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The enhancement of the electrical energy security of Navy bases within the continental U.S. has been studied using an approach based on modeling and simulation, with the intent to achieve real time control and energy management. The commercially available software packages are reviewed and the most suitable ones are indicated.

A notional base was developed and used for this study. Its format is general enough to be able to be used as a template for each specific Navy installation. Several preliminary simulations using commercial software have been performed on the power system of this notional base addressing a variety of operating scenarios including islanded mode and the impact of wind and solar power sources. Results of steady state and transient operation are also reviewed.
The results of these simulations indicate that existing software packages available today, with proper adaptations, can provide a well validated and consistent process for evaluating power system architectures and technologies and, therefore, can become a valuable tool for the implementation of the described plan for Navy bases.

The study concludes giving the details of the roadmap to move forward in the process of energy security enhancement of U.S. Navy bases through modeling and simulation.

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# Modeling and Simulation Roadmap to Enhance Electrical Energy Security of U.S. Naval Bases

Final Report for
Approaches to Enhancing Naval Energy Security
N00014-11-1-0642

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# 1 Executive Summary

The availability of a continuous energy supply to Navy bases sufficient to carry out their appointed missions has become of critical importance as energy can no longer be seen as a commodity. The enhancement of the electrical energy security of Navy bases within the continental U.S. has been studied, recognizing that the problem does not admit a static solution valid for all time, but is rather a continuous process that needs to be maintained and updated to face changing circumstances and challenges.

This project investigated a model-based approach. The approach is expected to yield the following four very significant benefits:

1. It provides the information needed to operate the system most efficiently during normal operations.

2. It provides the information and control needed to reconfigure the base power system to react to the evolution of emergency situations.

3. It provides the basis for assessing investments in renewable or conventional sources of power. With this model, one can plan for the multi-year evolution of a base power system balancing energy cost and energy security.

4. It is an approach to physical cyber-security for the base power system control that offers additional protection in the event that the supervisory control and data acquisition (SCADA) system of the utility system providing power is compromised.

The model-based approach was selected because the improvement of a base power system is a complex task with a large number of variables and multiple parameters optimization opportunities, needing effective operator's intervention on the system. Even though these attributes make it obvious that a model-based approach is a strong candidate, the choice of a suitable modeling and simulation platform is not self-evident. Since real-time simulation and energy management is highly desirable, the processing of the body of data from field sensors and meters and its output into a readily intelligible format leads also to the requirement of a sophisticated graphical user interface (GUI). The commercially available packages were reviewed and the most suitable ones are indicated.

This project focused not on the development of yet another software package, but on developing the modeling approaches needed to assess the anticipated advantages of model-based control. A notional base was developed to avoid highlighting the capabilities or vulnerabilities of any particular base. So this work is expected to provide a generic approach that can be individualized for each particular base.

Several preliminary simulations using commercial software have been performed on the power system of this notional Navy base. The simulations address a variety of operating situations including base operation with power from the external utility only, powering the base from a combination of the local utility and on-base solar and wind power, islanded operation using an on-base power station, islanded operation using an on-base power station in connection with wind and solar sources, and transient events including a transformer failure and the instabilities that may be induced during the transition to islanded operation.

The results of these simulations are summarized and indicate that existing software packages available today, with proper adaptations, can provide a well validated and consistent process for evaluating power system architectures and technologies and, therefore, can be a valuable tool for the implementation of the described plan for Navy bases.

The impact of emerging technologies, such as photovoltaic arrays and electric vehicles, was also investigated. Using electricity consumption data collected from the civilian sector, the impact to a Navy base's grid was demonstrated though the change in distribution transformer utilization. It is shown that most of the electrical impact on a grid is from photovoltaic arrays rather than electric vehicles.

Finally, a roadmap to move forward in the process of energy security enhancement is proposed. The roadmap is envisioned as being a three step approach:

1. Modeling and simulation validated by data on the existing system (baseline configuration) and extension to new desired configurations (system planning)

2. Gradual implementation of a new system with constant monitoring by direct feedback from deployed meters and sensors and comparison with expected data. Simulations can be run offline at each crucial point prior to implementing a new change. This step will generate a database of possible operational systems with attendant figures of merit and thus, will define a hierarchy of options available to base command.

3. Active intervention on the system via the established interface with the program to
    a. modify parameters settings of distributed hardware to achieve optimal performance (interactive control, possibly in real time)
    b. redefine the system into a different configuration based on previous simulation results (system reconfiguration).

# 2 Program Overview

## 2.1 Background

The U.S. Navy recognizes that energy is no longer simply a commodity but has become a mission-critical capability, and that investment in energy systems must be made carefully, taking into account both the present evolving energy landscape and the Navy's projected future needs. To this end, the U.S. Navy has set for itself some very ambitious goals in regard to the use of renewable energy resources [1]:

1. Derive 50% of naval land-based energy from renewable resources by 2020

2. Half of Naval bases to be net-zero to the grid by 2020

3. >20,000 smart meters among all installations

which dovetail very well with the stated overall Department of Defense goal of 25% renewable energy usage by 2025. While some notable installations have already been put into service, these do not seem to be part of a systematic approach that considers the overall energy needs of the Navy; rather, they appear to have been accomplished either because of specific local circumstances (*e.g.*, China Lake [2]), or perhaps were made in response to emerging energy policies (*e.g.*, San Clemente [3], Coronado [4]).

