DISTRIBUTED INTELLIGENT AGENTS FOR DECISION MAKING AT LOCAL DER LEVELS

Project Final Report for the Period July 2003 – December 2004

December 2004

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ABSTRACT

Distributed Energy Resources (DER), when integrated properly with the electric grid can provide both economic and societal benefits. Economic benefits in the form of reduced energy costs for end users that employ DER are well documented. Societal benefits in the form of achieving a more robust electric grid, less vulnerable to terrorist attack, are still more difficult to quantify. But it is safe to say that maintaining the historically high reliability of the U.S. power system is a fundamental requirement for the U.S. economy. Seamless penetration of DER assets is only possible with increased communications and information flow at all levels. Intelligent software agents can provide the needed communications, information and control enhancements.

The project team, Alternative Energy Systems Consulting, Inc. (AESC) and the Center for Networked Distributed Energy (CNDE) at Colorado State University developed a conceptual design for a multi-level agent/agency hierarchy for use in coordinating grid power transactions from the distribution up to the transmission level. The project team further refined the agent based concept at the distribution level into the “Power Neighborhood” agent-based control concept. In this case, a power neighborhood consists of multiple sites collaborating via a Dutch auction-based process to allocate DER resources in response to dynamic pricing or grid disturbances.

In order to evaluate the feasibility of the power neighborhood concept, AESC developed the Distributed Intelligent Agent for Decision Making (DIADM) simulation software. The DIADM simulation software was subsequently installed on computer(s) at Colorado State University and used to test basic functionality and the feasibility of the agent-based approach. The test scenarios examined by CNDE personnel were selected to demonstrate the feasibility of a decentralized architecture for power system control using agent-based modeling. Testing revealed that the site agents were able to cover their individual site critical loads, and their collective neighborhood loads by establishing bilateral transactions with other site agents (both within their own and adjacent neighborhoods) and the distribution substation agent via the auction website. The agents operating within the power neighborhoods were able to allocate DER assets amongst the various sites in both an hour-ahead auction environment as well as in response to a signal indicating the loss of grid supplied power. Testing showed that the agents, operating via Dutch auctions and without a central authority, quickly allocated DER assets and converged on a solution. Testing also showed how neighborhoods with disparate DER penetration levels are able to both reallocate resources within their respective neighborhoods as well as contribute to an adjacent neighborhood’s ability to respond. In doing so, neighborhoods with excess DER assets were able to reduce their overall costs through the sale of excess capacity.

The test results are qualitative in nature since timing and performance constraints imposed by both DER asset performance and the latency of inter-agent communications were not simulated. However, test results clearly show that a network of agents, acting within “power neighborhoods” can quickly allocate resources both in response to dynamic pricing and if signaled that a partial or total loss of grid supplied power is eminent. Furthermore, that use of a Dutch auction based process eliminates the need for a centralized control thus providing an inherently more open and extensible solution.

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**PREPARED FOR THE UNITED STATES
DEPARTMENT OF ENERGY
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EXECUTIVE SUMMARY

There is little question that DER, when integrated properly with the electric grid can provide both economic and societal benefits. Economic benefits in the form of reduced energy costs for end users that employ DER are well documented. Societal benefits in the form of achieving a more robust electric grid, less vulnerable to terrorist attack, are still more difficult to quantify. But it is safe to say that maintaining the historically high reliability of the U.S. power system is a fundamental requirement for the U.S. economy. Reliable power is a cornerstone of commerce and industry and our reliance on this resource will continue to increase as the U.S. economy continues to shift to an information-based economy.

Landis Kannberg of Pacific Northwest National Laboratory stated at a recent DOE workshop [DOE Workshop Proceedings May 2002] that seamless penetration of DER into the power system would result in "enhanced stability, security, crisis management" but would require "ubiquitous communications and information flow and advanced, transactive controls, prognostics and diagnostics at all levels…" It was the belief that intelligent software agents can provide the ubiquitous communications, transactive controls and prognostics/diagnostics referred to by Mr. Kannberg that provided the impetus for this SBIR Phase I effort.

The overall objective of the SBIR project was to successfully demonstrate the feasibility of using intelligent agents for DER level control. Specifically, the objectives of this Phase I effort were to:

- Identify a basic hierarchy of intelligent agents needed for electric grid system control using a "bottom-up" approach,
- Characterize basic agent requirements at the local site/appliance level,
- Demonstrate the feasibility of applying an agent-based approach at the local site level.

The information gathering process revealed that use of multi-agent technology for control of the electric power grid is not an entirely new idea. Use of agents appear well suited to the problem but the problem is complex and agent technology is immature. In fact, a wealth of past and current research relies on the use of agents at some level to provide site level decision-making support. This on-going support for an agent-based approach (at some level) would appear to also support the validity of the concept. While a great deal of relevant research is underway there still appeared to be a need for research directed at identifying specific agent functionality, especially at the site level. Additionally, these efforts, if successful appeared to be well positioned to take advantage of the more generalized efforts (CEIDS, GridWise) at establishing the needed protocols and infrastructure policies.

Using the information gathered during the first task, the project team then developed a conceptual design for a multi-level agent/agency hierarchy for use in coordinating grid power transactions from the distribution up to the transmission level. The project team further refined the agent based concept at the distribution level into the "Power Neighborhood" agent-based control concept. In this case, a power neighborhood consists of multiple sites collaborating via a Dutch auction-based process to allocate DER resources in response to dynamic pricing or grid disturbances.

In order to evaluate the feasibility of the power neighborhood concept, AESC developed the Distributed Intelligent Agent for Decision Making (DIADM) simulation software. The DIADM simulation software was subsequently installed on computer(s) in the Center for Networked Distributed Energy in the Department of Mechanical Engineering at Colorado State University and used to test basic functionality and the feasibility of the agent-based approach. The test scenarios examined by CNDE personnel were selected to demonstrate the feasibility of a decentralized architecture for power system control using agent-based modeling. Testing revealed that the site agents were able to cover their individual site critical loads, and their collective neighborhood loads by establishing bilateral transactions with other site (SM) agents (both within their own and adjacent neighborhoods) and the distribution substation (DS) agent via the auction website. The agents operating within the power neighborhoods were able to allocate DER assets amongst the various sites in both an hour-ahead auction environment as well as in response to a signal indicating the loss of part or all of the grid supplied power. Testing showed that the agents, operating via Dutch auctions and without a central authority, quickly allocated DER assets and converged on a solution. Testing also showed how neighborhoods with disparate DER penetration levels are able to both reallocate resources within their respective neighborhoods as well as contribute to an adjacent neighborhood's ability to respond. In doing so, neighborhoods with excess DER assets were able to reduce their overall costs through the sale of excess capacity.

The test results are qualitative in nature since timing and performance constraints imposed by both DER asset performance and the latency of inter-agent communications were not simulated. However, test results clearly show that a network of agents, acting within "power neighborhoods" can quickly allocate resources both in response to dynamic pricing and if signaled that a partial or total loss of grid supplied power is eminent. Furthermore, that use of a Dutch auction based process eliminates the need for a centralized control thus providing an inherently more open and extensible solution.

This Phase I effort was successful in demonstrating the feasibility of the power neighborhood concept. A logical next step would be a Phase II effort that provides for further refinement of the concept and agents involved with the objective being to implement the power neighborhood concept in a "real world" environment. Such an effort would require both the participation of an ESCO as well as a number of sites located within a single feeder circuit. Given the difficulty in involving such a large number of entities it is likely that a project of this type would need to involve both actual and simulated actions.

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1.0 INTRODUCTION

This report summarizes the results of DOE SBIR project DG02-03ER83604 titled, Distributed Intelligent Agents for Decision Making at Local DER Levels. The project team for this effort was comprised of Alternative Energy Systems Consulting, Inc. (AESC) and the Center for Networked Distributed Energy (CNDE) at Colorado State University (CSU).

The overall objective of the SBIR project was to successfully demonstrate the feasibility of using intelligent agents for DER level control. Specifically, the objectives of this Phase I effort were to:

- Identify a basic hierarchy of intelligent agents needed for electric grid system control using a "bottom-up" approach,
- Characterize basic agent requirements at the local site/appliance level,
- Demonstrate the feasibility of applying an agent-based approach at the local site level.

Under the first project task the project team gathered and reviewed available project-related information in order to establish the overall agency, and more specific site level agent requirements. Based on these requirements the project team then developed a conceptual design for a multi-level agent/agency hierarchy for use in coordinating grid power transactions from the distribution up to the transmission level. At the distribution level, the project team further refined the agent-based control concept into the "Power Neighborhood". The Power Neighborhood concept provides for collaboration of multiple site agents via an auction process to efficiently allocate distributed energy resources (DER) in response to dynamic pricing or in response to grid disturbances. Having defined the power neighborhood concept, AESC then developed demonstration software that simulated agents (up to 20 agents in two neighborhoods) participating in two power neighborhoods located within a single distribution substation. Personnel from the CNDE subsequently installed and tested the demonstration software at their facilities in Colorado State University.

The remainder of this report is divided into seven sections. These sections summarize the results of the various project tasks. Section 2, "Information Gathering Results" provides background information supporting the overall hierarchy design that is described in Section 3. Section 3, "Agent Hierarchy Description" contains a general discussion of the broader multi-level grid agency as well as a more detailed description of the "Power Neighborhood" agency concept employed at the distribution level. Section 4, "DIADM Simulation Software" describes the demonstration software that simulates operation of two power neighborhoods while Sections 5 and 6 summarizes the feasibility test activities conducted by CNDE personnel. Sections 7 & 8, "Project Conclusions" and "References" are self explanatory.

2.0 INFORMATION GATHERING RESULTS

Under the first project task the project team of Alternative Energy Systems Consulting, Inc. and the Center for Networked Distributed Energy at Colorado State University gathered and reviewed available project-related information in order to:

- ? Characterize the "world" as seen by a potential DER level agent,
- ? Review the results of past projects and/or objectives of current research technically relevant to our DER level agent development project, and
- ? Identify synergies between our current DER level development project and the related efforts of other private or publicly funded organizations.

The information gathering effort included a review of agent technology as well as operational issues and research associated with the electric power grid.

2.1 Agent Technology

For purposes of this discussion we assume that an intelligent software agent exhibits the following traits:

- ✍ Executes autonomously & operates in real-time
- ✍ Communicates with other agents or users
- ✍ Is able to exploit domain knowledge
- ✍ Exhibits goal-oriented behavior

A wide variety of agents have been identified and studied since agent research began in the late 1970's. For purposes of our research we can adopt an abridged agent typology that contains five agent categories based on agent mobility, thinking paradigm and other primary agent attributes. The five basic agent types are mobile agents, reactive agents, deliberative agents, collaborative agents and hybrid agents.

We have not attempted to define what constitutes agent intelligence but have instead maintained that "…a key attribute of any intelligent being is its ability to learn". Our agent definition does not strictly require that an agent collaborate/communicate with other agents to perform its tasks. Agents can act alone but, for our project, a single agent approach makes little sense given the distributed and varied nature of the electric power grid. Systems that employ multiple agents can provide a powerful distributed processing or decision making approach that would appear well suited to the problem of both electric grid and DER control. Therefore, for our project we will be focusing on utilizing a multi-agent system.

2.2 Electric Power Grid

In order to characterize the world as seen by a DER level agent it was necessary to review electric grid operation and the problems/issues that are unique to this highly complex and vital infrastructure. The research confirmed that:

- ? Operation of the electric grid can be characterized as having three basic modes, normal, disturbance and restorative, each with varying operational requirements.
- ? Operation of the electric grid is far more than scheduling and coordinating the transfer of power from point A to point B since it requires on-going control of power quality (voltage, frequency, etc.).

- ? Adverse interaction between existing distribution level protection systems and distributed generation is the most significant barrier to fully integrating on-site DG in the electric grid. This barrier stems from the basic design of the protection and control systems themselves and their design based on the unidirectional flow of power from centralized generation.
- ? In general, varying the generation (and import/export of power at interconnection points) at various points in the grid indirectly controls the flow of power at the transmission and subtransmission levels.
- ? The highly intermeshed nature of the electric grid at the subtransmission and transmission levels causes complex power flows that make the path of a power transaction uncertain. This interaction and associated uncertainty is minimized at the distribution system level where the system is not intermeshed but primarily radial in design.
- ? FACTS (Flexible AC Transmission Systems) technology can provide dynamic control and compensation within the grid. However, use of these devices can actually increase the size and speed of catastrophic events unless dynamic control systems with compatible analysis, decision and communications are utilized.

2.3 Relevant Research

A great deal of past and current research directly relates to our efforts. EPRI, CERTS, the "GridWise Alliance" sponsored by PNNL and DOE are the most prominent players in this area.

The Electric Power Research Institute (EPRI/CEIDS) has sponsored multi-agent and related technologies in support of "Self-Healing Grid" concept for over a decade. More recently, EPRI, through the Advanced Distribution Automation (ADA) effort under CEIDS, is developing an open communications architecture that will facilitate the use of distributed generation and storage technologies in the grid. The objectives of the project include development of standardized communication object models that will facilitate the application of DER in the grid as well as enable flexible reconfiguration of distribution systems into islands when needed. The ADA effort, while providing minimal details, includes the use of autonomous agents within its infrastructure and would thus appear well positioned to accept intelligent agent technology.

The CERTS "Grid of the Future" concept has evolved into one that emphasizes the use of DER within "local microgrids". These microgrids consist of a grouping of generating sources and end-use loads that operate in a semiautonomous fashion for the benefit of the microgrid participants. While the microgrid concept does not directly relate to our efforts, the issues associated with microgrid interaction with protection systems and on DER interaction within the microgrid are very relevant. Issues concerning control of the point of common coupling (PCC), energy management within the microgrid and protection coordination within the microgrid are of interest since agents operating at the site level would need to address these or similar issues.

The "GridWise" Alliance efforts have focused on integration of the traditional elements of supply and demand, transmission and distribution with new technologies such as distributed generation, energy storage, and customer load management, using information to make them function as a complex, integrated system. The emphasis is on market response in the form of residential, appliance level reaction to either pricing signals or upon detection of system upset. GridWise is moving toward an energy system that is controlled by a distributed network with the ability to dynamically reconfigure the system as needed in response to man-made and natural disasters. This approach optimizes energy resources by allowing all elements of the energy system to work together. These elements, or agents, are linked together in a dynamic, real-time information environment that can adapt to changes in environmental conditions.

2.4 Conclusions

The information gathering process revealed that use of multi-agent technology for control of the electric power grid is not an entirely new idea. Use of agents appear well suited to the problem but the problem is complex and agent technology is immature. In fact, a wealth of past and current research relies on the use of agents at some level to provide site level decision-making support. This on-going support for an agent-based approach (at some level) would appear to also support the validity of the concept. While a great deal of relevant research is underway there still appears to be a need for research directed at identifying specific agent functionality, especially at the site level. These efforts, if successful would appear to be well positioned to take advantage of the more generalized efforts (CEIDS, GridWise) at establishing the needed protocols and infrastructure policies.

