attack can be clearly seen from a simple two-bus system example shown in Fig. 1.

Generator output limits are: $0 \le P_1 \le 18MW$, $0 \le P_2 \le 30MW$. Transmission line capacity limit is $|PL| \le 5MW$. Load-shedding cost is $cs = 40\$/MWh$. Assume that the original system state is: $P_1 = 18MW$, $P_2 = 22MW$, $PL = -2MW$. Without attack, SCED should originally lead the system to the optimal state: $P_1' = 15MW$, $P_2' = 25MW$, $PL' = -5MW$. There should be no load shedding in the system and the total generation cost is $C' = 550\$/h$.

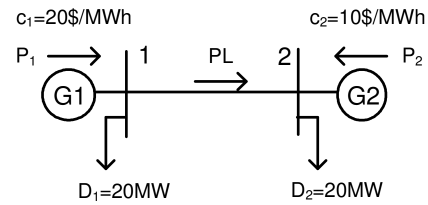

Fig. 1 Two-bus system

Assume that an LR attack ΔD_1, ΔD_2, and ΔPL manipulates the estimation of the system state to $D_{f,1}$, $D_{f,2}$, and PL_f. The control center implements SCED based on the false state estimation and directs the system into a deemed optimal state, $P'_{f,1}$, $P'_{f,2}$, and PL'_f, with possible load shedding $S'_{f,1}$ and $S'_{f,2}$ and total operation cost C'_f (generation cost + load shedding cost). However, the actual power flow is PL'_t instead of the deemed value PL'_f . The immediate effect of six different attacks is shown in Table 1.

Table 1 Immediate Damaging Effect to a Two-bus System
(Power Quantities in MW, Cost Quantities in $/h)

attack case		1	2	3	4	5	6
LR attack	ΔD_1	2	4	6	8	10	-10
	ΔD_2	-2	-4	-6	-8	-10	10
	ΔPL	-2	-4	-6	-8	-10	10
false state estimation	$D_{f,1}$	22	24	26	28	30	10
	$D_{f,2}$	18	16	14	12	10	30
	PL_f	-4	-6	-8	-10	-12	0
false SCED results	$P'_{f,1}$	17	18	18	18	18	10
	$P'_{f,2}$	23	21	19	17	15	30
	PL'_f	-5	-5	-5	-5	-5	0
	$S'_{f,1}$	0	1	3	5	7	0
	$S'_{f,2}$	0	0	0	0	0	0
	C'_f	570	610	670	730	790	500
actual	PL'_t	-3	-1	1	3	5	-10

In attack case 1, the false SCED leads the system into a non-optimal generation dispatch with an operation cost of 570$/h, which is 20$/h higher than that of the original case. In this case, there is no load shedding after the implementation of SCED solution. The false state estimation for line power flow (PL_f =-4MW) is well within the line capacity limit. For attack case 2, the attack magnitude increases to 20% of the original load. The falsely estimated line power flow (PL_f =-6MW) exceeds its capacity limit. In order to maintain a secure operation, SCED based on the false state estimation ($D_{f,1}$=24MW, $D_{f,2}$=16MW) leads the system to a false optimal operating state with a total operation cost of 610$/h and 1MW load shedding on bus 1. As the attack magnitude increases gradually up to 50% of the original load for case 3-5, load shedding and operation cost increase accordingly. For the above cases, we observe that to mislead the control center to shed load immediately, two conditions must be satisfied: 1) attack magnitude is big enough; 2) the falsely estimated power flow exceeds its corresponding transmission capacity limit. Even if load shedding does not happen after the attack, the false SCED may still result in a non-optimal dispatch or/and a false power flow, as shown in case 1. This damaging effect is realized immediately after the enforcement of SCED decision.

For attack case 6, false state estimation ($D_{f,1}$=10MW, $D_{f,2}$=30MW) leads to a false generation dispatch ($P'_{f,1}$=10MW, $P'_{f,2}$=30MW). The control center presumes that the line power flow is PL'_f=0 after the implementation of the false generation dispatch. However, since the actual system load is D_1=20MW, D_2=20MW, the false generation dispatch actually leads the power flow to PL'_l=-10MW, which is overloaded. However, control center will not be aware of this security problem until the next measurement is obtained. Without timely corrective actions, the overloaded line will trip in a delayed time. A new cycle of measurement collection, state estimation, and SCED processes will be initiated by this system topology change, and this two-bus system will be operated in a steady state P''_1=18MW, P''_2=20MW with 2MW load shedding on bus 1. This attacking case illustrates the potential threat of LR attacks to system operation security. In practical power systems, line outages may lead to wide load shedding. This effect can be viewed as an indirect physical terrorist attack to transmission lines; the difference is that the damage of LR attacks will be exposed in a delayed time after the enforcement of the false SCED results. It is worth mentioning that for the attack case in which the operation cost of the false SCED is lower than that of the original SCED, there must be line/lines operating out of its/their security range, since only relaxation on the transmission line capacity could render a lower operation cost. As shown in table 1, attack case 6 indeed has a lower operation cost 500\$/h as a false SCED solution. Note that if the system has enough transmission capacity, there may be no overloading in the actual line power flow.

From the above example, we observe that LR attacks may destroy the functioning of SCED and leave the system out of control, even result in security risk. Since the introduction of deregulation [17], increased levels of consumption and lack of investment on transmission system upgrade are driving the operation of power systems close to their static and dynamic limits, power systems are becoming increasingly vulnerable to LR attacks.

To protect the system from the LR attacks under limited protection resources, the control center has to first identify the most damaging attack. Since the damaging effects can be achieved in two time steps, this paper differentiates two attacking goals, i.e., immediate attacking goal and delayed attacking goal. Immediate LR attacks aim to maximize the operation cost immediately after the attacks; delayed LR attacks aim to maximize the total operation cost after the outage of overloaded lines, which is a delayed effect of LR attacks. This paper focuses on the modeling of the immediate LR attacks problem.

III. Bi-level Model of the Load Redistribution Attack

The goal of immediate LR attacks is to maximize the system operation cost subject to attacking resource limitation, under the logical assumption that the control center will implement feasible corrective actions to minimize the operation cost based on the false state estimation outcome. A bi-level model shown in Fig. 2 is proposed to identify the most damaging attack given posited attacking resources. The upper-level represents the attacker and determines the attack vector to be injected into original meter measurements in order to maximize the operation cost of the system. The system operator in the lower level problem optimally reacts to the false state estimation that has been successfully manipulated by the attack vector determined in the upper level. In this paper, this reaction only includes generation redispatch and load shedding, although the start-up of fast-response generators or the switching of transmission lines could also be effective means of reaction.

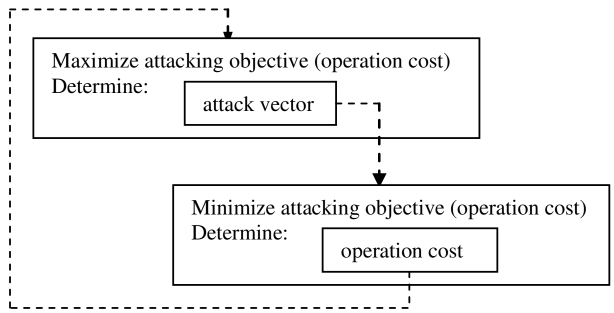

Fig. 2 Bi-level model for immediate attacking goal

As in most vulnerability analysis of the power systems under physical terrorist attacks, we use dc load flow model to characterize the behavior of the network. The mathematical modeling of the immediate LR attacks is shown below.