Since each installation is unique, energy efficiency and security solutions will need to be developed on a case-by-case basis; however, a well validated, consistent process for evaluating power system architectures and component technologies is needed to support the development and implementation of these new concepts. There are also significant policy issues that will need to be addressed not only to enable the implementation of novel energy technology but also to ensure the continued availability of a sufficient energy supply.

The desired solution would have attributes that achieve the following goals:

1. Enhance the ability to fulfill the Navy's organizational mission, particularly in the event of an emergency

2. Be cost effective

3. Reduce dependence on foreign energy resources

4. Minimize environmental impact

5. Ensure a proper level of energy security

This fifth requirement, an adequate level of energy security, may not have made the list only a few years ago, but recent events have demonstrated that it is instead critical to mission success. The term "energy security" is used in this report in the broad sense, to signify actions taken to counteract the following potential vulnerabilities:

- Insufficient energy supply (energy security in the strict sense)

- Compromise of any component of the infrastructure in the energy supply chain (physical security)

- Attack on the supervisory controls and protocols (cyber-security)

Ensuring the security of energy resources and enabling continued operations of military, and possibly nearby local civilian installations in the event of a disruption of the utility supply, is a vital concern [5]. Techniques to enable secure islanding of base installations and ensure the security of communication and control networks for these systems are increasingly being recognized as critical issues.

This study addresses precisely the last point in the list above, insofar as the supply of electric energy is concerned, and outlines a strategy for moving toward a higher level of energy security for Navy bases in the continental USA (CONUS).

Furthermore, this study shows that in general, decisions made to improve energy security also may have beneficial repercussions on some of the other objectives listed above, for example, mission capability and environmental impact.

## 2.2 Approach

This program was structured to assess the feasibility of a model based approach for the design and operation of an electricity distribution grid on a military base. The approach is expected to yield the following four very significant benefits:

1. It provides the information needed to operate the system most efficiently during normal operations.

2. It provides the information and control needed to reconfigure the base power system to react to the evolution of emergency situations.

3. It provides the basis for assessing investments in renewable or conventional sources of power. With this model, one can plan for the multi-year evolution of a base power system balancing energy cost and energy security.

4. It is an approach to physical cyber-security for the base power system control that offers additional protection in the event that the supervisory control and data acquisition (SCADA) system of the utility system providing power is compromised.

Earlier research [6] has shown that the first two benefits are naturally coupled. A power system control approach that can reconfigure the power system for optimum mission effectiveness during an emergency can also optimize the system configuration for maximum efficiency as loads change during normal operation. This has the advantage of not being an emergency system that has to be routinely tested to ensure it is in working condition in the event of an emergency. Rather, it is used daily so there is a high level of confidence that it will be available in emergency conditions. It is also important to realize that this approach provides emergency capability well beyond what one achieves by identifying critical infrastructure and planning for its continued operation. In an extended emergency, the critical infrastructure changes as the emergency changes. This approach permits dynamic response to dynamic situations.

The assessment of investments is critically important. Base commanders are required to choose power sources for their bases in a rapidly changing environment. Renewable technology is changing and improving. In this environment, it is important to make a consistent set of investments over time designed to take advantage of emerging technology while maintaining mission capability at the least cost. The model shows how yesterday's investments can be combined with emerging technologies to provide efficiency and mission effectiveness.

Physical cyber-security is essential, particularly recognizing the vulnerability of SCADA systems. By interfacing a model-based control system with a utility SCADA system, the military base has added protection against intrusions through the utility systems.

This work focused on developing the modeling approaches needed to assess these anticipated advantages of model-based control. A notional base was developed to avoid highlighting the capabilities or vulnerabilities of any particular base. So this work is expected to provide a generic approach that can be individualized for each base.

# 3 Selection of a Modeling Approach

## 3.1 Level of Modeling and Simulation

Key to a successful strategy for ensuring energy security is the method used in the assessment of the present status and the quantification of the potential benefits anticipated from any new course of action. Since extensive measurements and system monitoring are expensive in terms of manpower, physical resources, and time resources, computer modeling and simulations constitute the best tool to achieve our goal. Thus, the selection of a suitable level of modeling and simulation, and of a software platform capable of delivering the needed results, is critical to this research. It should be clear, however, that, given the very special nature of the subject of study, namely the Navy bases in the CONUS, and their broad range of characteristics dictated by the variety of their missions, considerable technology development in the application of the software is necessary to accomplish the task. In fact, it is improbable that commercial software designed for the requirements of conventional electrical utility networks can be used as a turn-key project; but more likely, it will need to be supplemented with specific technical and operational know-how for its successful implementation in enhancing the energy security of Navy bases.

The decision on the correct level of modeling and simulation is guided by the following considerations:

1. Whether real-time simulation and energy management are desirable
2. The variables that need to be calculated
3. The time resolution of these variables (this dictates the time step of the computation)
4. The type and intensity of data processing needed
5. The required degree of interaction among the operator, the deployed monitoring system, and the supervisory program (human interface, integration with existing hardware, interactivity, real-time control)
6. The sophistication of the program output in the form of reports, tabulations, plots, or more importantly, of operational displays (graphical user interface, dashboards, data and system visualization)
7. Interface with the local utility

Each of these items will be examined individually in more details in the following sections.