3.0 AGENT HIERARCHY DESCRIPTION

Using the information gathered during the first task, the project team then developed a conceptual design for a multi-level agent/agency hierarchy for use in coordinating grid power transactions from the distribution up to the transmission level. At the distribution level, the project team further refined the agent based concept into the "Power Neighborhood" agent-based control concept. In this case, a power neighborhood consists of multiple sites collaborating via an auction-based process to allocate DER resources in response to dynamic pricing or grid disturbances.

3.1 Overall Agent Hierarchy Description

The proposed agent hierarchy consists of five basic operating levels as depicted in Figure 1. The five operating levels are:

- Site,
- Feeder / Neighborhood,
- Distribution Substation,
- ESCO / Utility, and
- RTO / ISO.

The building agent that resides at the Site level will be the lowest level agent capable of decision-making and the agent representing the RTO / ISO will be the highest level agent. It is important to note that additional agents may eventually be created for specific lower level functions within each of the levels but that these agents are not relevant to the basic functioning of the hierarchy and are not therefore covered under this Phase 1 effort.

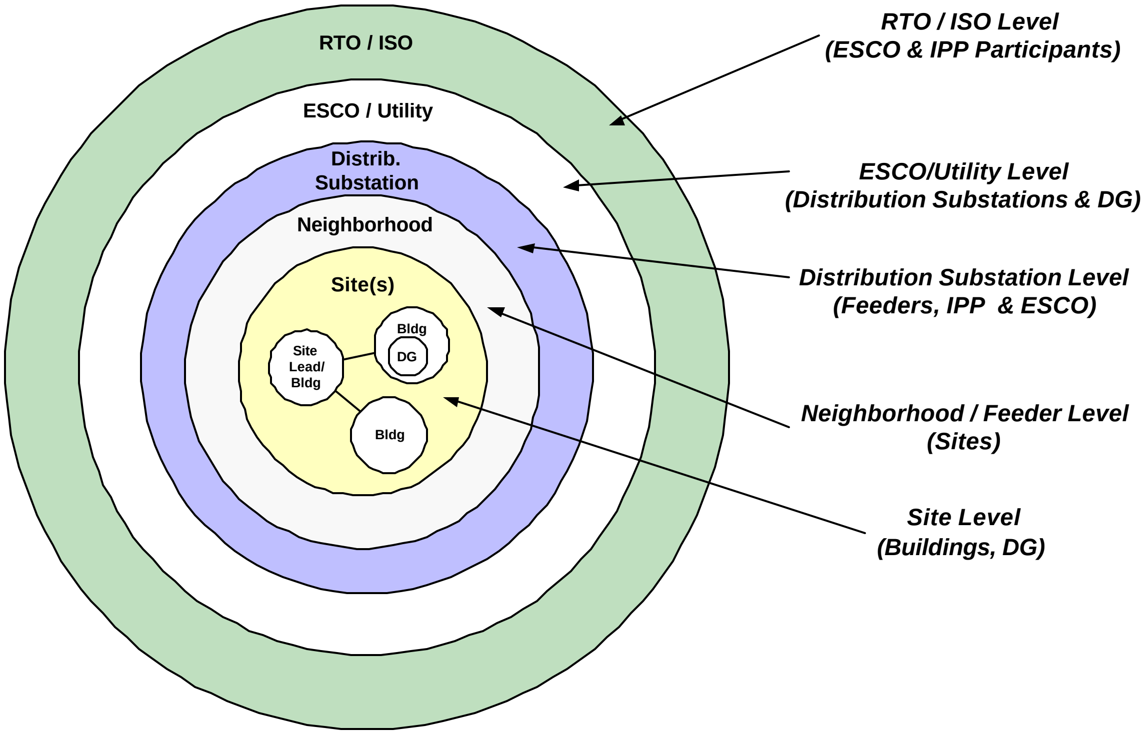


Figure 1: Overall Hierarchy Levels

In general, interaction between non-adjacent levels will be minimized. The hierarchy will emphasize local knowledge and data storage with communication of exceptions rather than routine data transfer.

The physical connectivity of the various levels is depicted in Figure 2. The site level will consist of one or more buildings each represented by a building agent. When multiple buildings are involved, a single building agent is designated as the "site manager" (SM) and this SM agent represents the interests of the site to external entities. It is assumed that all building agents within a site have a common owner and are not therefore "conflicted" allowing any of the building agents to represent the others.

Multiple sites located on a common distribution feeder become a "power neighborhood". Sites within a neighborhood are able to buy and sell capacity to/from their neighbors and/or they may purchase capacity from the local ESCO or another IPP. Multiple neighborhoods are connected to and governed by a distribution substation (DS) agent. The DS agent manages an Internet based auction board where neighborhood participants post auction sessions to buy and sell capacity. The DS agent represents the interests of the ESCO and posts auction sessions for the sale of ESCO power into the neighborhood. Any DG assets connected directly to the distribution system (not located at a site) capable of supplying power to the neighborhood are represented by their own agent and are able to access the auction board for any neighborhood that has connectivity with the DG asset.

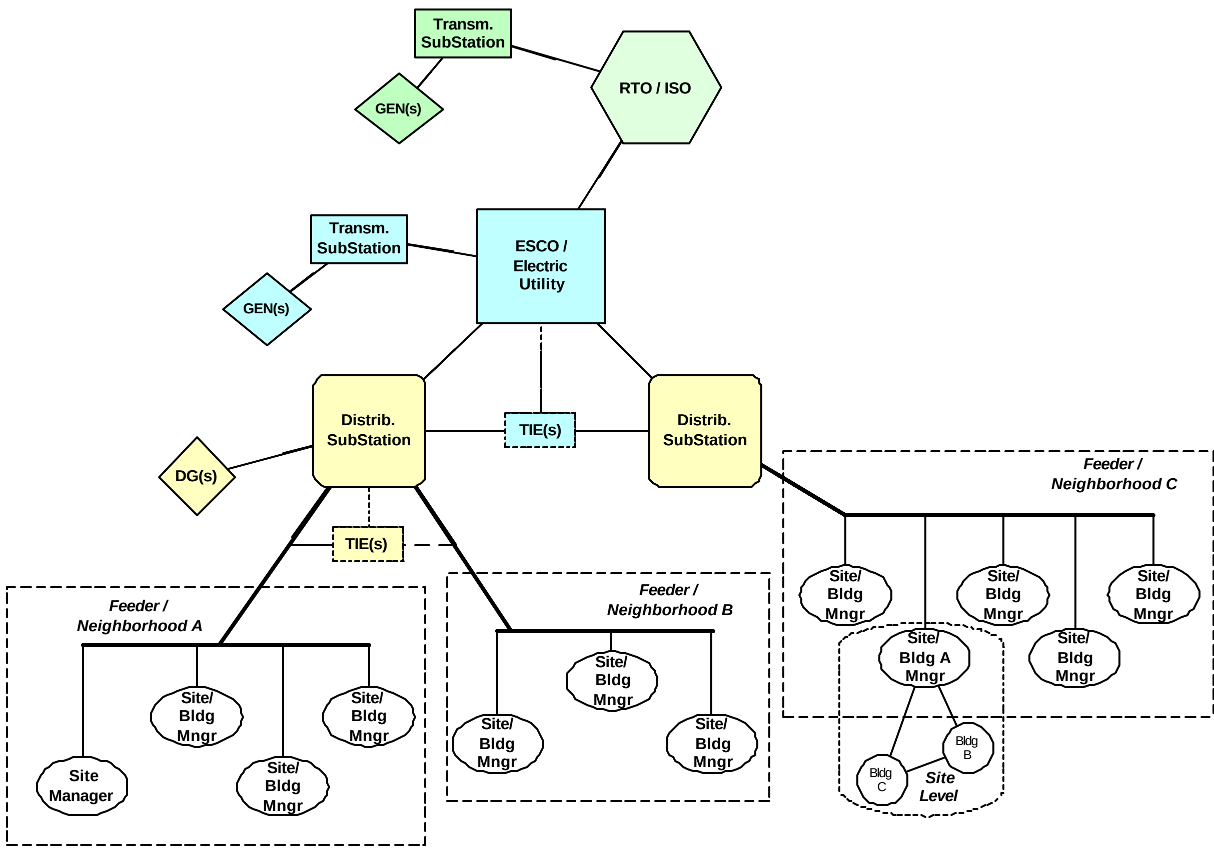


Figure 2: Hierarchy Connectivity

The auction process readily accommodates changing connectivity between adjacent feeders or neighborhoods. The DS agent monitors feeder connectivity and contracts or expands the auction board area so that affected neighborhoods may access additional or fewer auction sessions. Thus, this process may be used to facilitate adaptive islanding within the distribution system. It is important to note that the DS agent can use a variety of neighborhood traits to determine when and how to modify the connectivity of the system. The DS agent could therefore utilize neighborhood "fitness" criteria involving such things as the penetration level of DG or curtailable load etc. to determine the appropriate system connectivity.

This auction process is easily expanded to include the higher levels in the hierarchy. Thus the ESCO agent hosts an auction with the DS agents as participants and the RTO agent hosts an auction with ESCO and IPP participants.

3.2 *The Power Neighborhood Auction Concept*

As noted above, an auction process is used as the principal means of allocating resources at each of the five agent hierarchy levels. Thus, the auction process will not be used for physical level power grid control (i.e., frequency, fault detection, etc.) but will instead be used for tactical and strategic level control (i.e., economic dispatch, adaptive islanding, etc.). For this Phase 1 level of effort, it was assumed that power grid control at the physical level will either be handled via reactive level agents specifically designed for this purpose or by the existing infrastructure.

At the neighborhood level we will use a double Dutch auction format where SM agents (or the DS agent on behalf of the ESCO) post auction sessions for either the sale or purchase of capacity on the Internet-based auction board (managed by the DS agent). The Dutch auction format differs from the traditional "open outcry" a.k.a. "English" auction format in that bidding begins high and then declines at a predetermined rate (price decrement and timing). The bid price, decrement value, and decrement timing are posted as part of the auction session and are therefore known to all bidders. Under this format, bidders have the option of purchasing all or part of the offered capacity at the stated price or they may wait for the price to decline. However, sellers have the option of withdrawing the item (or the remaining capacity) at any time. Thus, a buyer's decision to delay a purchase to gain a lower price comes with the risk of either losing out to another buyer or the seller may pull the capacity from the auction altogether. Note that the auction process is inverted for the purchase of capacity. In other words a SM agent in need of capacity posts an auction session with a low initial bid price that then increases with time. Suppliers can choose to supply all or part of the requested capacity at the stated price or may choose to wait for a higher price (with the same risk factors as before).

Note that this concept is not limited to generated capacity but can also easily accommodate demand response or load curtailment. Sites with curtailable loads can create an excess in previously purchased capacity and then sell this excess to neighbors. Or, a site could offer the curtailable load capacity via the auction, which could then be aggregated by the ESCO and offered in a higher level auction hosted by the RTO/ISO for ancillary services (i.e., spinning reserve, replacement reserve, etc.). Thus an ESCO could use the auction processes as a means of aggregating curtailable loads.

The auction process therefore provides SM agents with the opportunity to participate in the energy markets by:

- Hosting an auction session to sell capacity to a neighbor, the ESCO or another 3rd party aggregator,
- Hosting an auction session to buy capacity from a neighbor, the ESCO or another 3rd party IPP, or
- Participating in one or more auction sessions hosted by other site managers, the ESCO, or a 3rd party IPP.

The Dutch auction process at first glance may appear counterintuitive, especially in comparison to the more traditional open outcry auction format where bids begin low and then proceed higher until bidding stops (oftentimes resulting in an inflated price or "buyer's remorse"). The Dutch auction format has actually been shown to be more efficient at establishing selling prices in line with the true value of the item since buyers tend to purchase items as soon as the bid price approaches the perceived worth.

In addition, the Dutch auction format is less susceptible to auctioneer dishonesty, which in this case could be a factor given that the DS agent represents the interests of the ESCO in the auction.

To further reduce the risk of auctioneer dishonesty we allow individual SM agents to interact directly with the SM agent hosting the individual auction session. The role of the DS agent is therefore not to match up buyers and sellers (a potential conflict of interest) but to define auction board access based on the connectivity of the feeders within the distribution system supplied by the distribution substation that it represents.

3.3 *Disturbance Response*

Since we are touting this approach as a means of responding to system disturbances we must address the consequences of a disturbance on existing agreements (executed transactions). As currently envisioned, a disruption in the power grid that prevents the delivery of capacity would:

- Cause the DS agent to re-evaluate the connectivity of the feeders to determine if neighborhoods can be temporarily subdivided and/or connected via sectionalizing breakers.
- Temporarily invalidate agreements that involve the affected sites (all or part of a neighborhood) in one hour increments. Thus, a fault or power outage affecting a neighborhood would cause existing agreements between affected sites for the current hour to be invalidated. The DS agent will identify and notify the affected areas (since all transactions are recorded with the DS agent). As an alternative, the DS agent may notify all connected SM agents that a "transaction event" has occurred and the individual SM agents would then need to evaluate the situation as it relates to them.
- Cause the DS agent to reconfigure the auction board (accessibility of the SM agents to auction sessions) to allow SM agents in adjacent neighborhoods additional access. The DS agent would then broadcast a "connectivity event" signal that would cause individual SM agents to re-evaluate their situation.

It is important to note that the DS agent must be able to differentiate between affected and unaffected sites as well as identify affected transactions or agreements.

3.4 *The Power Neighborhood Auction as an ESCO Service?*

As currently envisioned, the power neighborhood auction could be provided as an ESCO service similar to any other dynamic tariff. The ESCO would likely charge a monthly premium for auction participation and would be responsible for maintaining the distribution substation agent functionality. One possibility would allow sites to choose their level of participation and potentially to set up default delivery instructions. Sites within a neighborhood that choose not to participate would still appear in the neighborhood but with ESCO auction transactions (purchase power via the ESCO auction session) set up by default. In this way, sites could come and go with minimal effort and all sites, regardless of participation level would have access to dynamic pricing information. Aside from offering a premium service the ESCO would also have the ability to use the auction process to aggregate distribution level DER for potential sale to the ISO/RTO. This would be relatively straightforward in that the ESCO could either host and auction session or access existing SM agent hosted auction sessions to obtain load or capacity.

The ESCO auction service would therefore include:

- Neighborhood auction board maintenance (connectivity, web site hosting, etc.),
- Auction transaction recording,
- Dispute arbitration,
- Billing true-up (transaction audit function) based on data provided by SM agents, and
- Coordination of distribution system protection and control devices to facilitate neighborhood activities/market participation and potentially provide improved power quality.