$$\underset{\Delta\mathbf{D}}{Max} \sum_{g=1}^{N_g} c_g P_g^* + \sum_{d=1}^{N_d} cs_d S_d^* \tag{1}$$

$$\text{s.t.} \sum_{d=1}^{N_d} \Delta D_d = 0 \tag{2}$$

$$-\tau D_d \le \Delta D_d \le \tau D_d \quad \forall\, d \tag{3}$$

$$\Delta D_d = 0 \Leftrightarrow \delta_{D,d} = 0 \quad \forall\, d \tag{4}$$

$$\Delta PL_l = 0 \Leftrightarrow \delta_{PL,l} = 0 \quad \forall\, l \tag{5}$$

$$\sum_{d=1}^{N_d} \delta_{D,d} + 2\sum_{l=1}^{N_l} \delta_{PL,l} \le R \tag{6}$$

$$\{\mathbf{P}^*,\ \mathbf{S}^*\} = \arg\left\{ \underset{\mathbf{P},\mathbf{S}}{Min} \sum_{g=1}^{N_g} cg_g P_g + \sum_{d=1}^{N_d} cs_d S_d \right\} \tag{7}$$

$$\text{s.t.} \sum_{g=1}^{N_g} P_g = \sum_{d=1}^{N_d} (D_d - S_d) \qquad (\lambda) \tag{8}$$

$$\mathbf{PL} = \mathbf{SF}\cdot\mathbf{KP}\cdot\mathbf{P} - \mathbf{SF}\cdot\mathbf{KD}\cdot(\mathbf{D}+\Delta\mathbf{D}-\mathbf{S}) \qquad (\boldsymbol{\mu}) \tag{9}$$

$$-PL_l^{\max} \le PL_l \le PL_l^{\max} \quad \forall\, l \qquad (\underline{\alpha}_l, \overline{\alpha}_l) \tag{10}$$

$$P_g^{\min} \le P_g \le P_g^{\max} \quad \forall\, g \qquad (\underline{\beta}_g, \overline{\beta}_g) \tag{11}$$

$$0 \le S_d \le D_d + \Delta D_d \quad \forall\, d \qquad (\underline{\gamma}_d, \overline{\gamma}_d) \tag{12}$$

The attacker is represented by the upper-level problem (1)-(6). The attacker maximizes the system operation cost, which includes generation cost and load shedding cost as shown in (1), considering a set of attack constraints (2)-(6). Constraint (2) and (3) ensures that the attack is an LR attack and the attack magnitude for a load measurement does not exceed a limit defined by τ and its true value in order not to be suspected. Constraints (4) and (5) model the logic relationships between the attack vector and the resource it uses for each attackable measurements. Constraint (6) guarantees that the attack satisfies attack resource limitation. Suppose that system is fully measured, i.e., the power injections at all bus and the power flows of all lines on both directions are measured. Accordingly, to attack the power flow measurement of one line, the attacker needs to manipulate two meters. The system operator is represented by an SCED model in the lower-level problem (7)-(12), which is parameterized in terms of the upper-level decision variables $\Delta\boldsymbol{D}$. The system operator minimizes system operation cost (7), considering the SCED constraints (8)-(12). As is commonly assumed, a dc model of the transmission system is used. Note that only constraints under base case are considered.

The logical constraints (4) can be modeled in mixed integer linear form (4') by introducing additional binary variables.

$$\begin{cases}\Delta D_d+\tau D_d\delta_{D,d}\geq 0\\ \Delta D_d-\tau D_d\delta_{D,d}\leq 0\\ \delta_{D+,d}+\delta_{D-,d}-2\delta_{D,d}\leq 0\\ \Delta D_d+(-\tau D_d-\varepsilon)\delta_{D+,d}\geq -\tau D_d\\ \Delta D_d+(\tau D_d+\varepsilon)\delta_{D-,d}\leq \tau D_d\\ \delta_{D+,d}+\delta_{D-,d}+\delta_{D,d}\leq 2\\ \delta_{D+,d}+\delta_{D-,d}-\delta_{D,d}\geq 0\\ \delta_{D+,d},\ \delta_{D-,d},\ \delta_{D,d}\in\{0,1\}\end{cases}\quad \forall\ d \tag{4'}$$

Constraint (5) can be similarly transformed to (5').

$$\begin{cases}\Delta PL_l+M\,\delta_{PL,l}\geq 0\\ \Delta PL_l-M\,\delta_{PL,l}\leq 0\\ \delta_{PL+,l}+\delta_{PL-,l}-2\delta_{PL,l}\leq 0\\ \Delta PL_l+(-M-\varepsilon)\delta_{PL+,l}\geq -M\\ \Delta PL_l+(M+\varepsilon)\delta_{PL-,l}\leq M\\ \delta_{PL+,l}+\delta_{PL-,l}+\delta_{PL,l}\leq 2\\ \delta_{PL+,l}+\delta_{PL-,l}-\delta_{PL,l}\geq 0\\ \delta_{PL+,l},\ \delta_{PL-,l},\ \delta_{PL,l}\in\{0,1\}\end{cases}\quad \forall\ l \tag{5'}$$

Given the upper-level attack vector, which is determined by $\Delta\boldsymbol{D}$, the lower-level optimization problem (7)-(12) is linear and convex. Similar to [3] and [20], this bi-level model can be transformed into an equivalent single-level mixed-integer program by replacing the lower-level optimization problem with its Karush-Kuhn-Tucker (KKT) optimality conditions. KKT optimality conditions were used in [18] and [19] to deduce the sensitivity functions in order to solve the bi-level bidding problems for FTR and GENCOs in power market. As illustrated in [8], KKT-based method is computationally inefficient due to the handling of the linearization expressions of the nonlinear complementary slackness conditions proposed by Fortuny-Amat and McCarl [14]. A duality-based approach proposed in [4] proved to be more efficient in vulnerability analysis of the power system under physical terrorist attacks. However, it is not suitable in our model of LR attacks. Since the lower-level problem is based on the value of the upper-level continuous variables $\Delta\boldsymbol{D}$, a multiplication of these continuous variables and dual variables will appear in the strong duality equality, which cannot be modeled in mixed-integer linear form. Artificial intelligence methods, such as particle swarm optimization [22], generic algorithm and co-evolutionary algorithm [21] were also employed to solve bi-level problems. However, those methods are not suitable for large systems due to their search efficiency. So, in this paper, we adopt the KKT-based method despite its computational complexity. Other methods like Benders Decomposition are under study in order to solve large, real-world problems.

Using KKT-based method, the original bi-level problem (1)-(12) can be transformed into an equivalent single-level MILP model as follows.

$$\underset{\Delta\mathbf{D}}{Max}\ \sum_{g=1}^{N_g}c_gP_g^*+\sum_{d=1}^{N_d}cs_dS_d^* \tag{1}$$

s.t. (2), (3), (4'), (5'), (6)

(8) - (12)

$$cg+\lambda-(\mathbf{SF}\cdot\mathbf{KP}_{\bullet g})^T\cdot\boldsymbol{\mu}-\underline{\beta}_g+\overline{\beta}_g=0\quad \forall\ g \tag{13}$$

$$\mu_l-\underline{\alpha}_l+\overline{\alpha}_l=0\quad \forall\ l \tag{14}$$

$$cs+\lambda-(\mathbf{SF}\cdot\mathbf{KD}_{\bullet d})^T\cdot\boldsymbol{\mu}-\underline{\gamma}_d+\overline{\gamma}_d=0\quad \forall\ d \tag{15}$$

$$\underline{\alpha}_l,\overline{\alpha}_l,\underline{\beta}_g,\overline{\beta}_g,\underline{\gamma}_d,\overline{\gamma}_d\geq 0\quad \forall g,\forall l,\forall d \tag{16}$$

$$\begin{cases}\underline{\alpha}_l\leq M\,\omega_{\underline{\alpha},l}\\ PL_l+PL_l^{\max}\leq M\,(1-\omega_{\underline{\alpha},l})\\ \overline{\alpha}_l\leq M\,\omega_{\overline{\alpha},l}\\ PL_l^{\max}-PL_l\leq M\,(1-\omega_{\overline{\alpha},l})\\ \omega_{\underline{\alpha},l}+\omega_{\overline{\alpha},l}\leq 1\end{cases}\quad \forall\ l \tag{17}$$

$$\begin{cases}\underline{\beta}_g\leq M\,\omega_{\underline{\beta},g}\\ P_g-P_g^{\min}\leq M\,(1-\omega_{\underline{\beta},g})\\ \overline{\beta}_g\leq M\,\omega_{\overline{\beta},g}\\ P_g^{\max}-P_g\leq M\,(1-\omega_{\overline{\beta},g})\\ \omega_{\underline{\beta},g}+\omega_{\overline{\beta},g}\leq 1\end{cases}\quad \forall\ g \tag{18}$$

$$\begin{cases}\underline{\gamma}_d\leq M\,\omega_{\underline{\gamma},d}\\ S_d\leq M\,(1-\omega_{\underline{\gamma},d})\\ \overline{\gamma}_d\leq M\,\omega_{\overline{\gamma},d}\\ D_d+\Delta D_d-S_d\leq M\,(1-\omega_{\overline{\gamma},d})\\ \omega_{\underline{\gamma},d}+\omega_{\overline{\gamma},d}\leq 1\end{cases}\quad \forall\ d \tag{19}$$

$$\omega_{\underline{\alpha},l},\omega_{\overline{\alpha},l},\omega_{\underline{\beta},g},\omega_{\overline{\beta},g},\omega_{\underline{\gamma},d},\omega_{\overline{\gamma},d}\in\{0,1\} \tag{20}$$

(2)-(3), (4')-(5'), and (6) are the constraints of upper-level optimization problem. Constraints (8)-(20) are equivalent to the lower-level optimization problem. (8)-(12) are primal feasibility constraints. (13)-(20) represent the KKT necessary optimality feasibility constraints, in which constraints (17)-(20) are the linearized expression of complementary slackness conditions [14].