### 3.1.1 Real-time Energy Management

This is the first choice that should be made when selecting an appropriate software platform. If real-time energy management is desired for base control centers and operators, then it appears there are currently only two software packages capable of integrating both real-time simulation and energy management through virtual dashboards: DesignBase and ETAP. This choice reduces the selection of possible software platforms to two; however, the capabilities of other programs were also examined.

### 3.1.2 Problem Variables

The most important variables to be calculated and monitored are electrical: voltage, current, power (real, reactive, apparent), at both the bus and branch levels. But a choice must be made whether these variables are needed as instantaneous or rms quantities.

Instantaneous quantities provide a high-fidelity insight on the electromagnetic physics of power system at the expense of computation time. RMS quantities provide the measurements used by the utility industry to monitor power systems at significantly reduced runtimes. The tradeoff is fidelity vs. computation time.

For the current research efforts, which do not involve the design of new power apparatus or technologies, the use of rms quantities suffices to assess the impact of enhanced energy security to the utility, as well as inside the base perimeter.

Additional variables of interest are those that permit determining the overall energy efficiency of a given system under a particular operational scenario, which entails knowing the efficiency characteristic of at least the major system components. This would allow meaningful optimization studies.

An evaluation of the reliability of the system would also be of great help in comparing various concepts of operation (CONOPS).

Of further interest would be the ability to estimate the thermal performance of the major components and approximate their heat load on the auxiliary cooling system.

Finally, it would also be desirable to be able to assess the overall size and weight impact of a given assembly or subsystem for those cases where these items are of concern.

### 3.1.3 Computational Details

Three basic considerations can be made in this regard.

1. The incoming utility line power frequency is 60 Hz, which corresponds to a time period of 16.7 ms. Even allowing for power conversion onsite and operations at other frequencies, the power frequency will probably not exceed that used in aircraft equipment, namely 400 Hz with a period of 2.5 ms, and, in fact, if different than 60 Hz, will more likely be in the vicinity of 240 Hz (4.2 ms time period), based on prior work done for the Navy. These anticipated time periods for the main electric power exclude the

need for investigating phenomena at the sub-ms time level. At the system level in such power systems, transients are likely to develop with a minimum time constant in the hundreds of μs. Thus, it seems reasonable to expect the computation time step to be no less than 100 μs in order to avoid any unnecessary computational burden and speed up the calculations.

2. Although there may be interest in the dynamic behavior and impact of a particular component (*e.g.*, a power converter), the performance at the device level (*e.g.*, switching power transistor) is of no concern.

3. The times covered by the calculations are expected to be long, at least minutes, and typically several hours. Therefore, economy of data generated is important for effective use of the system's data storage, and computational speed is important if real-time or near real-time performance is desired.

### 3.1.4 Calculation Types

Commercially-available power system simulation packages can be broadly categorized into two families:

1. Transient simulation programs (*e.g.*, PSCAD, Simulink, EMTP, ATP, VTB, PSim, PSpice, and others) which have traditionally been most useful for problems covering at most a few seconds and with time steps less than 50 μs. The number of components also tends to be limited in order to keep the speed of computation reasonably fast.

2. Distribution system analysis programs (*e.g.*, ETAP, Paladin DesignBase, CYMEDist, EasyPower, PowerFactory, and others). These programs have been used traditionally in the analysis of steady state performance of power systems with up to many tens of thousands of buses. Their central nucleus is a load flow calculation, giving voltage magnitude and phase at each bus and power flow in each branch, around which additional modules are built for short circuit studies, reliability prediction, protective device coordination, transient stability, etc.

At this point, it must be added that the division above is not a rigid one, especially in view of the fact that programs of the first group often have features that belong more properly to the second group and, vice versa, programs of the second group incorporate elements more characteristic of the first. Furthermore, the classification presented above is evolving in time, as programs of one group tend to offer options that would be classifiable under the other. This dynamic landscape, in fact, would seem to point to a perhaps not too distant future when all programs will include all features, from fast transient analysis to steady state performance, under one single umbrella.

At the present time, however, the distinction between transient simulation programs and distribution system analysis programs is still generally valid so that our first decision regarding the software will be based on it. Thus, from what was said in the previous section regarding the typical computation times and time steps of interest in our problem, it appears that programs of the second type are more suitable to our task. Also the number of components involved in the model of an average base is expected to be in the several hundred, which would better fit a distribution system analysis program rather than a transient simulation program.

It is well to reiterate, however, that, in principle, several and possibly all programs listed above, as well as other similar ones not specifically mentioned, could be used in our case. Our choice was based on considerations of practicality and is not meant to be prejudicial.

### 3.1.5 Operator and Distributed Hardware Interface

The enhancement of a base electrical energy security is best achieved by a three step approach.