3.5 Agent Descriptions

Based on the preceding description we can summarize the basic functionality of the primary agents, the site and distribution substation agents, involved in the power neighborhood auction process.

Site Manager (SM) Agent

The SM agent represents the interests of a building owner/operator. While the SM agent can represent multiple buildings, we assumed that each SM agent represented a site having a single building for this Phase I effort. SM agent activities can therefore be divided into *local* and *power neighborhood* related activities.

Local activities are those activities related directly to the site or to the individual agent. For purposes of this Phase I effort, these activities include:

Site load management includes monitoring and forecasting of site electric demand. This function provides the SM agent with load data for the time period covered by the market of interest. For purposes of this Phase 1 effort, the overall site load profile was read from a data file containing 24 hourly readings for one of two different types of sites; small commercial or large commercial/industrial. To further simplify the simulation we defined three basic types of site load; critical, curtailable and normal.

DER asset management includes monitoring the asset(s) to evaluate status (availability, output, and performance, etc.), developing operating schedules based on market and local conditions, and implementing the operating schedule. To simplify the simulation effort we assumed that DER assets are always available, and that DER asset performance is consistent from one simulation run to the next (i.e., does not degrade over time.).

Situation management refers to the agent's ability to monitor, assess and act on state information for; 1) the agent itself, 2) the agent's intended goals, 3) other relevant agents in the system, and 4) the system environment. These data will reside in the SM agent's situation vector. For this effort, we will limit assessment and associated actions to the operational state of the SM agent, the state of the agent's goals and objectives relative to the system environment (i.e., allocation of resources to cover the projected loads, and ability to achieve ROR objectives).

Agent performance assessment / modification refers to the ability of the agent to assess how well it is performing and to subsequently take action to improve performance. Note that for our Phase 1 effort we observed agent performance from an external viewpoint du The Auction as an ESCO Service?

Neighborhood activities are those activities related to SM agent participation in the power neighborhood. These activities include:

Auction status update includes retrieval of auction session data from the power neighborhood website maintained by the DS agent. The SM agent must update auction status information: 1) periodically in order to identify new opportunities for the sale or purchase of excess capacity, 2) whenever it receives a signal from the DS agent indicating that auction board connectivity has changed, and 3) whenever the SM agent desperation level triggers immediate action. This update function is relatively simple and does not involve any SM agent decision-making.

Auction analysis consists of: 1) reviewing existing sessions for opportunities to bid either immediately or in the future[1], 2) identifying opportunities to post new auction sessions for sale or purchase of capacity, and 3) developing session information for submittal to the auction website.

Transaction management includes activities associated with generation or processing of bids associated with existing auction sessions. These activities include: 1) transaction status update (pending, final, canceled), 2) bid development and transmittal (response to existing session by others), 3) bid negotiation (incoming requests / responses), and 4) transaction execution (recording with DS agent).

Distribution Substation (DS) Agent

DS agent activities can be divided into two basic areas; coordination of protection and control systems and auction related.

Coordination of Protection and Control System activities include:

Local coordination of protection and control systems includes operation of the protection and control systems located throughout the distribution system served by its substation as well as communication of substation power quality data to the ESCO agent to facilitate ESCO agent coordination of higher level protection and control systems. The DS agent directly controls the variable tap transformers, sectionalizing breakers and switched capacitor banks using data provided by the SM agents to maintain power quality in the various power neighborhoods served by the substation. The DS agent monitors, but does not directly control the reclosers, manual switches and fuses. In this way, the existing infrastructure will remain essentially intact.

Simulation of power quality impacts is outside the scope of this Phase I effort so we focused on DS agent operation of sectionalizing breakers as it relates to operation of the power neighborhood auctions.

[1] Projecting when the bid price will fall below the target price would allow the agent to establish a good time to update the status again. – *Good Phase 2 topic*.

Auction related activities include:

Power neighborhood auction(s) activities are related to DS agent supply of neighborhood connectivity and ESCO related pricing information to the auction website. Thus to state that the DS agent "hosts" the power neighborhood auction is somewhat misleading. The DS agent does not host the auction website in the sense that it does not match buyers and sellers nor does the auction data transmitted to the auction website pass through the DS agent. The auction website is an independent entity that receives direction from the DS agent related to the connectivity of the various SM agents that access the auction data. The DS agent defines neighborhood boundaries based on feeder connectivity and transmits this information to the website. The website software then uses the boundary data to identify the auction sessions that may be accessed by individual SM agents within the various neighborhoods. Thus, the DS agent may expand or contract the auction boundaries in response to a grid disturbance.

Power neighborhood auction transaction record keeper activities include tracking and archiving all transactions involving SM agents located within its power neighborhoods. In this way, the DS agent can more easily identify transactions impacted by connectivity changes within the power neighborhoods as well as provide billing "true-up" services using metering data that are already accessible to the ESCO. As transaction record keeper the DS agent must:

1. Maintain a transaction registry for all participants.

2. Monitor distribution system connectivity to confirm overall integrity of transactions and notify SM agents of invalidated transactions. For instance, during disturbances the DS agent must identify invalidated transactions and notify the affected parties accordingly.

3. Work with SM agents and the ESCO agent to confirm that transactions were executed (provide "true-up") properly. During this Phase 1 effort we will ignore the "true-up" functionality since it is not directly related to our main project objective.

3.6 Agent Communications

For our Phase 1 effort we focused on the interaction of agents within power neighborhoods at the distribution substation level. Figure 3 illustrates the communication paths and basic data types involved at this level. As the figure shows, there are five basic data types: 1) Site Power Quality data, 2) Auction Session data, 3) Intersite Bid data, 4) Transaction records, and 5) Auction Board Connectivity data.

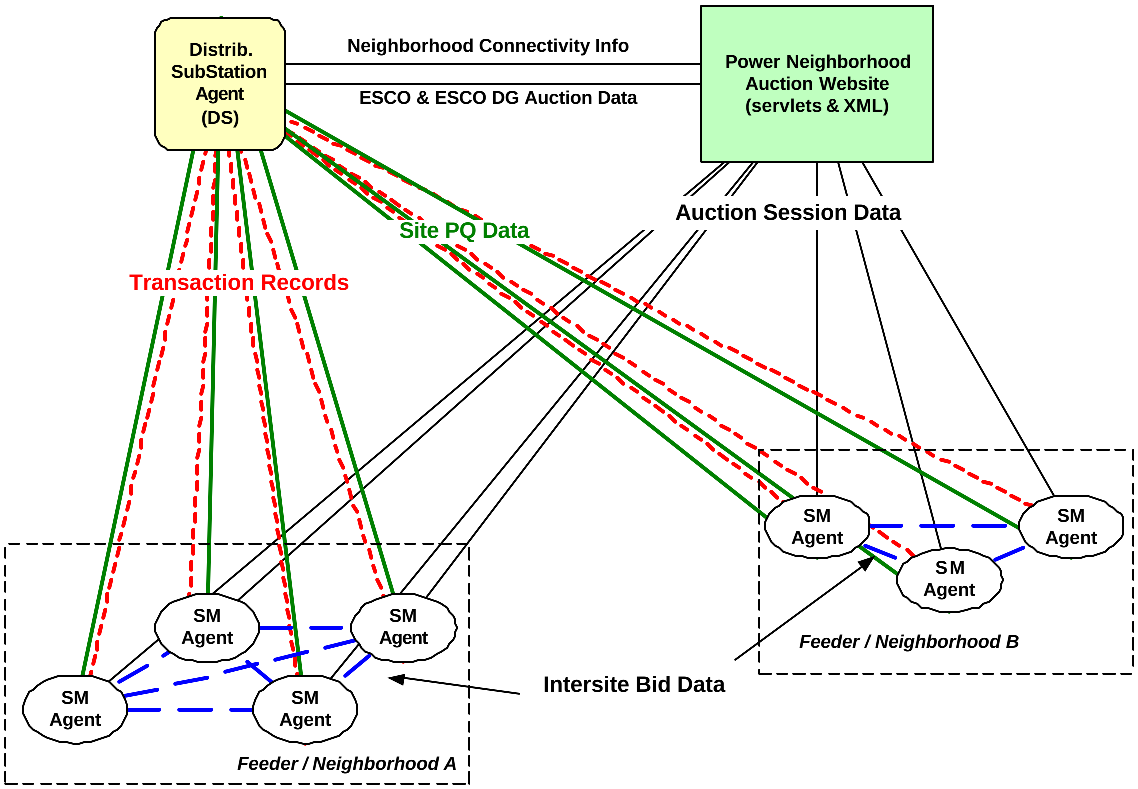


Figure 3: Agent Communication Paths and Data Types

These data are communicated between the DS and SM agents and as such are transmitted using the KQML data protocol used for agent-agent communications. A variety of communication media (RF, power line carrier, fiber optic, etc.) could potentially be used to implement the needed infrastructure. For purposes of our effort we will assume that the media ultimately applied will vary based on location and availability. We will assume that selection of the appropriate communication media will not determine the ultimate success or failure of the agent based concept.

4.0 DIADM SIMULATION SOFTWARE

The Distributed Intelligent Agent for Decision Making (DIADM) software developed during the Phase I effort was designed to demonstrate the use of an unsupervised double Dutch auction process that implements the "power neighborhood" concept of DER asset allocation. Site connectivity is depicted in Figure 4 below. The figure shows two neighborhoods or feeders connected to a single distribution substation. The feeders may be connected via a tie or breaker that separates them. Each feeder is populated with up to ten site level agents (only 6 are shown) that control on-site DER assets. These assets consist of a single distributed generator or a block of curtailable loads.

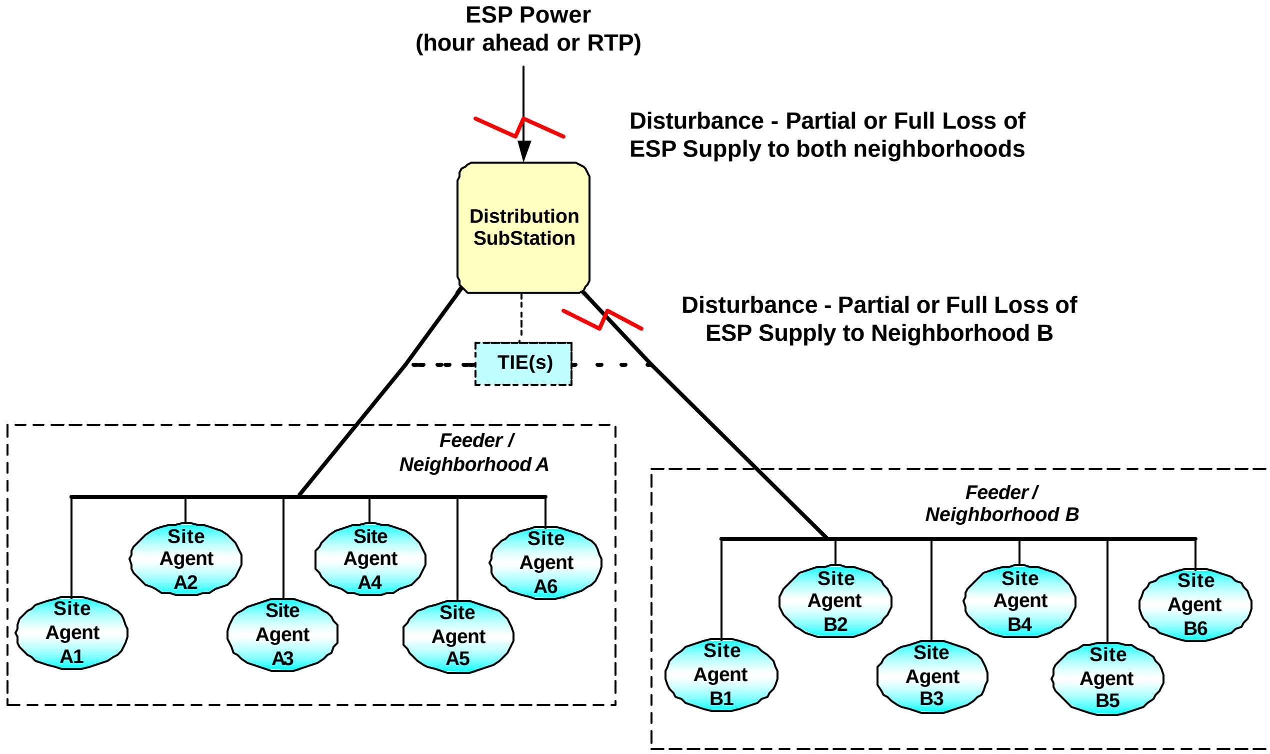


Figure 4: DIADM Simulation Neighborhood Configuration

The simulation software is designed to provide a two-part test where the first part simulates resource allocation in response to an "hour-ahead" or real-time pricing environment. The second part of the test allows the user to specify one of four potential disturbances consisting of:

1. 100% loss of total ESP supply to Neighborhood B
2. 100% loss of ESP supply to both neighborhoods,
3. 50% loss of total ESP supply to Neighborhood B, and
4. 100% loss of ESP supply to both neighborhoods.

Given the scope of this Phase I project, it was necessary to make some assumptions to limit the combinatorial possibilities of interactions in order to examine the feasibility of the agent-based auction approach. Therefore, it was assumed that:

? Testing simulates and observes agent operation and interaction at the "power neighborhood" level. The simulation environment includes a single DS agent and two power neighborhoods each with a maximum of ten SM agents.

- Auction sessions cover delivery / purchase of capacity for the next hour of operation. The hour of operation is a simulation variable so that variations in agent response at different times during the day can be observed.

- Two basic site load profiles are accommodated, small commercial and large commercial/industrial. Individual site peak demand is a simulation variable as is the relative amount of critical and curtailable load at each site. The presence and relative amount of distributed generation is also be a simulation variable.

- SM agents only attempt to purchase capacity equal to their needs and are not allowed to engage in speculation (i.e., purchase excess capacity for resale at a later time, etc.).

- SM agents do not attempt to anticipate the actions of other agents (i.e., will my neighbor bid for the capacity, if I do not, etc.).

- SM agents are not allowed to renege on existing valid transactions (for delivery or purchase) in an attempt to obtain more favorable pricing.

4.1 Simulation Software Operation

To run the simulation, the user opened a specially designed Excel workbook to configure up to 10 active agents in each of two neighborhoods. The user designates whether an agent is active (participating), the peak site demand, whether the site has DG installed and whether the site has critical and/or curtailable loads (see Figure 5).

Two types of sites or load profiles (large or small commercial) were provided in the simulation with the size of the peak demand determining the profile type. Sites with peak demands equal to or exceeding 500 kW were automatically designated as large commercial/industrial and other sites were small commercial. Once the user has defined the neighborhood agents, a save button causes the workbook to create a configuration file that is used to initialize the agents for the simulation.