IV. Effective Protection Strategy

For a specific attack, an efficient protection strategy has to first guarantee that the state estimator can detect the existence of the attack. As mentioned before, bad data injection attacks cannot be detected since they do not affect measurement residuals. Actually, a bad data injection attack can be viewed as a set of multiple interacting and conforming bad data. The reason for its success is that such a multiple interacting and conforming bad data set is complete. So, for a specific LR attack, an effective protection strategy has to satisfy two requirements:

1) Break the completeness of the multiple interacting and conforming bad data set so that measurement residuals are different from that of the original measurement. This can be achieved by protecting at least one measurement meter that is supposed to be attacked.

2) With the incomplete LR attacks, the weighted sum of squared measurement residuals of the system should exceed the detection threshold so that the state estimator can detect the presence of bad data. This is a problem of which measurement meters should be protected, or which measurement meters are effective protection choices.

Considering that the protection resources are usually limited, the control center will protect as small number of meters as possible, as long as this protection strategy can effectively expose the existence of the attack.

Suppose the measurement errors conform to normal distribution and the original measurement data can bypass bad data detection. Since the errors are stochastic, whether a measurement meter, if being protected, can expose the existence of the attack is not certain. For a specific attack vector $\boldsymbol{a}$, if its manipulation on measurement p fails, the distribution of weighted sum of squared measurement residuals $J_{a,p}$ can be studied. If the lower bound of $J_{a,p}$ exceeds the detection threshold, the attack can be detected. Protecting measurement p is then called an “effective” protection strategy. Its effectiveness is not influence by the stochastic measurement error in the original measurement data. The theory and criterion of determining “effective” protection strategies are explained in the appendix.

For a specific attack vector, once an effective protection strategy is implemented, the bad data detection will alarm the existence of attack. Subsequently, bad data identification process can successfully identify the incomplete attack using Combinatorial Optimization Identification (COI) method [15]. This method is based on the theory that the Euclidean norm of the multiple normalized residual corresponding to the bad data is the maximum. In the identification process, the measurement of the protected device is assumed to be a good measurement.

To sum up, for a specific attack vector, an effective protection strategy can avoid its damage.

V. Numerical Results

This section presents two case studies based on a modified IEEE 14-bus system with generator parameters shown in Table 2. The system is fully measured, with m=54 measurements. Measurements 1-20 are for the power flows from the sending end; measurements 21-40 are for the power flows from the receiving end; measurements 41-54 are for bus power injections. n=13 state variables need to be estimated. Attack magnitude for the load bus is limited at $\tau = \pm$ 50% of their actual load and attack resource is limited to 20 meters. Suppose that the cost of unmet demand is cs=100$/MWh.

Table 2 Generator Parameters

Gen. bus	1	2	3	6	8
P^{min} (MW)	0	0	0	0	0
P^{max} (MW)	300	50	30	50	20
c ($/MWh)	20	30	40	50	35

Case 1: Assume that there are no transmission capacity constraints. For this case, SCED based on the original measurement yields an operation cost of 5180$/h with generator 1 supplying all 59MW loads. Under any LR attack, false SCED yields the same operation cost and generation dispatch. It implies that the LR attack in this case has no immediate damaging effect to the system. The only difference between original SCED solution and false SCED solution is power flow. However, since transmission line capacities are assumed very high, the LR attack has no delayed damaging effect on the system.

Case 2: For illustration purposes, transmission capacities are modified to simulate the scenarios in which the system is operating close to its capacity limit. Transmission capacities of line 1 is 160MW, capacity of all other lines are 60MW.

In this case, 16 meters will be attacked in the most damaging LR attack as shown in Table 3.

Table 3 Most Damaging Immediate LR Attack for Case 2

Meas. p	Meas.	Attack quantity (MW)
1 & 21	PL_{12}& PL_{21}	1.3993 & -1.3993
2 & 22	PL_{15}& PL_{51}	-1.3993 & 1.3993
3 & 23	PL_{23}& PL_{32}	16.7348 & -16.7348
4 & 24	PL_{24}& PL_{42}	-2.2301 & 2.2301
5 & 25	PL_{25}& PL_{52}	-2.2614 & 2.2614
6 & 26	PL_{34}& PL_{43}	-21.6699 & 21.6699
42	P_2^{inj}	-10.8500 (-50%)
43	P_3^{inj}	38.4047 (40.77%)
44	P_4^{inj}	-23.9000 (-50%)
45	P_5^{inj}	-3.6547 (-48.09%)

As can been seen, the attack tries to transfer load on bus 2, 4, and 5 to bus 3, which originally has the highest load in the system. The attack tries to create a scenario in which 1) the load distribution is more focused on a certain bus compare to the original scenario; 2) the transmission line directly serving load bus 3 is overloaded so load shedding may be necessary to bring the flow on the overloaded line back to its secure range. It is observed that the most damaging attack choice depends on the original load distribution as well as the transmission capacity in each line.

Note that attack resource has not been used up for the most damaging LR attack in this case. Any attack on an additional load measurement or with additional attack quantity on a measurement may need cooperative manipulation on several other line power flow measurements. For example, if attacker tries to further worsen the load distribution by increasing attack quantity on load bus 5 injection power measurement from -3.6547MW (-48.09%) to -3.8MW (-50%) and adjust the manipulation on load bus 3 injection power measurement from 38.4047MW (40.77%) to 38.65MW (41.03%) accordingly, the attack must manipulate all the line power flow meters cooperatively, which is not possible due to the attacking resource limitation.

By simulating the most damaging attack, we observe that the false SCED leads to a load shedding of 12.9243MW on load bus 3. However, there is no load shedding in the original SCED results. The comparison of the false SCED and the original SCED is shown in table 4.

TABLE 4 COMPARISON OF FALSE AND ORIGINAL SCED FOR CASE 2

		False SCED	Original SCED
Generation dispatch on gen. bus (MW)	1	196.0757	180.4449
	2	0	44.7837
	3	30	13.7714
	6	0	0
	8	20	20
Total generation (MW)		246.0757	259
Operation cost ($/h)		7113.9	6203.3

Apparently, the attack leads the system to a non-optimal generation dispatch with unnecessary load shedding. The most damaging LR attack cause an immediate economic loss of 7113.9-6203.3=910.6$/h. Note that in this case, after the implementation of the false SCED decision, the actual power flow on line 1-5 is 63.1405MW, which violate the line capacity 60MW. This violation will cause line outage in a delayed time and lead to more load shedding. The modeling of delayed damaging attacks is beyond the scope of this paper.

For a strategy that protects measurement *p*, the value of $J_{a,p}^{true}$ and $J_{a,p}^{lower}$ are listed in Table 5. Significance level α is chosen to be 0.01 in this paper, so the detection threshold is $\chi^2_{41,0.01} = 64.9501$. Checking the effective protection criterion for each protection choice *p*, we conclude that the effective protection strategy of the most damaging attack is to protect one of the measurements 3,6,23,26,43,44. That is, if any one of these measurements is protected, the most damaging attack will be detected.