1. System planning and implementation (modeling and simulation validated by data on a system baseline configuration)

2. Constant monitoring of the implemented system (direct feedback from deployed meters and sensors and comparison with expected data calculated in the simulations)

3. Active intervention on the system via the established interface with the program to modify parameters settings of distributed hardware to achieve optimal performance (interactive control, possibly in real time), or to redefine the system into a different configuration based on previous simulation results (system reconfiguration)

In regard to the interface between software and hardware, both families of programs (transient simulation and distribution system analysis) identified in the previous section have at least some means to allow processing of data from peripheral units and remote control of hardware from program outputs. However, the transient simulation programs tend to be geared toward smaller systems, like laboratory hardware-in-the-loop demonstrations, whereas distribution system analysis programs have been designed for much larger systems, like those found in a typical utility, and when they do offer this dynamic interface it allows intervention on a large scale (thousands of feedback and control points). Therefore, the ability to interface with multiple peripheral sensors and controllers strongly favors the choice of a program from the second family for our base energy security enhancement project.

### 3.1.6 Graphical User Interface

The preference of a program of the distribution system analysis type is even more manifest if one considers the graphical display capabilities, which tend to be much more developed in programs of the second group than in the first. The reason is probably historical in that distribution system analysis programs were developed from the start with the electric utility in mind, where extensive displays of control gauge arrays and dashboard-type human interface has been the norm for decades. On the contrary, transient simulation programs have their origin in the calculation needs of device and subsystems engineering, where the display of data was designed to mimic laboratory oscilloscopes rather than macroscopic system information centers.

### 3.1.7 Interface with Local Utility

This point is definitely in favor of distribution system analysis programs since it is very likely that the local utility, with which the base has to interface, is actually using one of these programs already. Using analogous software types will certainly simplify the management of the tie point between the two systems.

### 3.1.8 Software Choice

Based on all considerations outlined above, the decision was made to use a program of the distribution system analysis family. Table 1 shows the distribution system analysis software packages examined in the course of this study. The examination was done within the rather stringent time and funding constraints of this work and, therefore, is not exhaustive and certainly not as in depth as would be necessary.

Because of the value of real-time validation and control, an effort was made to identify packages with real-time capabilities, namely able to "stream" data in real time from smart meters, relays, and other sources through existing SCADA systems. This capability can be very important for asset management and emergency response.

Furthermore, our interest was also directed at identifying software packages that could do, offline, a large sequence of load flows on the same system based on data collected from the field by smart meters, sensors, etc. For example, if data were collected at each minute during the day, this would require running 1,440 load flows, each with its own set of inputs, and producing plots of electrical variables versus time at all points in the system. This is referred to as time domain load flow.

As can be seen, no software package has all the desired characteristics [7]. Additionally, all would have to be adapted by the user to the modeling and simulation needs of the CONUS Navy bases. This means that no software package can fulfill all the needs of our specialized application in its "as is" state becoming a turn-key task, but a fair amount of what can be called technology development is necessary before it becomes a useful tool for Navy personnel and planners.

Table 1. Distribution system analysis software programs surveyed by UT-CEM in this study

| | **Paladin** | **ETAP** | **Sim Power** | **CYMDist** | **OpenDSS** | **GridLab-D** |
|---|---|---|---|---|---|---|
| **OpenSource** | No | No | No | No | Yes | Yes |
| **Renewables** | Yes | Yes | Partial | Yes | Yes | Yes |
| **EVs** | No | No | No | No | No | No |
| **Price-Influenced Loads** | No | No | No | No | No | Yes |
| **Energy Storage** | Yes | Yes | Yes | No | Yes | Yes |
| **Geo-display** | with follow-on product | with follow-on product | No | Yes | Partial | No |
| **Learning Curve** | Moderate | Moderate | Smooth | Moderate | Steep | Steep |
| **GUI** | Yes | Yes | Yes | Yes | Yes | No |
| **Custom Models** | Yes | Yes | Yes | No | - | - |
| **Time Domain Transient** | Partial | Partial | Yes | - | - | - |

To demonstrate the capabilities of distribution analysis (load flow) software, Paladin DesignBase was used to run the examples shown later in this report. The choice was based on the fact that this is one of the two tools that integrate real-time simulation and live energy management.

Moreover, the choice was influenced by the ease of obtaining access to the software on a trial basis, for an extended period of time, and with as few limitations as possible. Thus, the program used was the module DesignBase version 4, part of the Paladin family. This does not represent an endorsement of the product to the detriment of others, as the same examples could have been run with other packages. As said previously, our limitation stemmed from the finite resources of time and funds available for this project.

## 3.2 Development of a Notional Navy Base

### 3.2.1 Topographical Layout

To determine quantitatively the suitable level of modeling and simulation for a correct assessment of the energy security status of a U.S. Navy base and to demonstrate that the selected approach is the proper tool for the prudent upgrading of a base electric power system, a notional Navy base was developed. This was done after reviewing the wide variety of existing Navy installations in the CONUS: coastal bases, land bases, extended over a small or large area, located in all climate zones, etc. The intent was to develop a notional base that, while not aiming at duplicating the characteristics of any base in particular, incorporated the distinctive features of all in such a manner that it could function as a reference template, so to speak, with which one could generate significant models of actual bases by proper modification of the template parameters. Thus, it is hoped that the notional base can provide the engineering basis for a smooth transition from the technical R&D to an effective implementation on a real facility. In particular, the intention was to define a tool for the following practical objectives:

- Develop a template for a base general enough to be applicable to most real life implementations
- Define its optimal electrical system architecture
- Estimate the needed infrastructure
- List the equipment supporting the expected loads
- Assess the general power requirements at each load center and overall
- Anticipate the possible reconfiguration schemes based on expected operational scenarios and their impact on the various components
- Determine required redundancies
- Assess system stability and protection in all expected configurations
- Study power quality issues and transient effects on system performance
- Establish component stress levels and required rating
- Estimate needed amount and type of renewable energy
- Estimate needed amount and type of energy storage
- Gain insights into the required control scheme and security thereof
- Evaluate potential vulnerabilities to energy security and design effective countermeasures
- Develop management plans for extended utility power outages and islanded operation
- Provide an effective tool for personnel training

The general layout of the notional base used in this study is shown in Figure 1, and the details about its internal make-up are given in the following section.