The DIADM software is initialized with all active agents reporting to the simulation control agent (Figure 6a). The simulation control screen (Figure 6b) is used to vary the relative amounts of DG, critical load and curtailable load, as well as to establish the nature of the failure event. For each test scenario, the site asset percentages listed are applied to sites that were previously designated as having DG, critical or curtailable loads. Regarding the disturbance, the user was able to select 50% or 100% loss of ESCO supply to both neighborhoods or to a single neighborhood.

Upon initialization, the agents retrieve configuration information from the file discussed earlier, and begin the auction process. Once the agents have reached equilibrium in the hour-ahead market, the specified disturbance conditions are applied and the system is allowed to reach a new equilibrium (Figure 7).

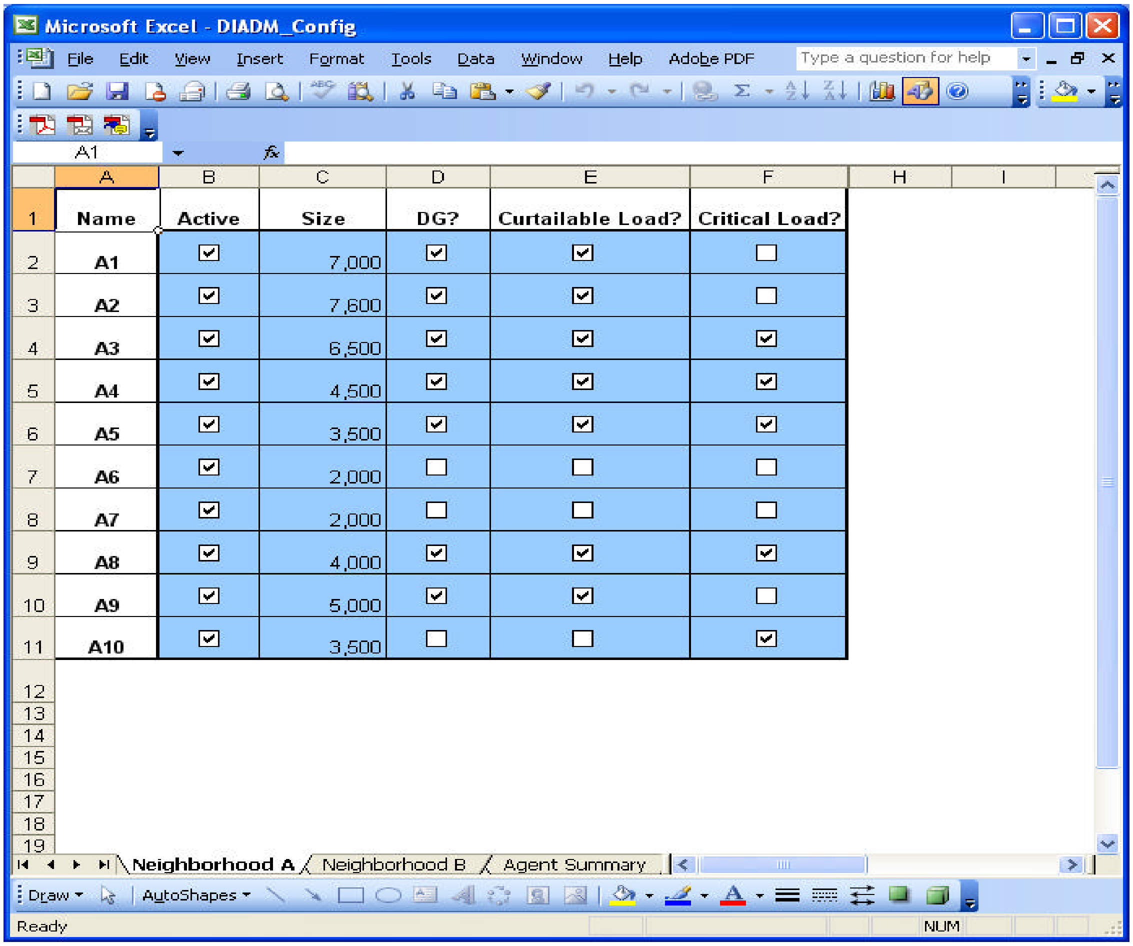


Figure 5: AESC DIADM Example Neighborhood Configuration.

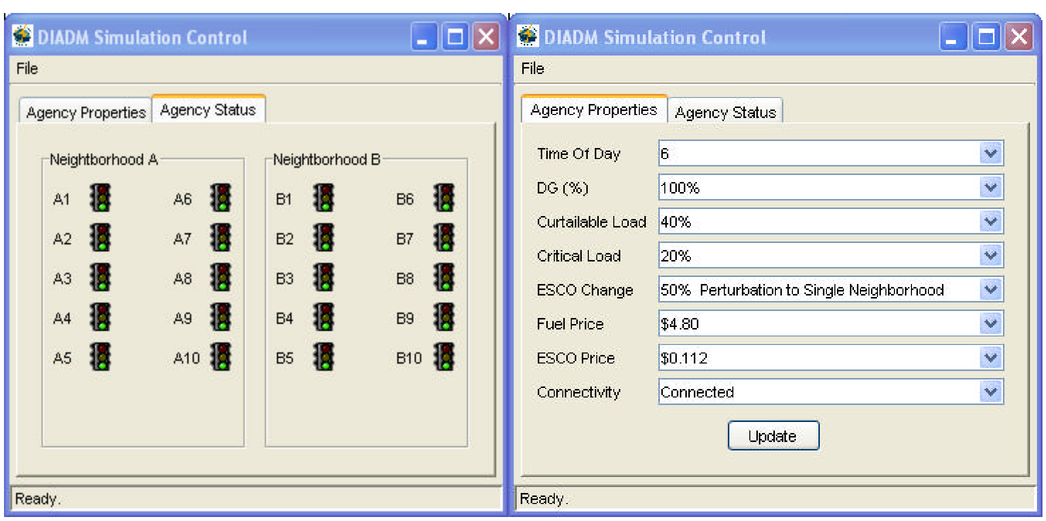


Figure 6: (a) AESC Agent Reporting Status, (b) Simulation Control Dialog.

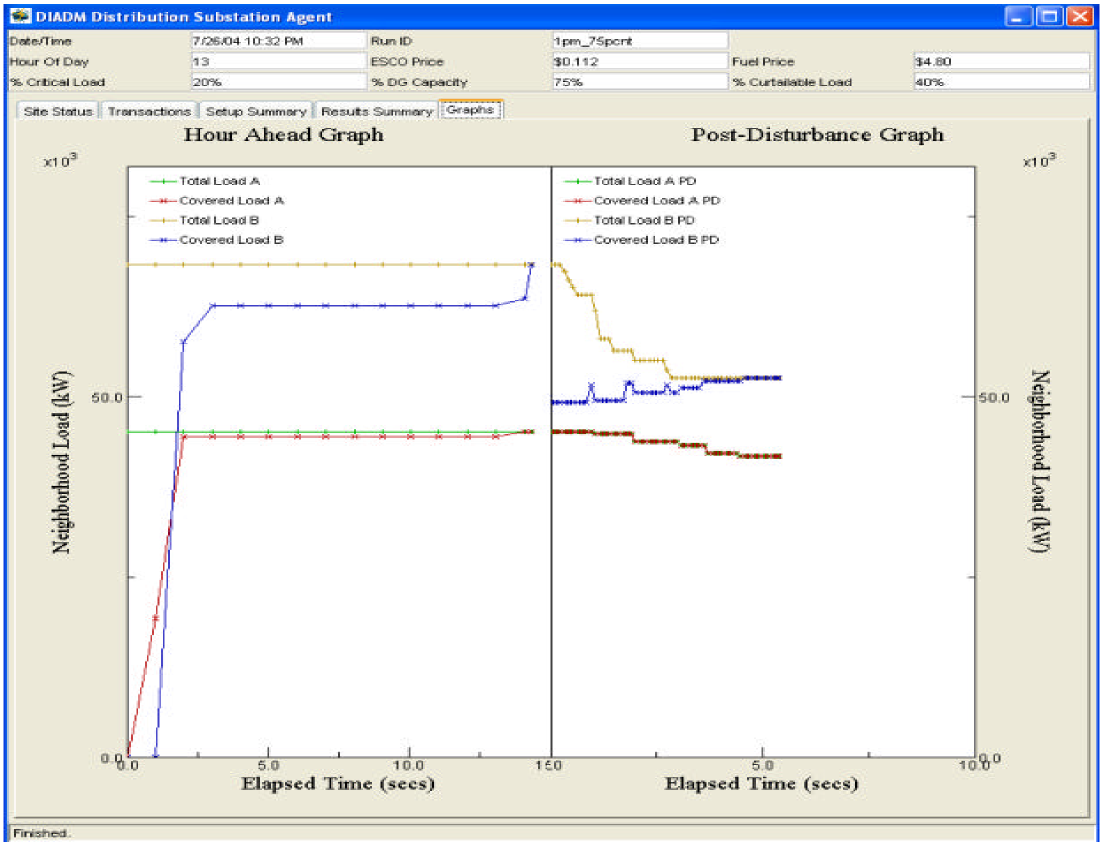


Figure 7: DIADM Sample Graphical Output.

5.0 FEASIBILITY TESTING

The DIADM simulation software developed by AESC was installed on computer(s) in the Center for Networked Distributed Energy in the Department of Mechanical Engineering at Colorado State University. Personnel (two undergraduate students and two graduate students) were used to test basic functionality and the feasibility of the agent-based approach.

The overall simulation (site and neighborhood interaction) and the DS agent in particular, were tested to demonstrate:

? Hour-ahead market convergence,

? Inter-neighborhood connectivity with a simulated failure event, and

? Quantitative and graphical model output.

Given the limited scope of this Phase 1 effort, it was necessary to focus the feasibility testing efforts while still demonstrating the robustness of the agent-based auction approach.

The agent-based auction simulation imposed both normal and critical operating conditions constituting the two scenarios. The response of the overall system to normal or disturbance conditions was monitored and the system behavior was observed.

5.1 Test Scenarios

To evaluate the feasibility of an agent-based approach to DER-Integrated power systems modeling, the following question needs to be addressed. What level of local DG and curtailable load are required to significantly improve the collective system response to an event such as a sudden loss of generation or transmission as seen at the DS level from an ESCO?

To address this question, the simulation will need to demonstrate that an agent-based "power neighborhood" is a viable approach by investigating the relationship(s) between the amount of installed capacity at the local level (i.e., within a neighborhood), the available curtailable loads, the relative amounts of critical and non-critical loads and the ability to supply critical loads during periods of disruption.

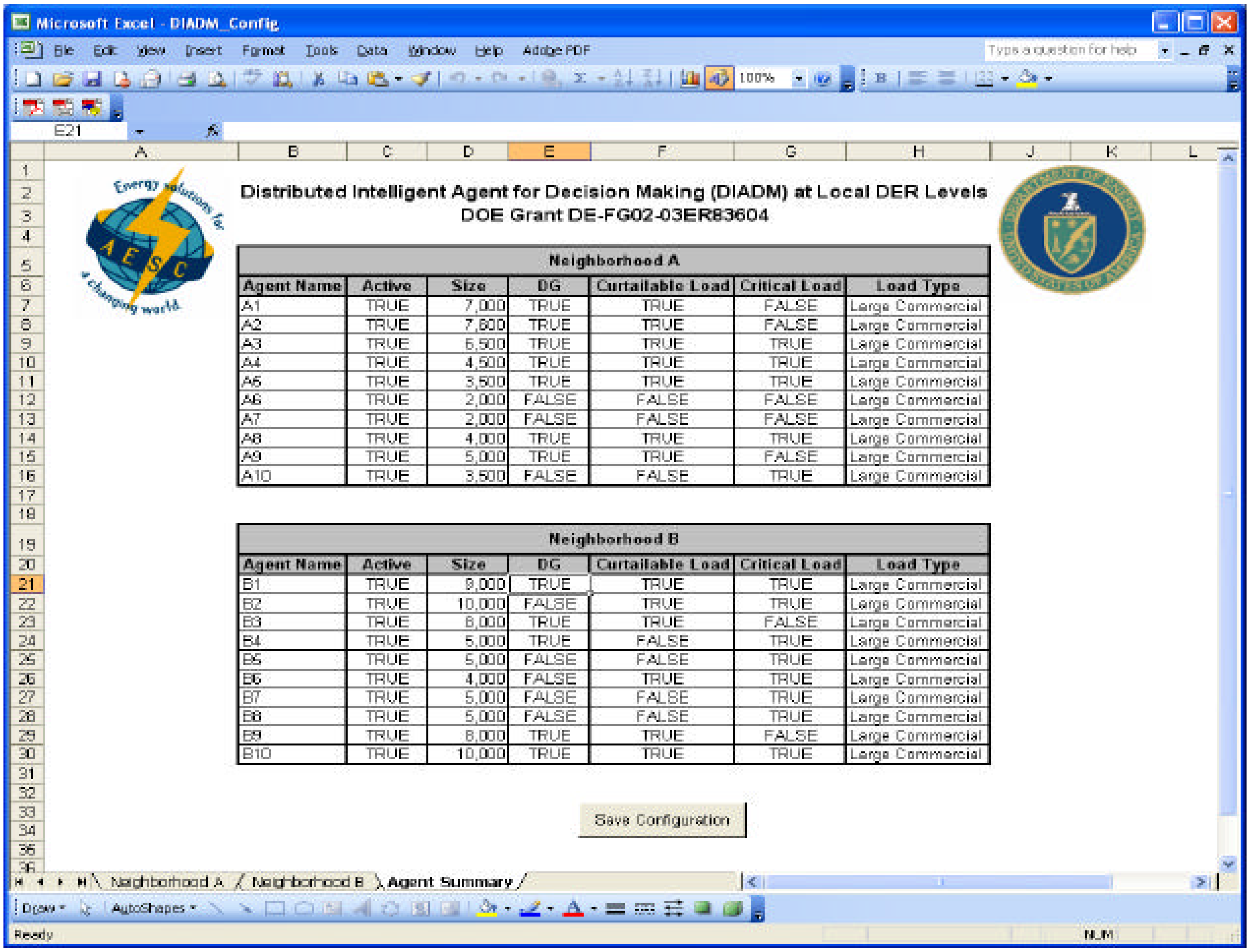
The simulations allowed the investigation of the agent-based approach by examining the collective (neighborhood) response to various environmental conditions, including energy pricing and system perturbations, for a given set of sub-neighborhood agent behavior response specifications. This approach provided insight into the relationship between load type, DER penetration and collective system response. An evaluation of the system performance will consider the coordinated response by both neighborhoods to subjugate negative consequences associated with the failure event, as well as post disturbance equilibrium energy pricing.

Simulation results discussed in the current section were all run using the agent parameterization configuration file summarized in Figure 8. It is important to note the variation of DER assets within each neighborhood in that not all sites have DG and/or curtailable loads. Thus, individual agents within each neighborhood must meet their site load requirements, both hour-ahead and post disturbance, using a mix of assets specific to each site. In addition, each neighborhood agent will respond, via the auction process, to the needs of other agents based on its ability to either generate excess power or to curtail load.