TABLE 5 EFFECTIVENESS CHECK OF PROTECTION STRATEGIES UNDER THE MOST DAMAGING ATTACK

p	$J_{a,p}^{true}$	$J_{a,p}^{lower}$
1 & 21	0.7474	18.4659
2 & 22	0.8318	18.2653
3 & 23	116.6135	74.7265
4 & 24	2.1193	16.2902
5 & 25	2.1842	16.2224
6 & 26	189.8589	130.0910
42	34.1290	21.9826
43	590.0887	467.2439
44	150.0439	99.4541
45	4.0000	14.9056

Table 6 shows the most damaging LR attack under different attacking resource limitations.

TABLE 6 MOST DAMAGING LR ATTACKS UNDER DIFFERENT ATTACKING RESOURCE LIMITATIONS

Attack Resource R	20	15	10	6
Attacked meas.	1,2,3,4,5,6, 21,22,23,24, 25,26,42, 43,44,45	3,4,6,7,10,23, 24,26,27, 30,41,42,43, 44,45	3,6,23, 26,41, 42,43	--
No. of attacked meas.	16	15	7	--
Operation cost ($/h)	7113.9	6434.3	6333.7	--
Load shedding (MW)	12.9243 (on bus 3)	1.6768 (on bus 3)	0	--
Effective protection choices	3,6,23,26, 43,44	43	43	--

From this table, we can see that the immediate damage of LR attacks decreases as attacking resources decreases. And we observe that protecting measurement 43 is always an effective choice for a wide range of attack resources. Moreover, for case 2, the least number of measurements to be attacked for a complete LR attack is 7, as shown in the fourth column of Table 6. Its attack vector is actually corresponds to the third column of the matrix **H** of the IEEE 14-bus system provided in [10]. As can be seen from the matrix **H**, column 8 has only 4 nonzero elements. However, the attacks based on this column need to manipulate the meter on bus 7 (a zero-injection bus) and meter on bus 8 (a generation bus), and thus they are not legitimate LR attacks by definition.

VI. CONCLUSIONS AND FUTURE WORK

This paper first defines a special kind of false data injection attacks – load redistribution attacks (LR attacks) with realistic assumptions on power system state estimation. For an LR attack, its damage to system operation can be quantitatively analyzed through the increased operation cost that a false SCED leads to. From the damaging effect analysis, we differentiate two attacking goals, i.e., immediate attacking goal and delayed attacking goal. Immediate LR attacks aim to maximize the total operation cost immediately after the attack; delayed LR attacks aim to maximize the total operation cost after the tripping of actually overloaded lines, which is the delayed effect of LR attacks. For the immediate attacking goal, a bi-level model is established and a KKT-based method is used to find the most damaging attack from an attacker's perspective. Effective protection strategies are then identified so that a control center can always effectively avoid the harm of the most damaging attack.

Although the solution to the bi-level model may also heuristically guide the defender to prevent more than just a single most damaging attack plan, the multiple choices of effective protection strategy for each attack plan makes the heuristic determination of the best defense plans difficult and time-consuming. A tri-level model as [6] can be designed in the future to actively deploy limited protection resources in anticipation of an attack. Unlike physical attack in [6], not all the to-be-attacked measurement devices are effective protection choices for a specific attack, so the criterion of determining the effectiveness of protection choices should be incorporated in the model.

The modeling for delayed attacking goal will be more complex than that for the immediate attacking goal. It includes three steps: 1) attacker decides an attack vector; 2) control center performs SCED function based on the attacked state estimation and overloading lines are identified; 3) control center performs SCED again after the outage of the overloaded lines. A tri-level model will be needed to find the most damaging attack for the delayed attacking goal. The solution methodology of solving this tri-level problem is now under study.

APPENDIX

The dc state estimation problem relates measurement vector $\mathbf{z}=(z_1,z_2,...,z_m)^T$ to state vector $\mathbf{x}=(x_1,x_2,...,x_n)^T$, i.e.,

$$\mathbf{z}=\mathbf{Hx}+\mathbf{e} \quad \text{(A.1)}$$

where m is the number of measurements and n is the number of state variables. $\mathbf{H}$ is the Jacobian matrix.

Assume random measurement errors $\mathbf{e}=(e_1,e_2,...,e_m)^T$ are normal and independent with $e_i \sim N(0,\sigma_i^2)$. Then the measurement residuals can be expressed as

$$\mathbf{r}=\mathbf{Se} \quad \text{(A.2)}$$

where matrix $\mathbf{S}$ is called residual sensitivity matrix, representing the sensitivity of measurement residuals to the measurement errors [16]. Matrix $\mathbf{S}$ has the property $\mathbf{SH}=\mathbf{0}$. The weighted sum of squared measurement residuals based on $\mathbf{z}$ is

$$J=(\mathbf{Se})^T\mathbf{W}(\mathbf{Se}) \quad \text{(A.3)}$$

Let $\mathbf{z}_a$ represent the observed measurement that has been attacked by a complete LR attack $\mathbf{a}$, i.e., $\mathbf{z}_a=\mathbf{z}+\mathbf{a}$. Since LR attacks are a special type of false data injection attacks, the attacking vector can be expressed as $\mathbf{a}=\mathbf{Hc}$, where $\mathbf{c}$ is a nonzero $n\times 1$ vector. Thus, the measurement residual based on $\mathbf{z}_a$ is

$$\mathbf{r}_a=\mathbf{S}(\mathbf{e}+\mathbf{a})=\mathbf{Se}+\mathbf{SHc}=\mathbf{Se} \quad \text{(A.4)}$$

From (A.2) and (A.4), a complete LR attack will not change the measurement residuals. The weighted sum of squared measurement residuals based on $\mathbf{z}_a$ is $J_a=J$. Since the widely used bad data detection methods are all based on measurement residuals, $\mathbf{z}_a$ will bypass bad data detection as long as no bad data is detected in $\mathbf{z}$.

Suppose a nonzero element a_p in attack vector $\mathbf{a}$ cannot be successfully injected since measurement p is protected. Let $\mathbf{a}'$ denote the incomplete attack vector, which is equal to $\mathbf{a}$ except that its element p is zero. The measurement residuals based on $\mathbf{z}'_a=\mathbf{z}+\mathbf{a}'$ is

$$\mathbf{r}'_a=\mathbf{S}(\mathbf{e}+\mathbf{a}')=\mathbf{S}(\mathbf{e}+\mathbf{a}-\mathbf{a}_p)=\mathbf{Se}-\mathbf{Sa}_p \quad \text{(A.5)}$$

where $\mathbf{a}_p$ is $m\times 1$ vector, $\mathbf{a}_p=\mathbf{a}-\mathbf{a}'$.

Assume that there is no measurement error in $\mathbf{z}$, i.e., $\mathbf{e}=\mathbf{0}$, the weighted sum of squared measurement residuals based on $\mathbf{z}'_a$ is:

$$J_{a,p}^{true}=(-\mathbf{Sa}_p)^T\mathbf{W}(-\mathbf{Sa}_p)=(\mathbf{Sa}_p)^T\mathbf{W}(\mathbf{Sa}_p) \quad \text{(A.6)}$$

where matrix $\mathbf{W}$ is the inverse of the covariance matrix of the measurement errors, $\mathbf{R}_\mathbf{z}$. If error $\mathbf{e}\neq\mathbf{0}$, the weighted sum of squared measurement residuals based on $\mathbf{z}'_a$ is:

$$\begin{aligned} J_{a,p} &= \mathbf{r}'^T_a\mathbf{W}\mathbf{r}'_a=(\mathbf{Se}-\mathbf{Sa}_p)^T\mathbf{W}(\mathbf{Se}-\mathbf{Sa}_p) \\ &= J-2(\mathbf{Sa}_p)^T\mathbf{W}(\mathbf{Se})+J_{a,p}^{true} \end{aligned} \quad \text{(A.7)}$$

Since $\mathbf{e}\sim N(\mathbf{0},\mathbf{R_z})$, $(\mathbf{Sa}_p)^T\mathbf{W}(\mathbf{Se})$ is normal distributed with

$$E\{(\mathbf{Sa}_{\{p\}})^T\mathbf{W}(\mathbf{Se})\}=0 \quad \text{(A.8)}$$

$$D\{(\mathbf{Sa}_p)^{'}\mathbf{W}(\mathbf{Se})\}=(\mathbf{Sa}_p)^T\mathbf{WSR_zS}^T\mathbf{W}(\mathbf{Sa}_p) \quad \text{(A.9)}$$