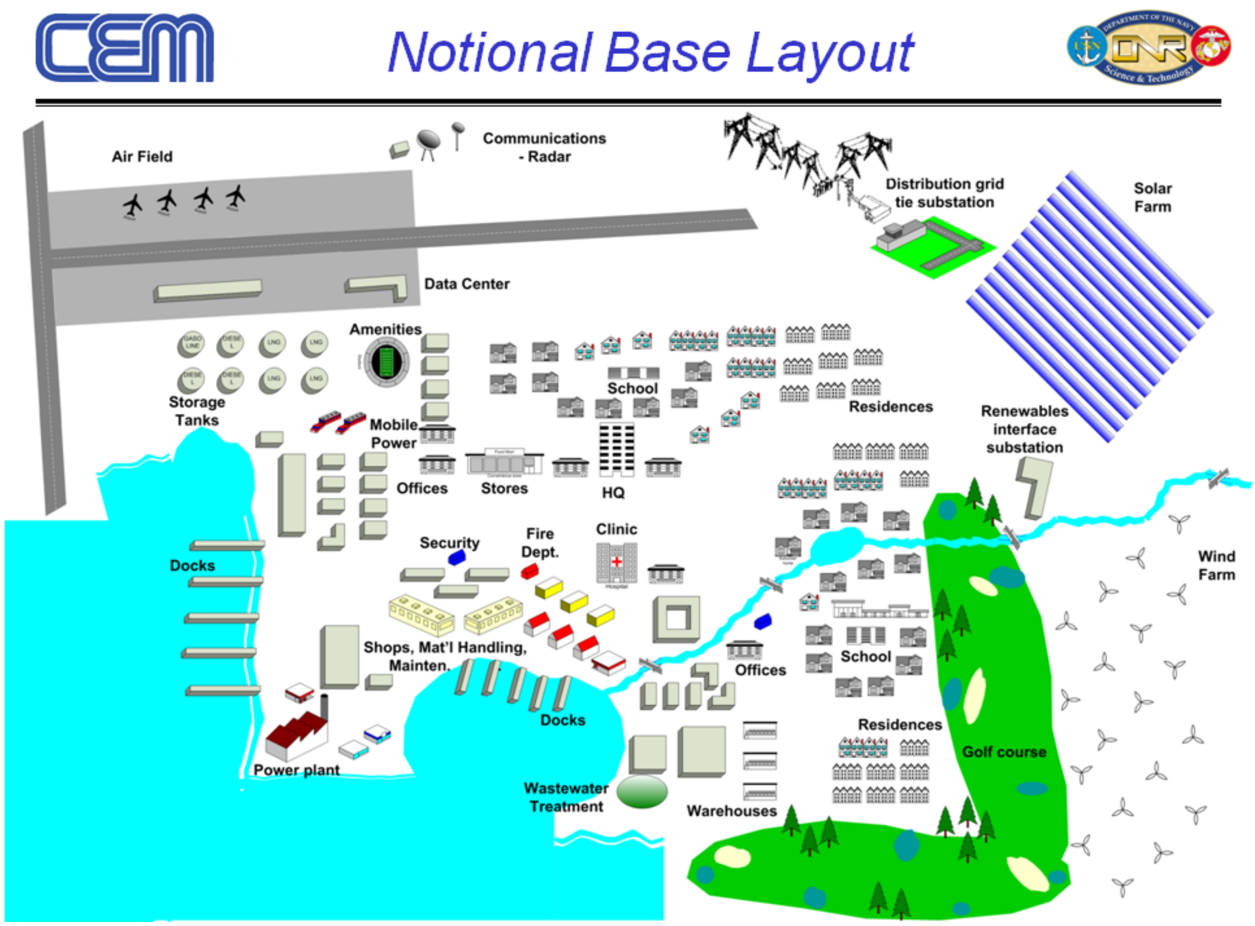


Figure 1: Geographical layout of the notional CONUS Navy base.

### 3.2.2 Notional Base Details

Data for the notional base composition were entered and processed initially via a spreadsheet. The inputs required can be grouped in the following categories:

- Make-up of on-base and off-base personnel (number and basic demographic data)
- Local availability of renewable energy resources
- Possible abnormal conditions (duration, level of service, load classification)
- Desired make-up of energy storage

The spreadsheet estimates the following requirements:

- Number and types of buildings
- Infrastructure needed
- Power available from renewable energy resources
- Energy storage inventory required
- Total installed power capacity
- Power required by the various base functions at different levels of emergency
- Base survivability during emergencies.