The software control screen was then used to vary environmental conditions such as %DG, %Curtailable Load, %Critical Load and failure event time-of-day, the resulting twenty-three test scenarios are summarized in Table 1.

5.2 Testing Observations

In the test scenarios listed in Table 1, the agents reached equilibrium in the hour-ahead auction-based market, as well as in the post-disturbance simulation, and as will be seen in the following diagrams, the neighborhoods work as cohesive units in response to the simulated failure event.



Neighborhood A						
Agent Name	Active	Size	DG	Curtailable Load	Critical Load	Load Type
A1	TRUE	7,000	TRUE	TRUE	FALSE	Large Commercial
A2	TRUE	7,800	TRUE	TRUE	FALSE	Large Commercial
A3	TRUE	6,500	TRUE	TRUE	TRUE	Large Commercial
A4	TRUE	4,500	TRUE	TRUE	TRUE	Large Commercial
A5	TRUE	3,500	TRUE	TRUE	TRUE	Large Commercial
A6	TRUE	2,000	FALSE	FALSE	FALSE	Large Commercial
A7	TRUE	2,000	FALSE	FALSE	FALSE	Large Commercial
A8	TRUE	4,000	TRUE	TRUE	TRUE	Large Commercial
A9	TRUE	5,000	TRUE	TRUE	FALSE	Large Commercial
A10	TRUE	3,500	FALSE	FALSE	TRUE	Large Commercial

Neighborhood B						
Agent Name	Active	Size	DG	Curtailable Load	Critical Load	Load Type
B1	TRUE	9,000	TRUE	TRUE	TRUE	Large Commercial
B2	TRUE	10,000	FALSE	TRUE	TRUE	Large Commercial
B3	TRUE	8,000	TRUE	TRUE	FALSE	Large Commercial
B4	TRUE	5,000	TRUE	FALSE	TRUE	Large Commercial
B5	TRUE	5,000	FALSE	FALSE	TRUE	Large Commercial
B6	TRUE	4,000	FALSE	TRUE	TRUE	Large Commercial
B7	TRUE	5,000	FALSE	FALSE	TRUE	Large Commercial
B8	TRUE	5,000	FALSE	FALSE	TRUE	Large Commercial
B9	TRUE	8,000	TRUE	TRUE	FALSE	Large Commercial
B10	TRUE	10,000	TRUE	TRUE	TRUE	Large Commercial

Figure 8: DIADM Site Configuration

In general these test scenarios simulate system conditions along a severity continuum, where some environmental and failure event conditions combine to produce a *less-stressed* scenario and others a *more-stressed* scenario. The first set of scenarios for this example was run with a fuel price of $4.80. This low fuel price acts as an incentive for the DER agents to use all available DG capacity, rather than purchasing from the ESCO. Thus, the post-disturbance portion of these scenarios are run with zero available DG capacity. The second set of scenarios is at an increased fuel price, which allows for available DG capacity post-disturbance. Scenario #3 is one of the least stressed scenarios as the failure event is a 50% failure of a single neighborhood, occurs at 6 a.m., a time with which the DIADM software associates a lower global demand profile, and its %DG is 100%. On the other end of this spectrum is a scenario such as Scenario #18. The failure event is a 50% loss to both neighborhoods at 1 p.m., which has a higher global load profile, and only has a 50% DG coverage.

The graphical output for scenarios #3 and #18 are shown in Figures 9 and 10, respectively, and although only qualitative, there are several behavioral differences to note between the test cases. The agents in Scenario #3 are coping with the 50% loss of power to neighborhood B through curtailment only, where the agents in scenario #18 are using curtailment as well as the DG capacity available at the time of the 50% loss of power to both neighborhoods.

Table 1: DIADM Simulation Scenarios.

#	Failure Mode	Failure Event Time of Day					% DG Penetration			
		6am	1pm	%DG Capacity	% Curtailable	% Critical	A	B	Total	*Fuel Price*
1	50% B	x		75	40	20	72	50	59	$4.80
2	50% B	x		75	60	40	72	50	59	4.80
3	50% B	x		100	40	20	96	67	79	4.80
4	50% A+B	x		100	40	20	96	67	79	4.80
5	100% B	x		100	40	20	96	67	79	4.80
6	100% B	x		75	60	40	72	50	59	4.80
7	50% B		x	75	40	20	63	44	52	4.80
8	50% B		x	75	60	40	63	44	52	4.80
9	50% B		x	100	40	20	85	59	69	4.80
10	50% A+B		x	75	60	40	63	44	52	4.80
11	50% A+B		x	100	40	20	85	59	69	4.80
12	100% B		x	75	60	40	63	44	52	4.80
13	100% B		x	100	40	20	85	59	69	4.80
14	100% A+B		x	100	40	20	85	59	69	7.20
15	100% A+B		x	100	60	20	85	59	69	7.20
16	100% A+B		x	75	60	20	63	44	52	7.20
17	100% A+B		x	50	60	20	42	29	34	7.20
18	50% A+B		x	50	40	20	42	29	34	7.20
19	50% A+B		x	50	60	20	42	29	34	7.20
20	100% B	x		50	60	20	48	33	39	7.20
21	100% B		x	50	60	20	42	29	34	7.20
22	100% B		x	50	40	20	42	29	34	6.00
23	50% B		x	50	40	20	42	29	34	6.00

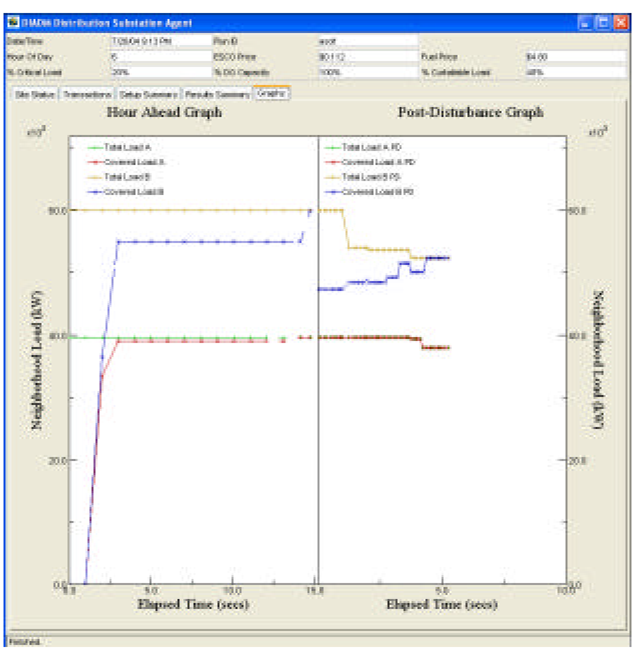


Figure 9: Scenario #3 Graphical Output.

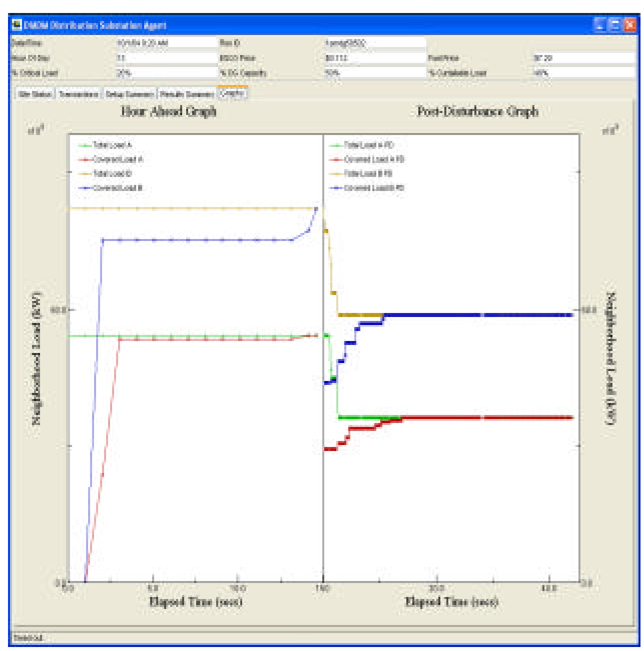
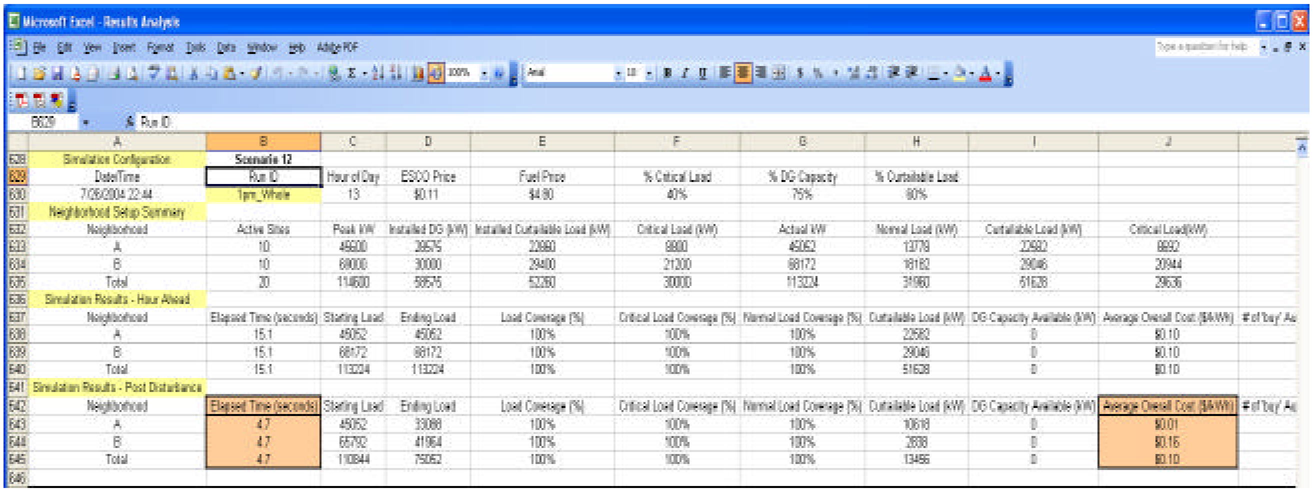


Figure 10: Scenario #18 Graphical Output.

Scenarios #1 through #13 explore the collective neighborhood responses for varying setup conditions, such as disturbance time of day, %curtailable and %critical load; however, the %DG does not affect these scenarios because of the low fuel price as discussed previously. The graphical output for these scenarios can be found in Appendix A.

In Figure 11, Scenario #12 was analyzed using the raw data output utility provided by the DIADM software in the form of several Excel files. Figure 12 shows the form of some of this output, with highlighting added. Of particular interest is the Average Overall Cost ($/kWh) on the lower right of the figure. From an hour-ahead equilibrium cost of $0.10/kwh, the post-disturbance cost for neighborhood A drops to $0.01/kwh and the cost for neighborhood B rises to $0.16/kwh. Thus neighborhood A is able to profit from the sale of capacity to neighborhood B and neighborhood B is able to cover its load, but at an added cost.



	A	B	C	D	E	F	G	H	I	J	
628	Simulation Configuration	Scenario 12									
629	Date/Time	Run ID	Hour of Day	ESCO Price	Fuel Price	% Critical Load	% DG Capacity	% Curtailable Load			
630	7/26/2004 22:44	1pm_Whole	13	$0.11	$4.80	40%	75%	60%			
631	Neighborhood Setup Summary										
632	Neighborhood	Active Sites	Peak kW	Installed DG (kW)	Installed Curtailable Load (kW)	Critical Load (kW)	Actual kW	Normal Load (kW)	Curtailable Load (kW)	Critical Load(kW)	
633	A	10	45600	28575	22880	8800	45052	13778	22582	8892	
634	B	10	69000	30000	29400	21200	68172	18182	29046	20944	
635	Total	20	114600	58575	52280	30000	113224	31960	51628	29836	
636	Simulation Results - Hour Ahead										
637	Neighborhood	Elapsed Time (seconds)	Starting Load	Ending Load	Load Coverage (%)	Critical Load Coverage (%)	Normal Load Coverage (%)	Curtailable Load (kW)	DG Capacity Available (kW)	Average Overall Cost ($/kWh)	# of 'bay' Ac
638	A	15.1	45052	45052	100%	100%	100%	22582	0	$0.10	
639	B	15.1	68172	68172	100%	100%	100%	29046	0	$0.10	
640	Total	15.1	113224	113224	100%	100%	100%	51628	0	$0.10	
641	Simulation Results - Post Disturbance										
642	Neighborhood	Elapsed Time (seconds)	Starting Load	Ending Load	Load Coverage (%)	Critical Load Coverage (%)	Normal Load Coverage (%)	Curtailable Load (kW)	DG Capacity Available (kW)	Average Overall Cost ($/kWh)	# of 'bay' Ac
643	A	4.7	45052	33088	100%	100%	100%	10618	0	$0.01	
644	B	4.7	65792	41964	100%	100%	100%	2838	0	$0.16	
645	Total	4.7	110844	75052	100%	100%	100%	13456	0	$0.10	
646											

Figure 11: DIADM Data Output – Scenario 12.

The data per time step was also analyzed and is shown in Figure 12. This data can then be analyzed for more specific information. Figure 13 shows one such analysis. In Figure 13, we can see that the neighborhood behavior has been accurately reproduced. We have also added a parameter that makes explicit the overall goal of the neighborhood power systems, which is to minimize the blue and yellow lines in the lower section of Figure 13. These data represent the difference between the Covered Load and Total Load for each neighborhood. Neighborhood A, as represented by the yellow line, begins the post disturbance sequence already in equilibrium since the disturbance is limited to neighborhood B only. Neighborhood B (dark blue line) experiences a significant deviation in the covered load but is able to use the auction process to "cover" this loss. Neighborhood B accomplishes this using a combination of load curtailment within neighborhood B (agents curtail local site loads as well as purchase curtailments from neighbors) and via the purchase of curtailments from neighborhood A (as evidenced by reduction of the neighborhood A covered load line). When both neighborhoods have reduced this difference to zero, the simulation has reached equilibrium.