Let

$$\sigma_{a,p}^2=(\mathbf{Sa}_p)^T\mathbf{WSR_zS}^T\mathbf{W}(\mathbf{Sa}_p) \quad \text{(A.10)}$$

we have $0.5(J_{a,p}-J_{a,p}^{true}-J)\sim N(0,\sigma_{a,p}^2)$. The probability that the following relation holds is 99.7%:

$$-3\sigma_{a,p}\le 0.5(J_{a,p}-J_{a,p}^{true}-J)\le 3\sigma_{a,p} \quad \text{(A.11)}$$

which yields

$$-6\sigma_{a,p}+J_{a,p}^{true}+J\le J_{a,p}\le 6\sigma_{a,p}+J_{a,p}^{true}+J \quad \text{(A.12)}$$

So, the lower bound of $J_{a,p}$ is

$$J_{a,p}^{lower}=-6\sigma_{a,p}+J_{a,p}^{true}+\chi_{K,\alpha}^2 \quad \text{(A.13)}$$

Suppose measurement $\mathbf{z}$ can pass the bad data detection test under significance level α, then the probability that J lies in the following range is $1-2\alpha$

$$\chi_{K,\alpha}^2\le J\le\chi_{K,1-\alpha}^2 \quad \text{(A.14)}$$

where $K=m-n$ is the degree of freedom for the chi-square distribution of J. If this lower bound exceeds the detection threshold, i.e.,

$$J_{a,p}^{lower}\ge\chi_{K,1-\alpha}^2 \quad \text{(A.15)}$$

it is safe to say that the existence of attack can be detected. Then protecting measurement p is an effective strategy. (A.15) is called effective protection criterion.

For a specific attack vector $\mathbf{a}$ and a measurement p, $J_{a,p}^{true}$ and $\sigma_{a,p}$ can be calculated through (A.6) and (A.10) respectively. If (A.15) is satisfied, then protecting measurement p is an effective strategy, and its effectiveness is insensitive to the measurement error in the original measurements. Note that (A.15) is easy to implement and no original measurement $\mathbf{z}$ is needed.

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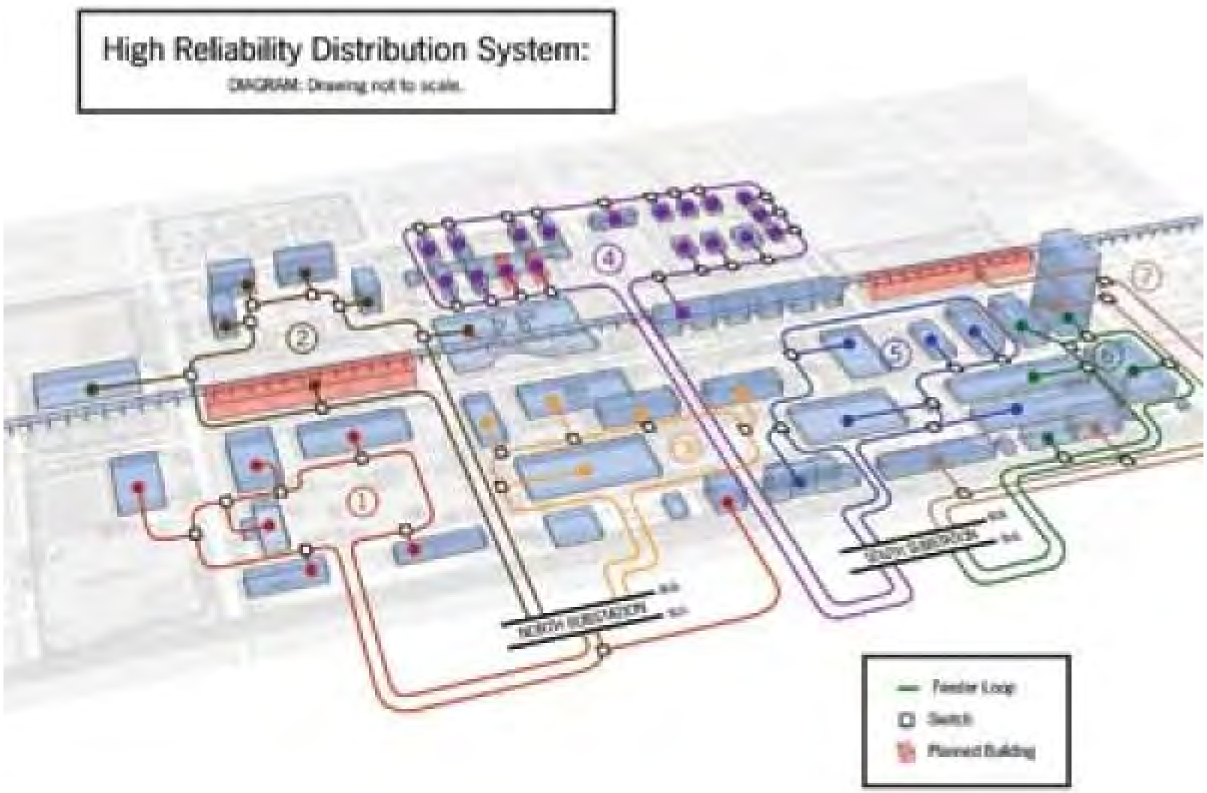
Close

Perfect Power at Illinois Institute of Technology

Alex Flueck, Illinois Institute of Technology



From 2004-06, Illinois Institute of Technology (IIT) experienced 12 power outages. Each cost up to $500,000. Because IIT owns the 4.16 kV on-campus distribution system, it decided in 2006 to solve its costly reliability problems by exploring advanced technology. At the same time, the university was planning to launch a major sustainability program. These issues led to an opportunity to merge reliability and energy efficiency upgrades as it investigated smart grid technology for IIT's distribution system.

Four electrical and computer engineering department faculty joined experts from the facilities department and several outside organizations, including the Galvin Electricity Initiative (GEI), Commonwealth Edison Co. (ComEd), S&C Electric Co. and a consulting group that became Intelligent Power Solutions. The team developed a conceptual model for the IIT distribution network called Perfect Power based on S&C Electric's High-Reliability Distribution System (HRDS).

In 2007, the team submitted a $12 million proposal to the U.S. Department of Energy's Renewable and Distributed Systems Integration program. The project launched in fall 2008. By the end of 2009, the team had achieved the first year's milestones, as well as additional milestones.

2006 Backdrop

In summer 2006, the GEI hosted a workshop on microgrids spurring innovation in the heavily regulated electric power delivery sector. IIT power engineering faculty attended to see if we could help with long-term research. At the time, IIT was experiencing three or four outages per year, with some outages costing the university roughly $500,000. In addition, the university's load demand was increasing, and the facilities department was exploring constructing a $5 million substation on the east side of campus.

Based on the GEI microgrid workshop, an IIT follow-up meeting discussed the possibility of implementing advanced technology on IIT's campus to address rising energy use and costs, the school's rising carbon footprint, reliability problems and the integrating renewable sources into the campus power grid. New technology required capital. Preliminary economic analysis showed that the payback period was about five years because of the high outage costs. Hence, the Perfect Power project was launched.

Perfect Power Goals, Technology

The Perfect Power project has several goals in three categories: technical, financial and leadership. The technical goals include demonstrating Perfect Power's key capabilities regarding reliability, demand response load reduction, energy efficiency load reduction and renewables integration. The financial goals include deferring major capital costs, reducing energy and outage costs and the influx of ancillary services' revenues. The leadership goals include reducing the university's carbon footprint, creating a living laboratory and the opportunity to lead smart grid development through the Perfect Power project.

Perfect Power incorporates advanced technologies including a few being developed through the research thrusts in parallel with the commercial equipment deployment.