**NOTIONAL NAVY BASE**

**ELECTRIC POWER ONLY - ESTIMATED NEEDS (EXCLUDING NUCLEAR)**

| | INPUTS | REF. |
|---|---|---|
| **OFFICERS** | | |
| Number of officers | 100 | |
| Percent of officers with family | 75 | |
| Officer residences per bldg. cluster | 4 | |
| Single Officer Residence sq.ft. | 845 | 845 |
| Percent officers working in office | 80 | |
| **NON-OFFICERS** | | |
| Number of non-officers | 900 | |
| Percent of non-officers with family | 25 | |
| Non-officer residences per bldg. cluster | 10 | |
| Single Non-officer residence sq.ft. | 500 | 845 |
| Percent non-officers working in office | 40 | |
| **OFF-BASE PERSONNEL** | | |
| Number of off-base personnel - office | 500 | |
| Office sq.ft./person | 750 | 890 |
| Number of off-base personnel - shop | 400 | |
| Shop sq.ft/person | 1500 | |
| Number of off-base personnel - other | 100 | |
| **DEMAND FACTORS** | | |
| Peak/average power, residence | 3 | |
| Peak/average power, office | 1.5 | |
| Peak/average power, shop | 4 | |
| Peak/average power, clinic | 5 | |
| Peak/average power, fire & security sta. | 2 | |
| Overall peak/average power | 1.25 | |
| **ABNORMAL CONDITIONS** | | |
| Abnormal conditions duration, days | 30 | |
| Level of service during abnormality, % | 100 | |
| **RENEWABLES** | | |
| Wind farm land area, km^2 | 2.5 | |
| Wind turbine rated power output, MW | 1.5 | |
| Wind-mill distribution density, no./km^2 | 6 | |
| Wind power utilization factor | 0.25 | |
| Solar farm land area, km^2 | 1 | |
| Average local insolation, W/m^2 | 150 | |
| Solar-electrical conversion efficiency, % | 12 | |
| Solar power utilization factor | 0.25 | |
| **ENERGY STORAGE** | | |
| Gasoline storage, % | 20 | |
| Diesel storage, % | 50 | |
| LNG storage, % | 30 | |

| | BUILDINGS |
|---|---|
| **RESIDENCES** | |
| Number of officers with family | 75 |
| Number of single officers | 25 |
| Number of clusters - officer with family | 19 |
| Number of clusters - single officer | 7 |
| Officer with family residence sq.ft. | 1267 |
| Total number of officers and family members | 218 |
| Number of non-officers with family | 225 |
| Number of single non-officers | 675 |
| Number of clusters - non-officer with family | 23 |
| Number of clusters - single non-officer | 68 |
| Non-officer with family residence sq.ft. | 750 |
| Total number of non-officers and family members | 1254 |
| **OFFICES** | |
| Officers working in office | 80 |
| Non-officers working in office | 360 |
| Total personnel - office work | 940 |
| Total office area, sq.ft. | 705000 |
| Number of large office buildings (100,000 sq.ft.) | 4 |
| Number of small office buildings (14,000 sq.ft.) | 22 |
| **REPAIR SHOPS, MAT'L HANDLING, MAINTENANCE, ETC.** | |
| Officers working in shop | 20 |
| Non-officers working in shop | 540 |
| Total personnel - shop work | 960 |
| Total shop area, sq.ft. | 1440000 |
| Number of large shop buildings (200,000 sq.ft.) | 4 |
| Number of small shop buildings (30,000 sq.ft.) | 21 |
| **SCHOOLS** | |
| Number of spouses on base | 300 |
| Number of children on base | 172 |
| Number of school buildings | 2 |
| Total school area, sq.ft. | 27800 |
| **AMENITIES, STORES, GYMS, CLUBS, CINEMAS, ETC.** | |
| Total number of on-base people | 1472 |
| Total number of off-base people | 1000 |
| Number of general purpose buildings | 2 |
| Average area of general purpose building, sq.ft. | 32126 |
| Total area general purpose buildings, sq.ft. | 64252 |
| **INFRASTRUCTURE (CLINIC, FIRE STATION, STREETS)** | |
| Clinic, sq.ft. | 12472 |
| Fire Station, sq.ft. | 10000 |
| Security Stations, sq.ft. | 20000 |
| Street average width, ft. | 60 |
| Illuminated street length, miles | 5 |
| Street surface area, sq.ft. | 1584000 |
| Wastewater treatment plant, kW/person | 0.2 |
| Water pump, kW/person | 0.33 |
| **BASE OPERATIONS (RADAR, COMMUNICATIONS)** | |
| Estimates | |

| | RENEWABLES POWER |
|---|---|
| **WIND** | |
| Peak wind power, MW | 23 |
| **SOLAR** | |
| Peak solar power, MW | 18 |