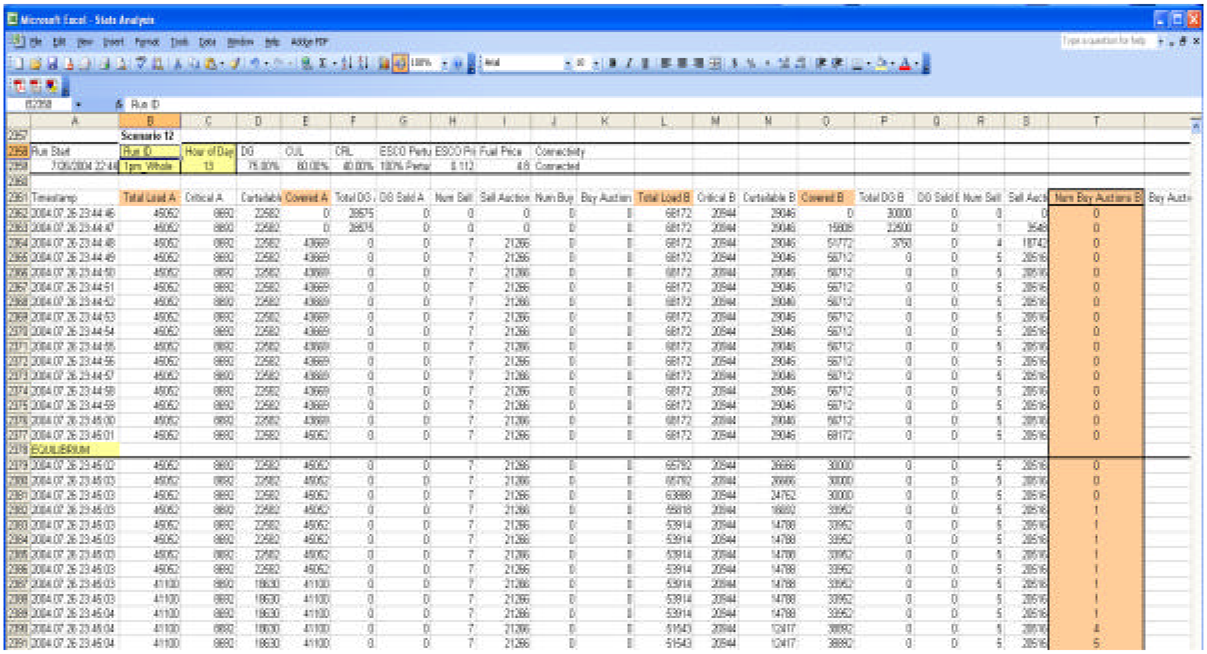


Figure 12: DIADM Data Output Per Time Step – Scenario 12.

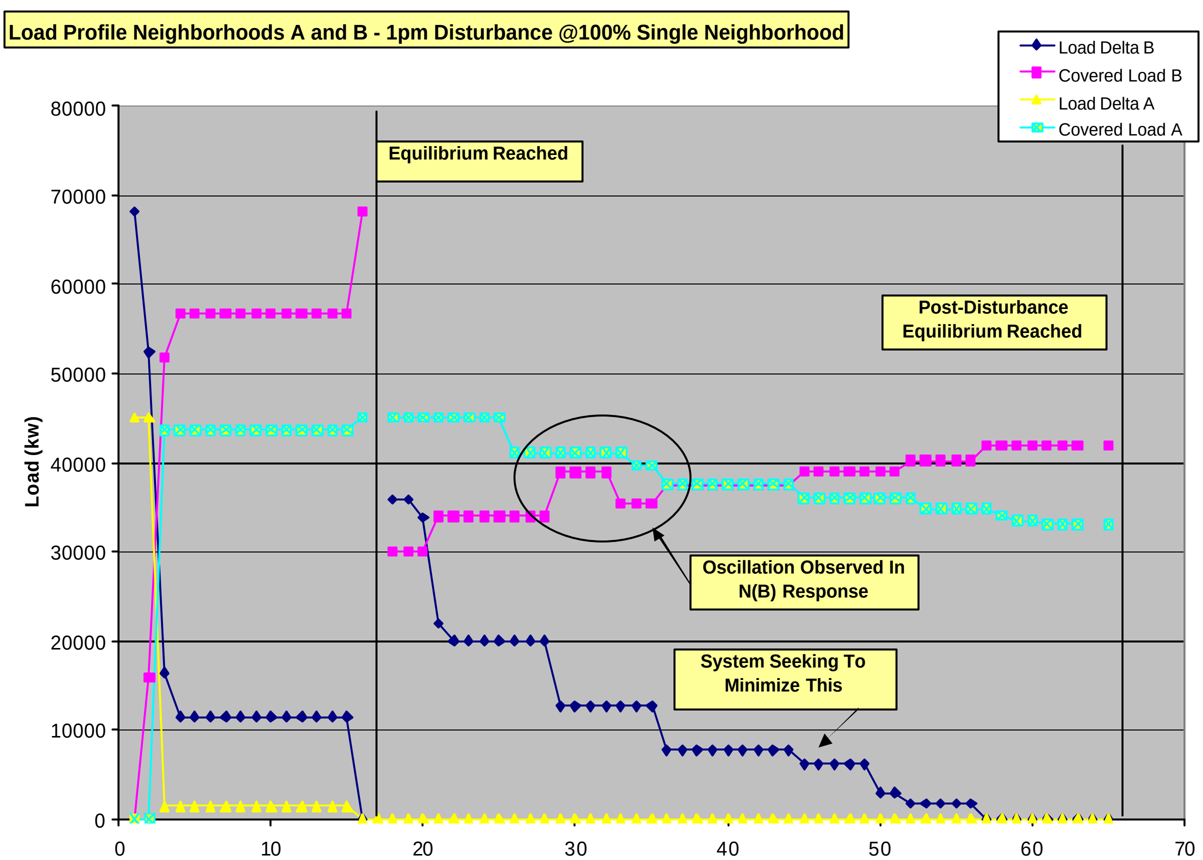


Figure 13: DIADM Data Output Graphical Analysis – Scenario #12.

The remaining scenarios (Scenarios #14 through #23) explore the collective neighborhood responses for varying setup conditions similar to Scenarios #1 through #13, but with a significant difference: The high fuel price in these scenarios causes the DER agents to purchase ESCO power rather than use DG capacity, thus leaving available DG capacity at the time of disturbance. These scenarios then are affected by the setup parameter of %DG, which specifies the percent of available DG that will be applied to the scenario within the DIADM software. Scenarios #14, #15 and #16 specify fairly high %DG of 75% to 100%, but the remaining scenarios specify only 50% available DG capacity, thus further constraining the neighborhoods to respond to the simulated disturbance.

Figure 14 illustrates the graphical output for scenario #21 (100% loss of ESCO supply to Neighborhood B). The 100% loss to neighborhood B is reflected in the immediate and significant load curtailment by neighborhood B, which is joined by the use of DG capacity in both neighborhoods, as well as load curtailment in neighborhood A. To effectively respond to this disturbance, the agents in neighborhood B responded in three different ways: Load curtailment, DG capacity conversion and generation purchase from agents in neighborhood A. Agents in neighborhood A respond to the purchase requests by selling excess DG capacity, and by curtailing load, which is then sold to neighborhood B agents at a higher price.

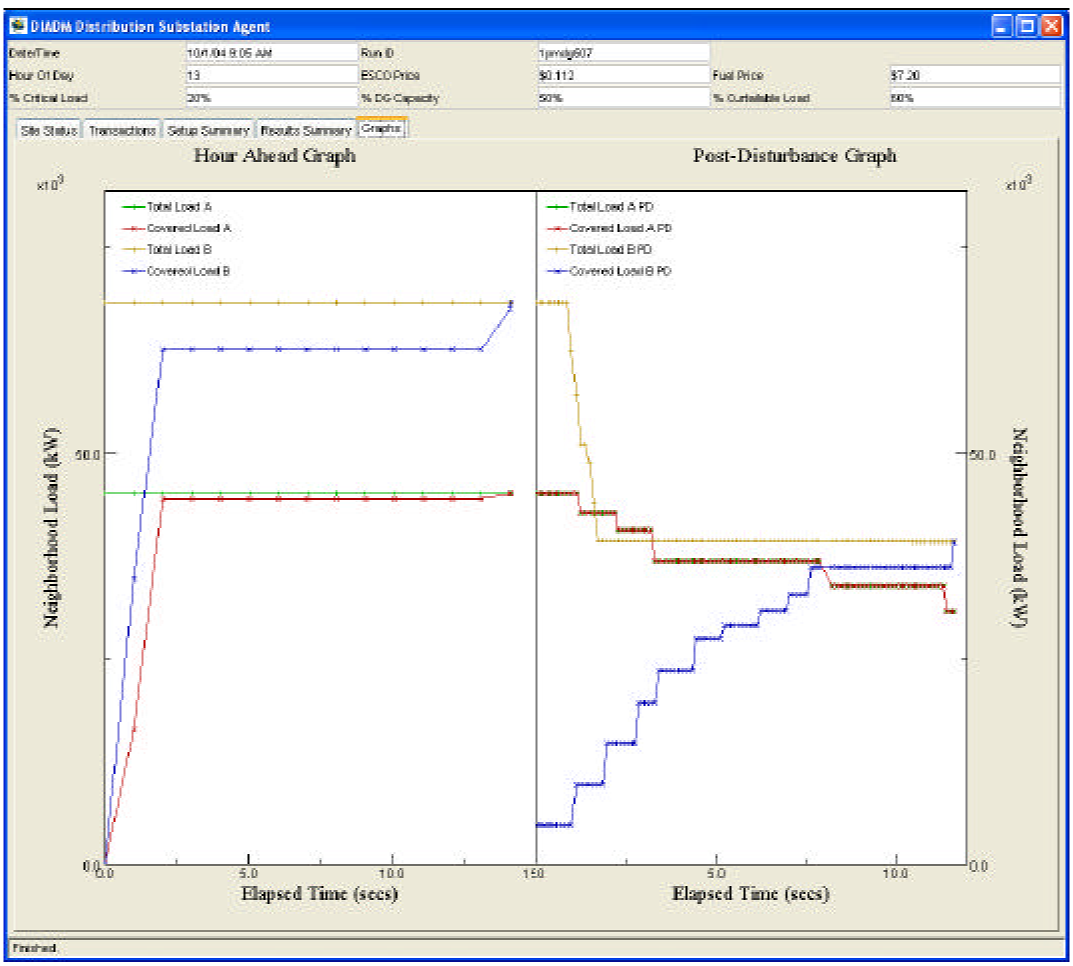


Figure 14: Neighborhood Behavior for Scenario #21

These simulation scenarios also provided insight on the impact of the global load profile, as represented by the time of day parameter, on the behavior of the neighborhoods. Scenarios #20 and #21 are identical in all setup parameters except the disturbance time of day, which is 6am and 1pm respectively. For the 6 a.m. case, the %DG penetration of scenario #20 is 48% and 33% for neighborhoods A and B respectively, whereas for 1 p.m. it is only 42% and 29% (scenario #21). Figure 15 illustrates the behavior of the neighborhoods in these scenarios.

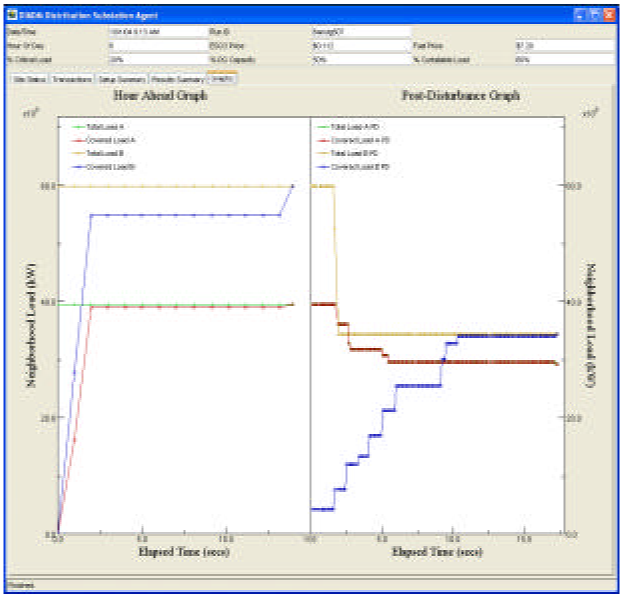


Figure 15: Scenario #20 Graphical Output.

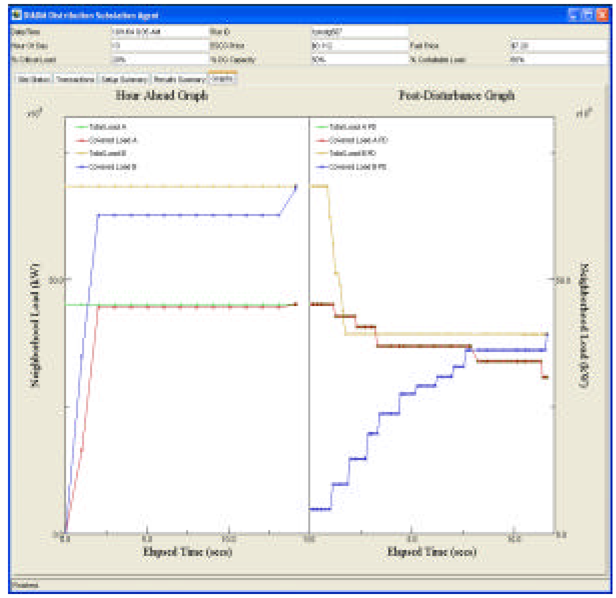


Figure 16: Scenario #21 Graphical Output.

6.0 TESTING SUMMARY

The feasibility of the agent-based approach for DER-integrated power systems modeling were addressed in these tests. In cases where the ESCO price and fuel price settings were favorable to DG, little or no DG capacity was available after the hour-ahead market was finished since it was more economical to use the DG rather than purchase ESCO power. As one would expect, the post disturbance behavior was always related to curtailment for these cases. This also has the effect of reducing the overall size of the disturbance since less ESCO power will be purchased during the hour-ahead market. Prices used were fixed to facilitate comparisons between the various scenarios. Another scenario was used to show the hour-ahead and post disturbance responses when higher fuel costs are used. Again, as expected, more DG capacity was available after completion of the hour-ahead market, the size of the disturbance was greater (due to increased ESCO purchases in the hour-ahead market, and the disturbance response included both DG and load curtailment.

In Table 1, neighborhood A and B shows the DG and DER penetration levels at the two times of day (6 am, 1 pm) used. Each neighborhood is able to cope with the disturbance, however, neighborhood A has significantly more DER coverage than neighborhood B and as such is better able to cope with the disturbance. In addition, neighborhood A is able to reduce its post disturbance costs through the sale of capacity to neighborhood B.

Testing showed that the ability of the neighborhood agents to converge to a post disturbance solution is only a function of the availability of DER assets. If there are sufficient assets (DG and load curtailment) to respond to the disturbance, then the agents will always be able to reallocate the resources using the auction process (converge).

The different scenarios tested attempted to provide a range of environmental and operational conditions for the software agents in order to observe their collective behavior under various constraint combinations. From the graphical output one can see that certain scenarios appear to be more complex than others from the standpoint of the emergent neighborhood behavior. In general, the fewer resources the system has available relative to the size of the disturbance, in the form of %DG, %Curtailable and global load profile, the more transactions will be executed by the individual software agents as the neighborhoods attempt to equalize load requirements.