Components include:

- Smart grid and technology-ready infrastructure (HRDS, IPPSC, smart meters and demand response, ZigBee load control, on-site generation and storage, renewables)
- Intelligent distribution system and system controllers (HRDS, IPPSC)
- On-site electricity production and storage (turbines, backup gensets, uninterruptible power supply (UPS))
- Renewable energy sources (rooftop photovoltaic (PV), on- and off-campus wind)
- Demand response capability (consumer-driven load control—Siemens controllers and wireless ZigBee controls for large and small air conditioning, lighting, major loads, office and laboratory

plug loads)
- Intelligent Perfect Power system controller (coordinate demand response actions with local utility and independent system operator (ISO); eventually real-time markets; smart meter application for a commercial customer; energy analytics)
- Sustainable energy systems and green buildings and complexes (PV, wind; carbon dioxide reduction; improved efficiency—insulation, building envelope upgrades, major mechanical upgrades).

Perfect Power—Deployment Timeline

The Perfect Power project will span five years. The first two phases are complete. In addition, the first loop of the HRDS has been installed and commissioned. Four of the core academic buildings have equipment supplying power to the building loads. The next loop of the HRDS will be installed this summer. Major construction will begin immediately after the university's spring commencement ceremony.

Deployment Phases

Phase I (complete)

- Energy efficiency upgrades (lighting, high-efficiency HVAC, hot water building loops) (reduced energy usage: five- to 10-year payback)
- Utility supply reliability repairs, upgrades (provided by ComEd)

Phase II (complete)

- Upgrade two existing 4-MW turbines for fast start capability (capital cost)
- Enroll in demand response programs (manual operation) (annual revenues to IIT)

Phase III (in progress)

- High-reliability distribution system (permissive overreaching transfer trip with backup directional comparison blocking; primary faults cleared in fewer than six cycles; fiber communication loop)
- Intelligent Perfect Power system controller (demand response coordination and electricity market monitoring)

Phase IV (future)

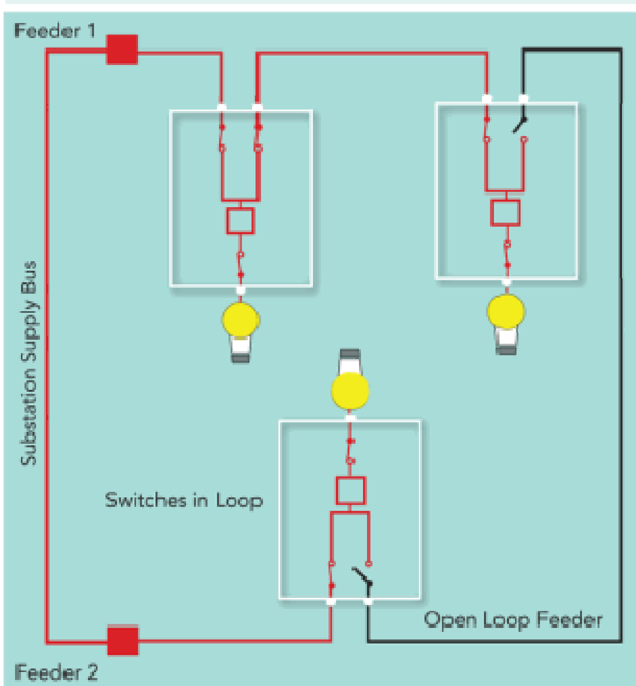
- UPS
- Solar PV
- IPPSC (full implementation)
- Optimal efficiency, reliability, demand response, ancillary services

Perfect Power—High Reliability Distribution System

The HRDS is a major improvement over the typical, radial distribution system with manual switches. The figures illustrate the advantages of the HRDS compared with a traditional, radial distribution system.

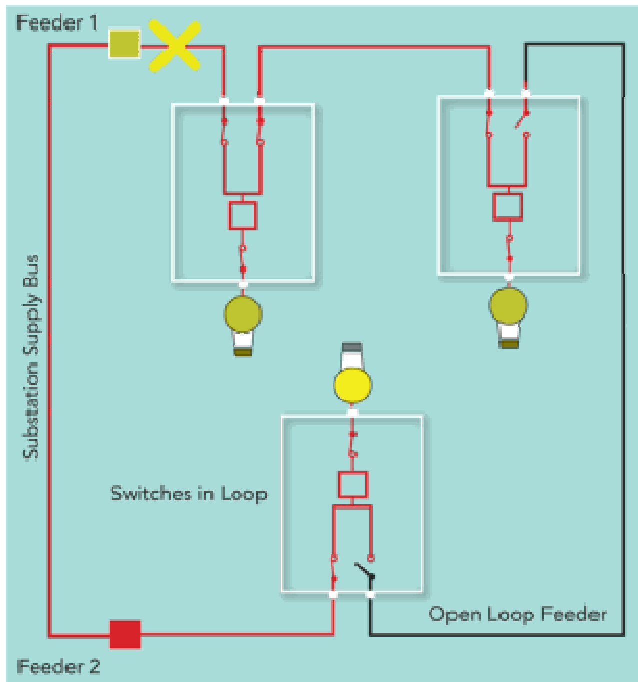
First, a typical radial system appears in Figure 1. Feeder 1 serves two loads, shown by the switchgear blocks in white and the light bulbs in yellow. Feeder 2 serves one load. A de-energized alternate feeder is connected to two open switches, one at each end of Feeders 1 and 2.

RADIAL SYSTEM WITH MANUAL SWITCHING — NORMAL OPERATION 1



If a fault occurs, as in Figure 2, then the substation breaker must open to clear the fault. All of the loads on the faulted feeder are out of service, shown by gray light bulbs. The outage could last anywhere from a few hours to half a day, assuming that the alternate feeder has sufficient capacity all the way back to the substation.

RADIAL SYSTEM—POWER INTERRUPTED TO TWO LOADS DUE TO FAULT 2



Following power loss, an electrician would be notified of the outage. In a typical distribution system, the steps required to restore power to all customers, and the time required for each step, are shown below:

- Respond: one to four hours,
- Locate fault: one to four hours,
- Isolate fault: manual—one hour,
- Close tie: manual—one hour,
- Total outage time: four to 10 hours.

Figure 3 shows the final arrangement of switches with the loads restored.

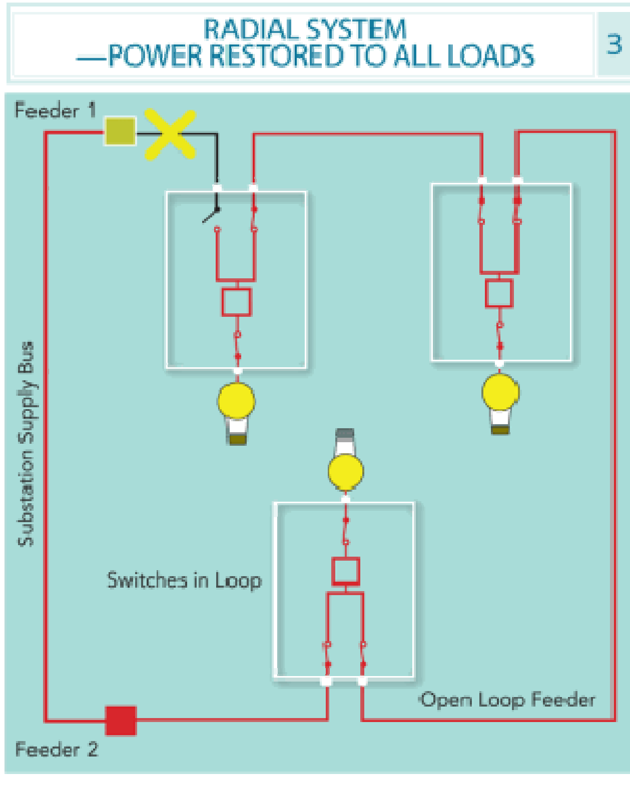
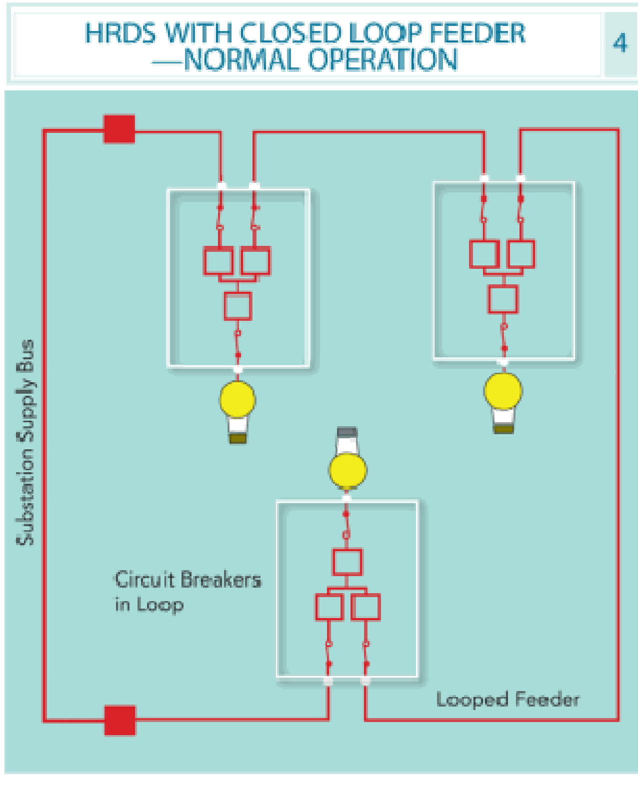