| | REQUIRED POWER | PERCENT LOAD RETENTION FOR DESCRIBED ABNORMALITY LEVEL: EXTREME | CRITICAL | SEVERE | MILD | NORMAL |
|---|---|---|---|---|---|---|
| Number of on-base households | 1000 | | | | | |
| Average power per household, kW | 1.31 | | | | | |
| Peak power per household, kW | 3.93 | | | | | |
| Total peak houses electric power, MW | 3.93 | 0 | 0 | 30 | 70 | 100 |
| Average power per office worker, kW | 3.85 | | | | | |
| Average power office, kW/sq.ft. | 0.004445 | | | | | |
| Average power, office (worker base), MW | 3.62 | | | | | |
| Average power, office (area base), MW | 3.13 | | | | | |
| Average power required, office, MW | 3.62 | | | | | |
| Total peak offices electric power, MW | 5.42 | 10 | 20 | 50 | 70 | 100 |
| Average power per shop worker, kW | 7.69 | | | | | |
| Average power shop, kW/sq.ft. | 0.008890 | | | | | |
| Average power, shop (worker base), MW | 7.38 | | | | | |
| Average power, shop (area base), MW | 12.80 | | | | | |
| Average power required, shop, MW | 12.80 | | | | | |
| Total peak shop electric power, MW | 51.21 | 10 | 30 | 60 | 80 | 100 |
| Average power schools, kW/sq.ft. | 0.004445 | | | | | |
| Average power, schools, MW | 0.124 | | | | | |
| Total peak school electric power, MW | 0.19 | 0 | 0 | 20 | 60 | 100 |
| Average yearly energy g.p. bldg., kWh/sq.ft. | 22.44 | | | | | |
| Average power g.p. bldgs., kW/sq.ft. | 0.005123 | | | | | |
| Average power, g.p. bldgs., MW | 0.329 | | | | | |
| Total peak gen. purp. bldgs electric power, MW | 0.49 | 0 | 0 | 20 | 60 | 100 |
| Clinic power, MW | 0.28 | 20 | 30 | 60 | 80 | 100 |
| Fire station power, MW | 0.09 | 20 | 30 | 60 | 80 | 100 |
| Security station power, MW | 0.18 | 20 | 30 | 60 | 80 | 100 |
| Street lighting power, MW | 0.06 | 10 | 20 | 40 | 70 | 100 |
| Wastewater treatment plant, MW | 0.49 | 20 | 30 | 60 | 80 | 100 |
| Water pump, MW | 0.82 | 10 | 20 | 40 | 70 | 100 |
| Radar, MW | 1 | 100 | 100 | 100 | 100 | 100 |
| Communication, MW | 0.1 | 100 | 100 | 100 | 100 | 100 |
| Air Field, MW | 0.5 | 100 | 100 | 100 | 100 | 100 |
| Data Center, MW | 1 | 100 | 100 | 100 | 100 | 100 |
| Total required installed electric capacity, MW | 66 | | | | | |
| Required power under abnormal conditions, MW | | 9 | 20 | 38 | 52 | 66 |
| Base survivability under abnormal conditions, days | | 230 | 101 | 51 | 38 | 30 |

| NORMAL | MILD | SEVERE | CRITICAL | EXTREME |
|---|---|---|---|---|
| 66 | 52 | 38 | 20 | 9 |
| 30 | 38 | 51 | 101 | 230 |

| | STORAGE REQUIRED |
|---|---|
| **STORAGE REQUIRED** | |
| Energy required in abnormal period, MWhe | 37877 |
| Probable energy from renewables, MWhe | 7290 |
| Net energy required from storage, Mwhe | 30587 |
| **GASOLINE TANKS** | |
| Energy stored as gasoline, Mwhe | 6117 |
| Gasoline energy content, kWh/gal | 33.41 |
| Gasoline coversion efficiency to electric, % | 20 |
| Amount of gasoline to be stored, gal | 915513 |
| Above ground storage tank capacity, gal | 500000 |
| Underground storage tank capacity, gal | 10000 |
| Number of above ground gasoline tanks | 1 |
| Number of underground gasoline tanks | 42 |
| **DIESEL TANKS** | |
| Energy stored as diesel, Mwhe | 15294 |
| Diesel energy content, kWh/gal | 37.95 |
| Diesel coversion efficiency to electric, % | 20 |
| Amount of diesel to be stored, gal | 2014973 |
| Above ground storage tank capacity, gal | 500000 |
| Underground storage tank capacity, gal | 10000 |
| Number of above ground diesel tanks | 4 |
| Number of underground diesel tanks | 2 |
| **LNG TANKS** | |
| Energy stored as LNG, Mwhe | 9176 |
| LNG energy content, kWh/gal | 21.98 |
| LNG coversion efficiency to electric, % | 20 |
| Amount of LNG to be stored, gal | 2087395 |
| Above ground storage tank capacity, gal | 500000 |
| Underground storage tank capacity, gal | 10000 |
| Number of above ground LNG tanks | 4 |
| Number of underground LNG tanks | 9 |

| | POWER |
|---|---|
| **MOBILE GENERATING UNITS** | |
| Unit 1, MW | 1 |
| Unit 2, MW | 1 |

| BASIC LOAD FLOW | MW | PF | kVA |
|---|---|---|---|
| Residences 1 | 2.45 | 0.85 | 2.88 |
| Communications | 1.1 | 0.9 | 1.22 |
| Offices 1 | 3.50 | 0.88 | 3.98 |
| Data Center | 1 | 0.95 | 1.05 |
| Air Field | 0.5 | 0.85 | 0.59 |
| Tanks / Shops | 15.36 | 0.82 | 18.73 |
| Mtl. Handling / Shops | 20.48 | 0.8 | 25.60 |
| Warehouses / Offices 2 | 17.53 | 0.83 | 21.12 |
| HQ / Clinic / etc. | 1.92 | 0.89 | 2.15 |
| Residences 2 - School | 1.67 | 0.85 | 1.96 |
| Renewables Interface | 1 | 0.9 | 1.11 |
| Total | 66.51 | | |

**Conductor Ampacity for total power required**

| 34500 Vac | 25000 Vac | 12470 Vac | 4160 Vac |
|---|---|---|---|
| 1100 | 1519 | 3045 | 9126 |

Figure 2: Front page of Excel spreadsheet for estimating the composition of the notional base.