6.1 Feasibility of Simulation Software

The DIADM software provides significant insight into the relationship between individual agent design, or parameterization, and the emergent global behavior of a system comprised of such agents. The simulation provides a unique scenario with two groups of agents called neighborhoods, which effectively act as a microgrid, where some or all ESCO provided power can be curtailed from one or both neighborhoods. The individual agents' behavior is consistent with a decentralized system, where they have only locally available information in the form of auction-style buy/sell and price, and more global information is transmitted through a variety of means. The design and control of a decentralized electric power system will contain many of the high-level attributes demonstrated in the DIADM software.

6.2 Significance of Test Results

The scenarios examined in this testing demonstrate the feasibility of a decentralized architecture for power system control using agent-based modeling. The agents were able to cover their individual critical loads, and their collective neighborhood loads by establishing bilateral transactions with SM agents and the DS agent via the auction website. We notice from Table 1 that neighborhood A has significantly more DER coverage (%DG Penetration) than neighborhood B, which contributes to neighborhood A's ability to cope with the disturbance. Neighborhood A is also able to reduce its post disturbance costs through the sale of capacity to neighborhood B.

7.0 PROJECT CONCLUSIONS

The test scenarios examined by CNDE personnel were selected to demonstrate the feasibility of a decentralized architecture for power system control using agent-based modeling. Testing revealed that the site agents were able to cover their individual site critical loads, and their collective neighborhood loads by establishing bilateral transactions with other site (SM) agents (both within their own and adjacent neighborhoods) and the distribution substation (DS) agent via the auction website. The agents operating within the power neighborhoods were able to allocate DER assets amongst the various sites in both an hour-ahead auction environment as well as in response to a signal indicating the loss of part or all of the grid supplied power. Testing showed that the agents, operating via Dutch auctions and without a central authority, quickly allocated DER assets and converged on a solution. Testing also showed how neighborhoods with disparate DER penetration levels are able to both reallocate resources within their respective neighborhoods as well as contribute to an adjacent neighborhood's ability to respond. In doing so, neighborhoods with excess DER assets were able to reduce their overall costs through the sale of excess capacity.

The test results are qualitative in nature since timing and performance constraints imposed by both DER asset performance and the latency of inter-agent communications were not simulated. However, test results clearly show that a network of agents, acting within "power neighborhoods" can quickly allocate resources both in response to dynamic pricing and if signaled that a partial or total loss of grid supplied power is eminent. Furthermore, that use of a Dutch auction based process eliminates the need for a centralized control thus providing an inherently more open and extensible solution.

This Phase I effort was successful in demonstrating the feasibility of the power neighborhood concept. A logical next step would be a Phase II effort that provides for further refinement of the concept and agents involved with the objective being to implement the power neighborhood concept in a "real world" environment. Such an effort would require both the participation of an ESCO as well as a number of sites located within a single feeder circuit. Given the difficulty in involving such a large number of entities it is likely that a project of this type would need to involve both actual and simulated actions.

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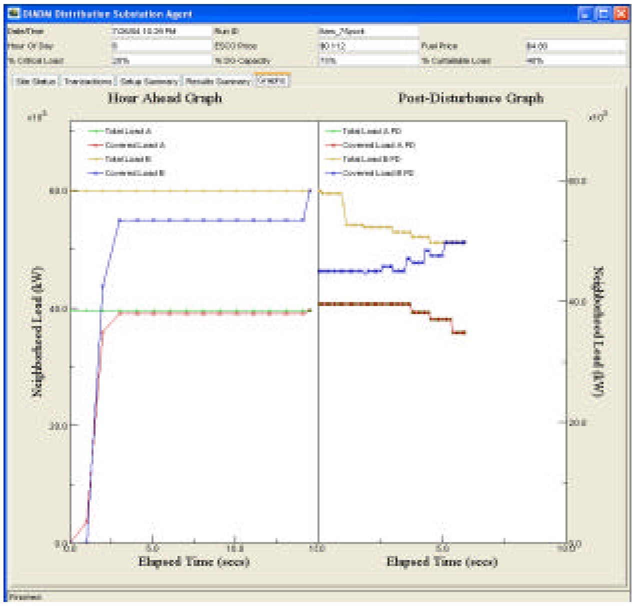
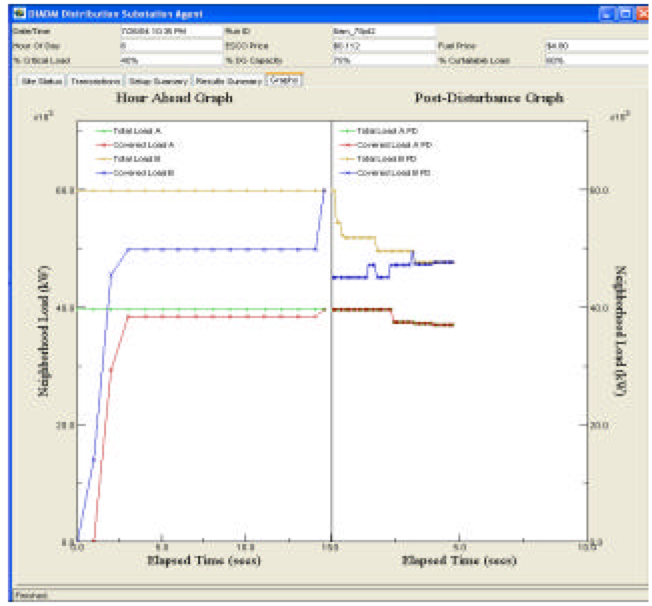
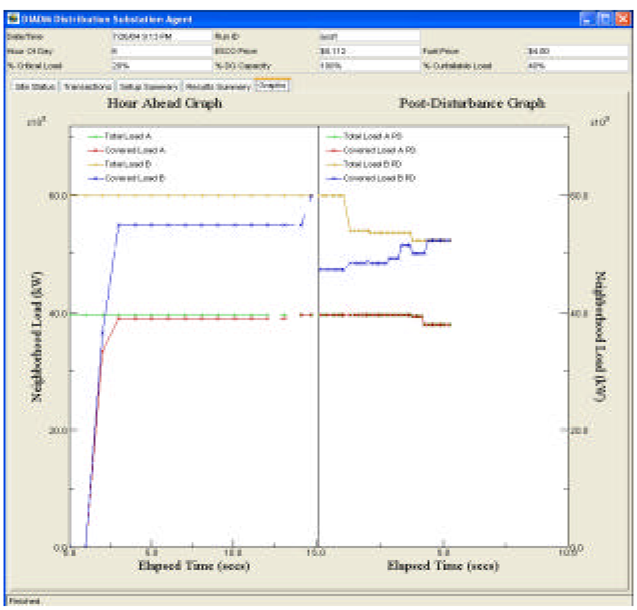
APPENDIX A – TEST SCENARIO GRAPHICAL RESULTS



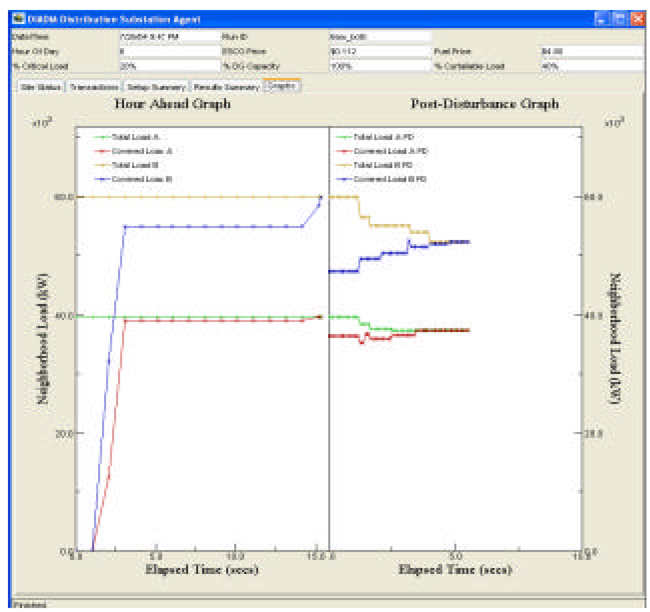
Scenario 1: 6 a.m., 50% B, 75-40-20, $4.80



Scenario 2: 6 a.m., 50% B, 75-60-40, $4.80



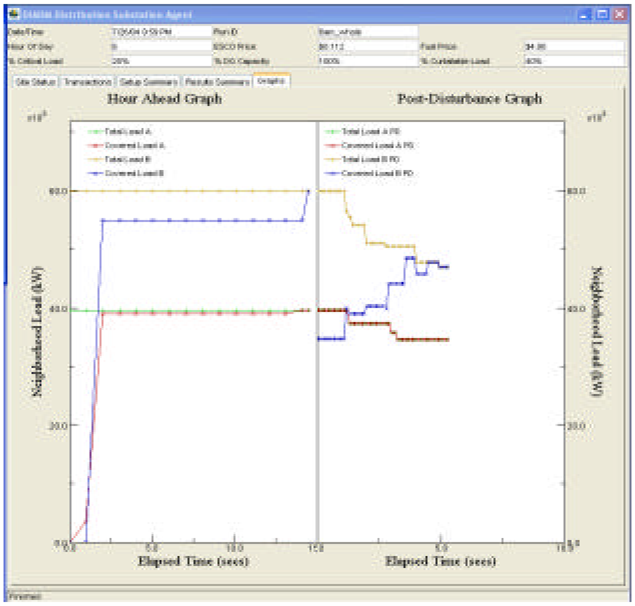
Scenario 3: 6 a.m., 50% B, 100-40-20, $4.80



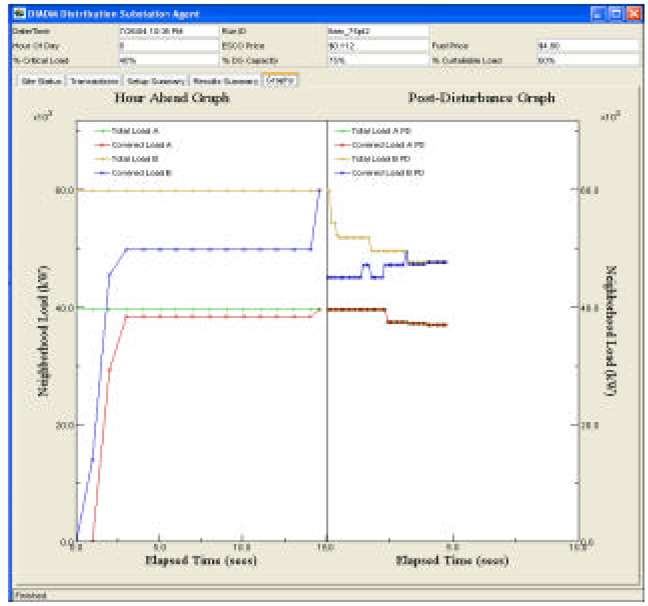
Scenario 4: 6 a.m., 50% A&B, 100-40-20, $4.80

Where Scenario description includes:
Scenario #: Time of Day, Failure Mode, %DG-%Curtailable-%Critical, Fuel Price

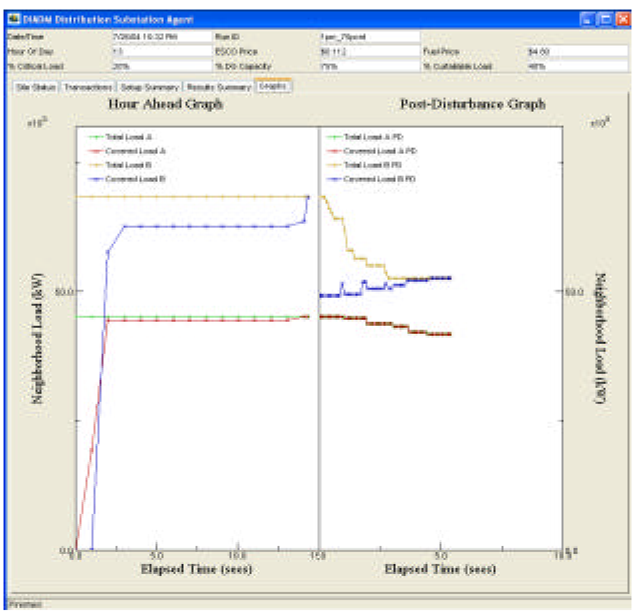
Appendix A: Test Scenario Graphical Results



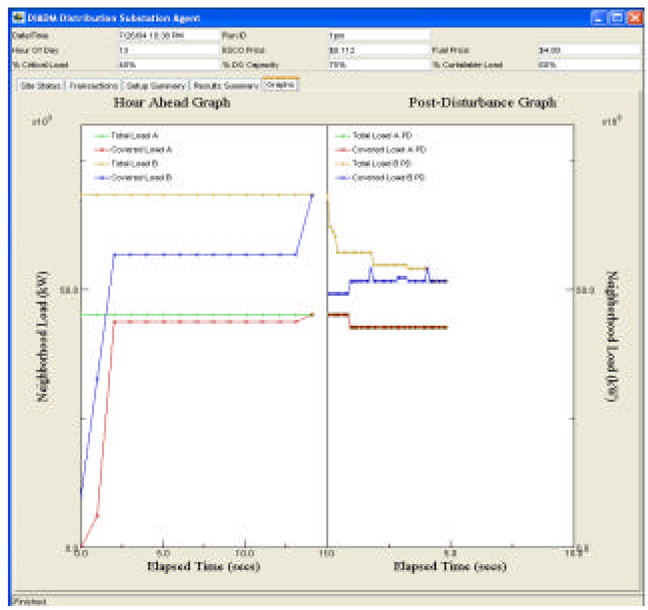
Scenario 5: 6 a.m., 100% B, 100-40-20, $4.80



Scenario 6: 6 a.m., 100% B, 75-60-40, $4.80



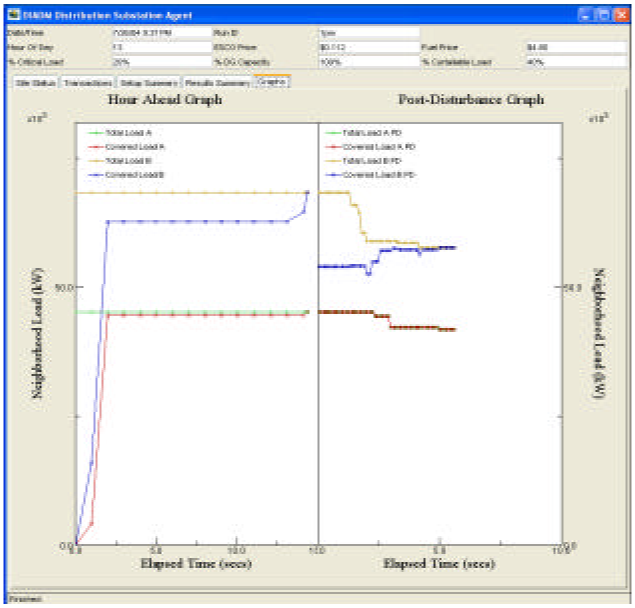
Scenario 7: 1 p.m., 50% B, 75-40-20, $4.80