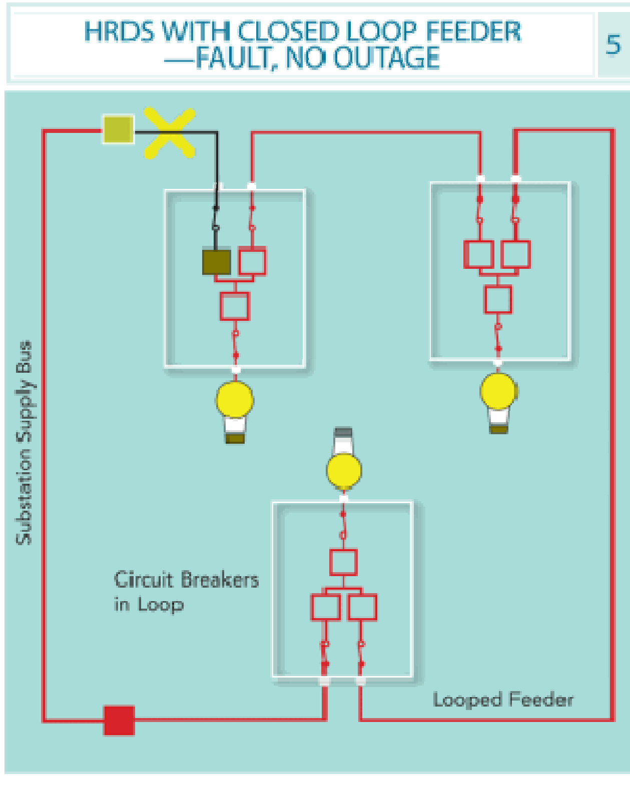
Figure 4 illustrates a major improvement to the traditional radial system presented above. An HRDS solution has the following features:

- Closed loop=single feeder,
- Simultaneous dual feeds to loads,
- Circuit breaker protection within the loop,
- Faults on main feeder cleared without outage.



If the same fault occurs in an HRDS (see Figure 5), then the event is over in less than one-tenth of a second, and no load experiences any outage. The sequence of events is as follows:

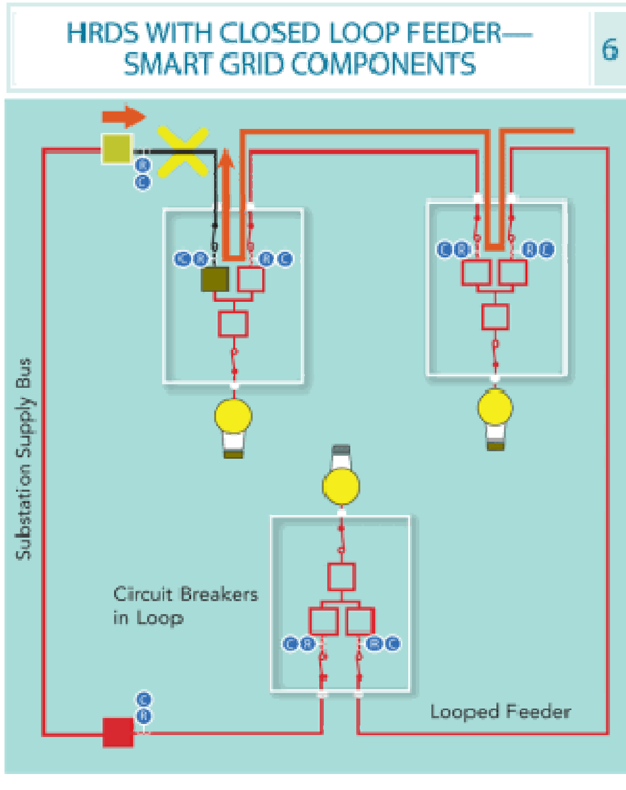
- Breakers isolate fault to only one section,
- Location: nearly instantaneous
- Isolation: 0.1 seconds
- Restoration: instantaneous
- Total outage time: zero seconds.



The key innovation in the HRDS is that the entire loop remains energized during the fault scenario presented. Additional equipment is required in an HRDS beyond the typical equipment in a traditional radial system with manual switches.

Figure 6 presents the smart grid components necessary for the HRDS. The components include:

- High-speed relaying for fault detection,
- High-speed communications between breakers,
- Coordinated operation: the right breakers open,
- High-speed interruption: fault cleared without outage.



Although the HRDS solution has an upfront capital cost, those costs are earned back as the university avoids the high cost of outages, such as lost productivity, food spoilage, ruined experiments, and off-site student housing.

Perfect Power—Research Thrusts

While the bulk of the Perfect Power project focuses on the four deployment phases, a significant portion of the funding targets several research thrusts. Three research areas will be presented briefly, including advanced distribution automation, ZigBee load control and the intelligent Perfect Power system controller.

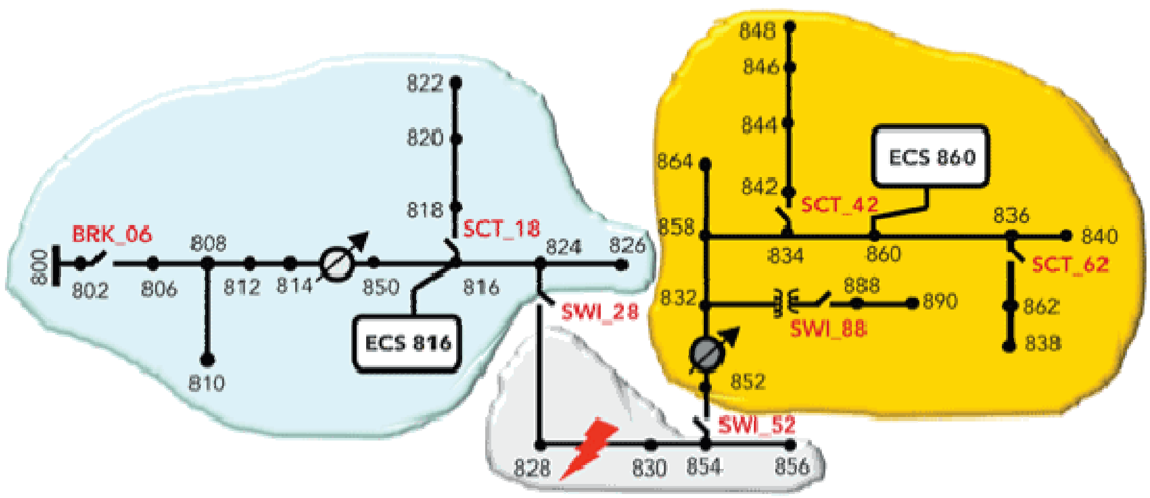
Advanced Distribution Automation

Beyond available products, the Perfect Power team is exploring advanced, autonomous, agent-based controls for high-level distribution automation functions, including loss reduction and integration of distributed resources such as renewable solar PV generation and electronic converter storage. An example of an electronic converter storage system is a power electronic inverter system interfaced with a chemical energy conversion device, e.g., a battery or fuel cell.

To intelligently and safely incorporate distributed resources in a distribution system, an autonomous, agent-based control requires an appropriate model of the generation or storage device, as well as a communication network and framework for decision-making. If the distributed resource coordinates with the rest of the distribution feeder, then the opportunity exists to leverage the resource during normal and emergency operation, such as when a radial feeder segment is de-energized because of a fault.

Figure 7 illustrates a fault scenario on the IEEE 34 node three-phase unbalanced distribution feeder test system with additional smart switches and electronic converter storage (ECS) modules. The substation is at the left end of the feeder at bus 800. If a permanent fault occurs between nodes 828 and 830, then once the fault is cleared, switches SWI_28 and SWI_52 can be opened to isolate the fault. For the de-energized, yet unfaulted portion of the network, it might be possible for ECS 860 to supply power to some portion of the local load. Personnel safety is the No. 1 concern, so the coordination of ECS 860 and the rest of the distribution equipment is critical.

IEEE THREE-PHASE UNBALANCED TEST FEEDER WITH SMART SWITCHES AND ELECTRONIC CONVERTER STORAGE (ECS) MODULES 7

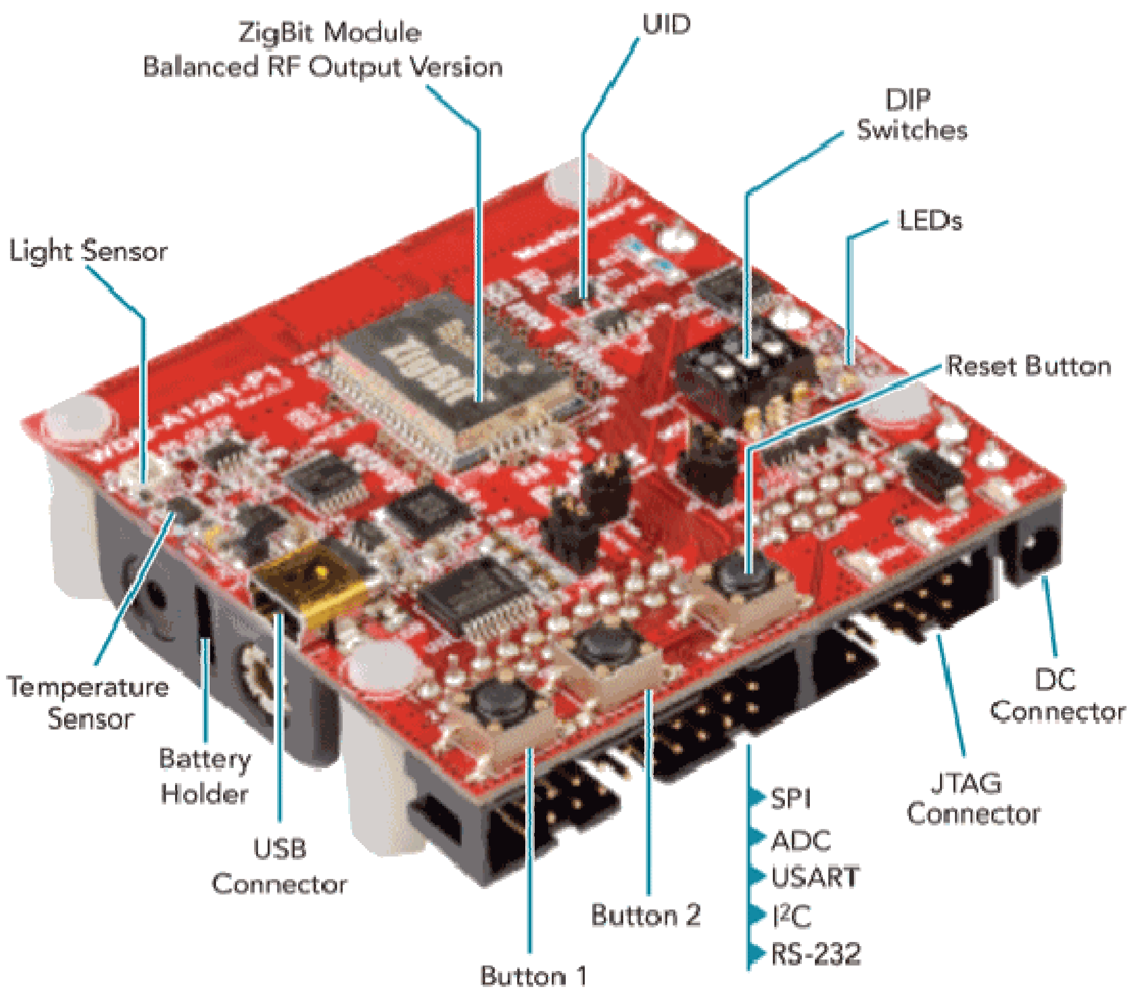


ZigBee Load Control

A second research thrust focuses on wireless sensor networks applied to load control. This work is led by professor Chi Zhou of IIT. The motivation for this research comes from our demand response objectives. If we need to reduce load on campus suddenly during a demand response event, then we have two options: Increase on-campus generation to reduce the overall load on the utility's distribution grid, or curtail load on campus. If we need to curtail load, there are two methods: Shut down entire buildings via smart switches in the HRDS, or control individual loads within buildings.

Figure 8 presents a MeshBean ZigBee Mote from MeshNetics, now part of Atmel. The board contains a ZigBee radio for communication and several sensors and expansion connectors. The first applications of the ZigBee Mote include lighting and HVAC control. A research goal is to deploy a low-power wireless sensor or actuator network to interface with smaller loads distributed throughout the campus buildings. A few large loads, such as large air conditioner compressors, will be connected to a Siemens energy management building controller. Hundreds of smaller loads, however, must be monitored and controlled, which the ZigBee wireless network can do effectively and efficiently.

MESHBEAN ZIGBEE MOTE FROM MESHNETICS 8



Intelligent Perfect Power System Controller

A third research thrust explores the creation and deployment of a hierarchical Intelligent Perfect Power System Controller (IPPSC). John Kelly and Greg Rouse of Intelligent Power Solutions lead this work. The controller must supervise the entire on-campus energy system by communicating with the upstream utility, ComEd; and ISO, PJM; as well as the campus distribution system, HRDS; on-site generation, fast-start natural gas turbines and renewable sources such as solar PV and wind; on-site storage, UPS; and individual building load controllers, Siemens energy management building controllers and wireless ZigBee sensor network controllers.

Some of the IPPSC's tasks will include:

- Starting and stopping local generators and storage devices,
- Controlling local loads based on a predetermined sequence of operations and a load-reduction priority scheme,
- Automatic switching of loads to alternate transformers, campus feeds and substations,
- Placing a building or the entire campus in island mode.

The overall site energy system control scheme will consider economic, environmental, comfort, disturbance threats and other end-use objectives to decide the proper operating modes and sequences. The IPPSC enables perfection by anticipating system needs and taking action to mitigate system reliability and performance threats.

In the words of Robert W. Galvin, "Perfection is a journey, not a destination." Transforming the U.S. power grid will be a journey with monumental change. As Perfect Power enters its second year, IIT continues looking for ways to align engineering and technical talent with society's changing needs. The U.S. work force must be prepared to implement and sustain this change.

The Perfect Power project's advances are helping impel the eventual power grid transformation. As it grows, Perfect Power at IIT will provide a living laboratory for advanced technology and a training ground for power engineers and technical personnel. IIT is expanding its energy programs by establishing the newly funded Smart Grid Education and Workforce Training Center. In April IIT received $5 million in American Recovery and Reinvestment Act funding to support a total $12.6 million collaborative effort to establish the center, which will offer smart grid technology courses and certification for people of all ages via on-campus and distance-learning classes.

IIT's Perfect Power, smart grid and power engineering infrastructures will help train groups from utilities, corporations, labor unions, veterans, kindergarten through 12th-grade educators, universities, and community colleges to be the strongest work force in the world, taking on global smart grid challenges in technology, energy independence, clean tech and sustainable energy. The center will be complete within three years and is expected to train nearly 49,000 people in its first three years of operation. As IIT continues its journey, we invite you to track our progress and push for perfect power.

Alex Flueck is a professor in IIT's Department of Electrical and Computer Engineering. Perfect Power is funded by the DOE, IIT and S&C Electric under Award DE-FC26-08NT02875 and led by IIT professor Mohammad Shahidehpour. Founded in 1890, IIT has more than 7,700 students.

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