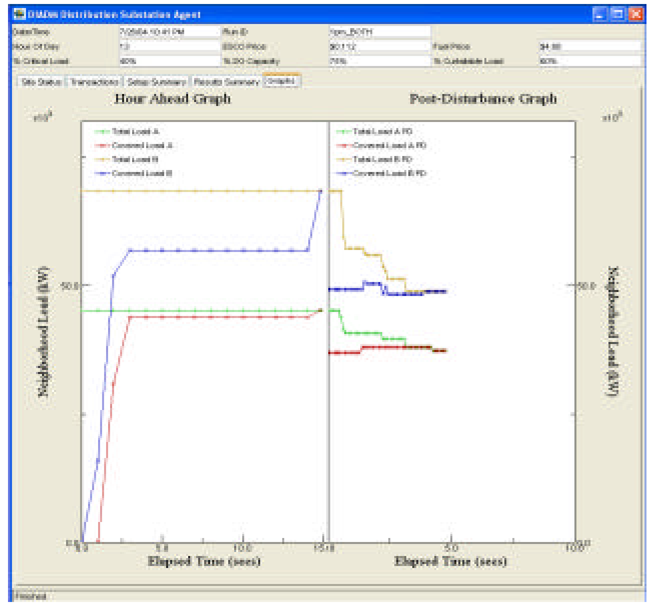
Scenario 8: 1 p.m., 50% B, 75-60-40, $4.80

Where Scenario description includes:
Scenario #: Time of Day, Failure Mode, %DG-%Curtailable-%Critical, Fuel Price

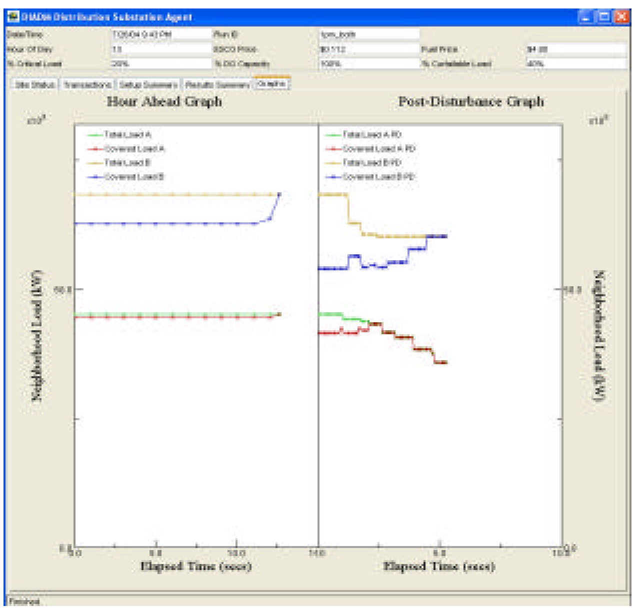
Appendix A: Test Scenario Graphical Results



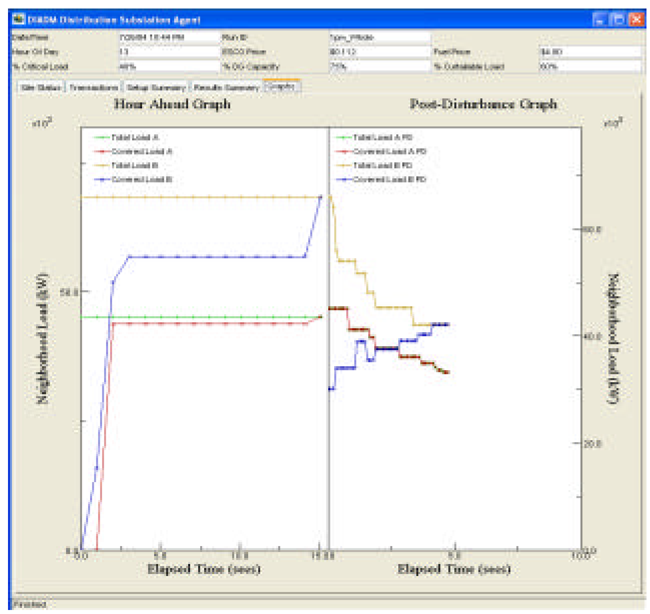
Scenario 9: 1 p.m., 50% B, 100-40-20, $4.80



Scenario 10: 1 p.m., 50% A&B, 75-60-40, $4.80



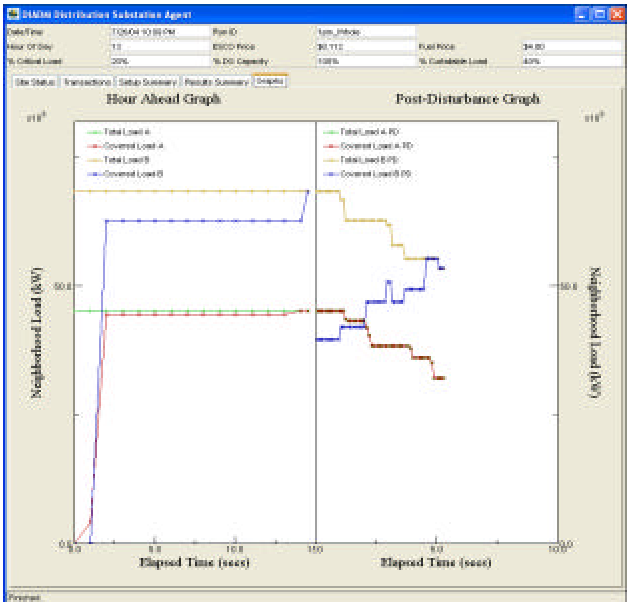
Scenario 11: 1 p.m., 50% A&B, 100-40-20, $4.80



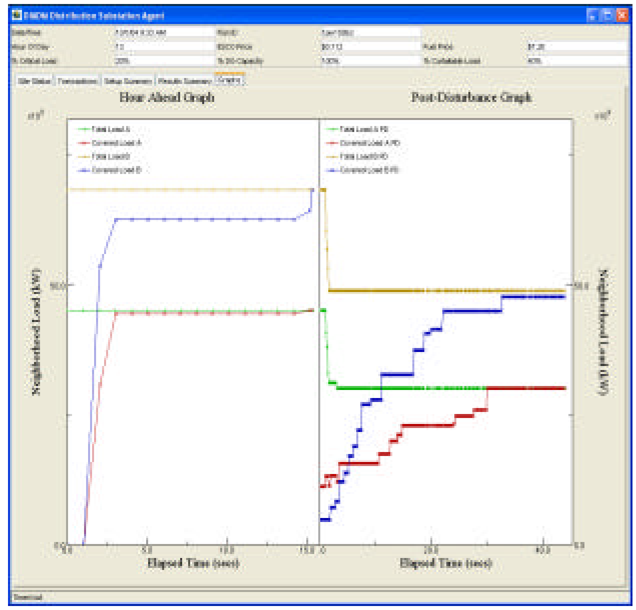
Scenario 12: 1 p.m., 100% B, 75-60-40, $4.80

Where Scenario description includes:
Scenario #: Time of Day, Failure Mode, %DG-%Curtailable-%Critical, Fuel Price

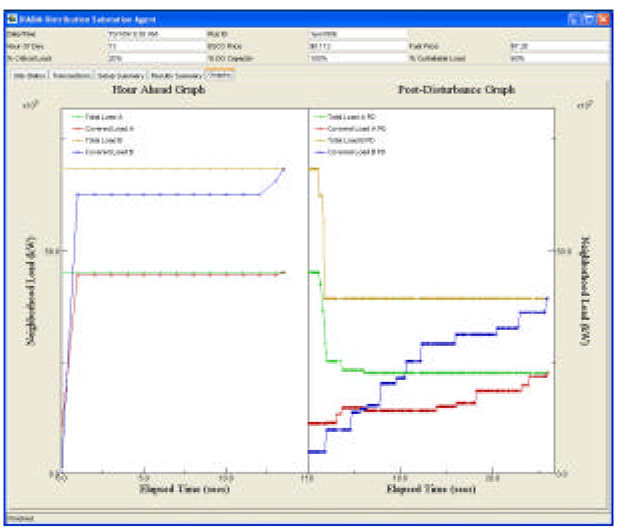
Appendix A: Test Scenario Graphical Results



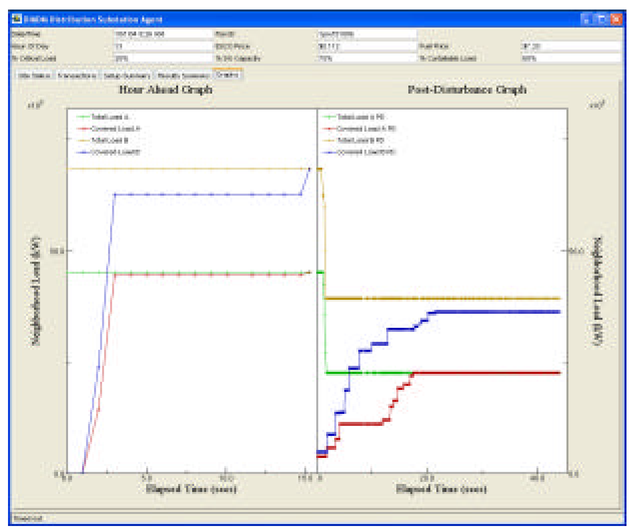
Scenario 13: 1 p.m., 100% B, 100-40-20, $4.80



Scenario 14: 1 p.m., 100% A&B, 100-40-20, $7.20

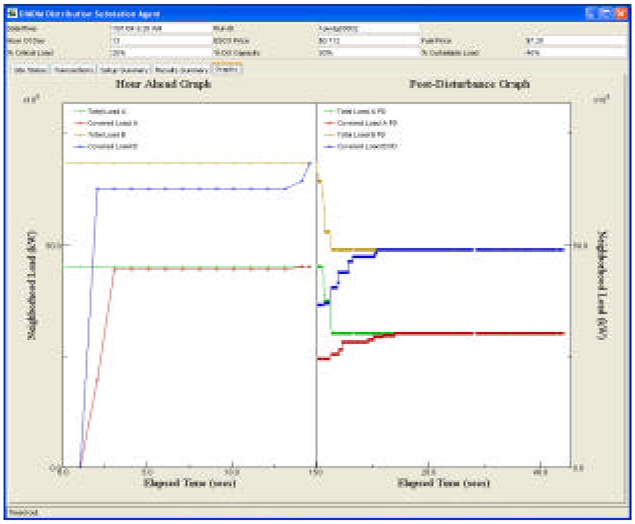


Scenario 15: 1 p.m., 100% A&B, 100-60-20, $7.20

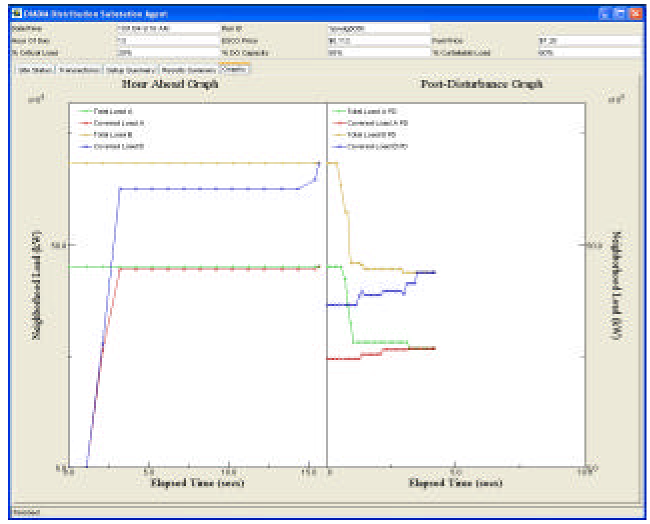


Scenario 16: 1 p.m., 100% A&B, 75-60-20, $7.20

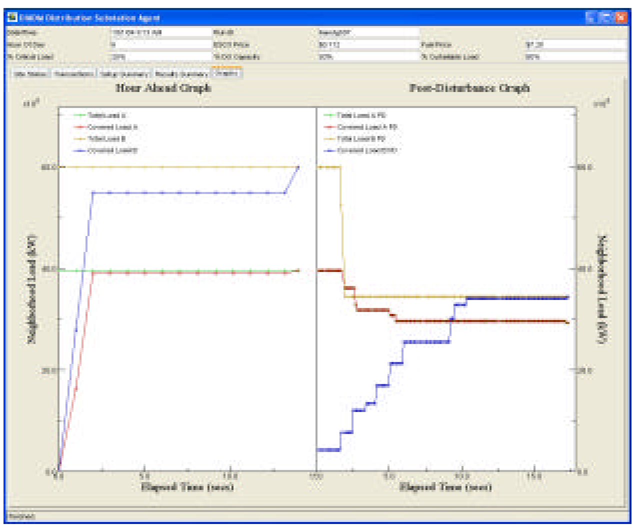
Where Scenario description includes:
Scenario #: Time of Day, Failure Mode, %DG-%Curtailable-%Critical, Fuel Price



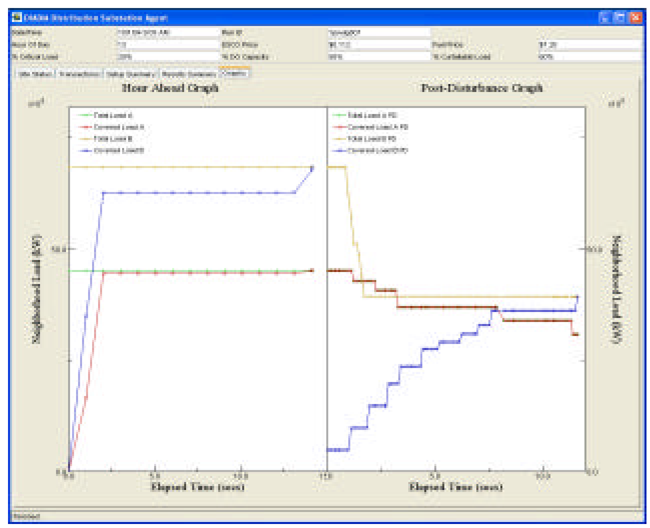
Scenario 18: 1 p.m., 50% A&B, 50-40-20, $7.20



Scenario 19: 1 p.m., 50% A&B, 50-60-20, $7.20



Scenario 20: 1 p.m., 100% B, 50-60-20, $7.20



Scenario 21: 1 p.m., 100% A&B, 50-60-20, $7.20

Where Scenario description includes:
Scenario #: Time of Day, Failure Mode, %DG-%Curtailable-%Critical, Fuel Price