The front page of the spreadsheet is shown in Figure 2 as a general reference for orientation only. The actual electronic spreadsheet is included with this report as part of the deliverables package.

The user should have no difficulty in using the spreadsheet, as the items are grouped into logical categories and are well labeled. As guidance, the following color coding has been adopted:

- Required inputs are shaded in yellow
- Reference data that may be adjusted are shaded in red
- Calculated items of interest are shaded in green

Every effort has been made to base the spreadsheet calculations on verifiable data. Much of the supporting information has been tabulated in sheets two and three of the same spreadsheet. These additional sheets, not shown in this report, contain data about residential and commercial building energy usage retrieved from documentation available from the websites of the Department of Energy (DOE) [8], [9], [10], [11], [12], the National Renewable Energy Laboratory (NREL) [13], and other sources [14], [15], [16], [17]. Some supplementary information has also been obtained from papers and textbooks and, being of a rather basic reference material type, should be of general acceptance, save for possible minor changes (*e.g.*: diesel fuel energy content figures).

Where necessary, some assumptions had to be made to generate a working model (*e.g.*, that a married officer needs 50% more living space than a single one), but these have been kept to the bare minimum and can be changed. It is hoped that the spreadsheet, as constructed at present, provides at least a framework that can easily be completed as necessary and adapted to the actual needs without excessive rework, once better information becomes available.

The sample base that was used in this study has the following characteristics:

- 1,000 on-base personnel
- 1,000 off-base personnel
- Nominal maximum renewable power capacity:
  - Wind 23 MW
  - Solar 18 MW

The energy storage inventory consists of the following:

- Gasoline: 1 above ground tank (500,000 gal) and 42 underground tanks (10,000 gal)
- Diesel: 4 above ground tanks (500,000 gal) and 2 underground tanks (10,000 gal)
- LNG: 4 above ground tanks (500,000 gal) and 9 underground tanks (10,000 gal)

As mentioned above, the spreadsheet calculations are based on available published data. For example, to estimate the average power ***Pob*** required in an office building, the following procedure is used:

***Pob*** *= Max{* ***Pow * Now, Poa * Soa*** *},*

where

***Pow*** *= Average power per office worker = (MWh/worker/year) *1000 / [52* (Hours/week)]*

***Poa*** *= Average power per office unit area = (kWh/unit area/year) / [52* (Hours/week)]*

***Now*** *= Number of office workers (calculated based on inputs)*

***Soa*** *= Surface area of office (calculated based on inputs)*

and the figures for *(MWh/worker/year)* and *(kWh/unit area/year)* are obtained from the sources cited previously.

Based on the DOE and NREL data, and making some assumptions regarding energy consumption and renewable resources availability, as can readily be appreciated examining the details of the spreadsheet, it is expected that this notional base would need 66 MW of installed conventional power generation capacity, and that it would be able to survive for 30 days operating continuously at rated load.

If an emergency situation were to occur, the base command would respond in a manner adequate to the perceived threat. For sake of argument, four levels of emergency have been envisioned for the notional base, which are labeled somewhat loosely in order of increasing severity as mild, severe, critical, and extreme, with no attempt to quantify them in terms of a specific numerical index. The only general expectation is that, as the severity of the emergency increases, the base command would progressively reduce the energy consumption, starting from the more discretionary loads, trying to keep the more vital loads powered as long as possible. A typical result of this exercise is a plot like the one shown in Figure 3 that shows the length of time the base is expected to maintain its operations under conditions of various reductions of energy consumption. For additional details, the reader is encouraged to look into the actual structure of the spreadsheet.

These are rather macroscopic results. More detailed performance can be obtained only after a model of the electrical infrastructure of the base and of the loads present therein is made. As was explained in a previous section of this report, this model was developed using the commercial software module DesignBase, provided by Paladin for practical reasons, although the same task could have been accomplished with other programs. DesignBase is only one and the most foundational of three major modules making up the complete Paladin design software suite. It allows the user to perform the basic simulations familiar to engineers working in the electric power utility field: power flow, load stability, fault analysis, protective device coordination, transient analysis, and harmonic analysis. The other two modules have the following functions:

- Paladin Live: Allows the real-time monitoring of a power system via direct feedback from meters and other peripherals
- Paladin SmartGrid: Allows the real-time management of a grid that includes nonconventional energy resources

Whereas DesignBase provides the necessary calculation engine to model and simulate a power system, the most advanced graphic capabilities of the Paladin family are contained within the Paladin Live and Paladin SmartGrid modules. With these it is possible to display the results of the simulations and of the data obtained in real time from the meters installed throughout the system on a true shipboard energy dashboard screen. Consistent with the resources of this study, it has not been possible to engage the real-time and display capabilities of Paladin Live and Paladin SmartGrid, which would have given a dramatic visualization of what can be achieved with state of the art software when properly adapted to the modeling and simulation needs of Navy bases. The results obtained with DesignBase are discussed in the next section.

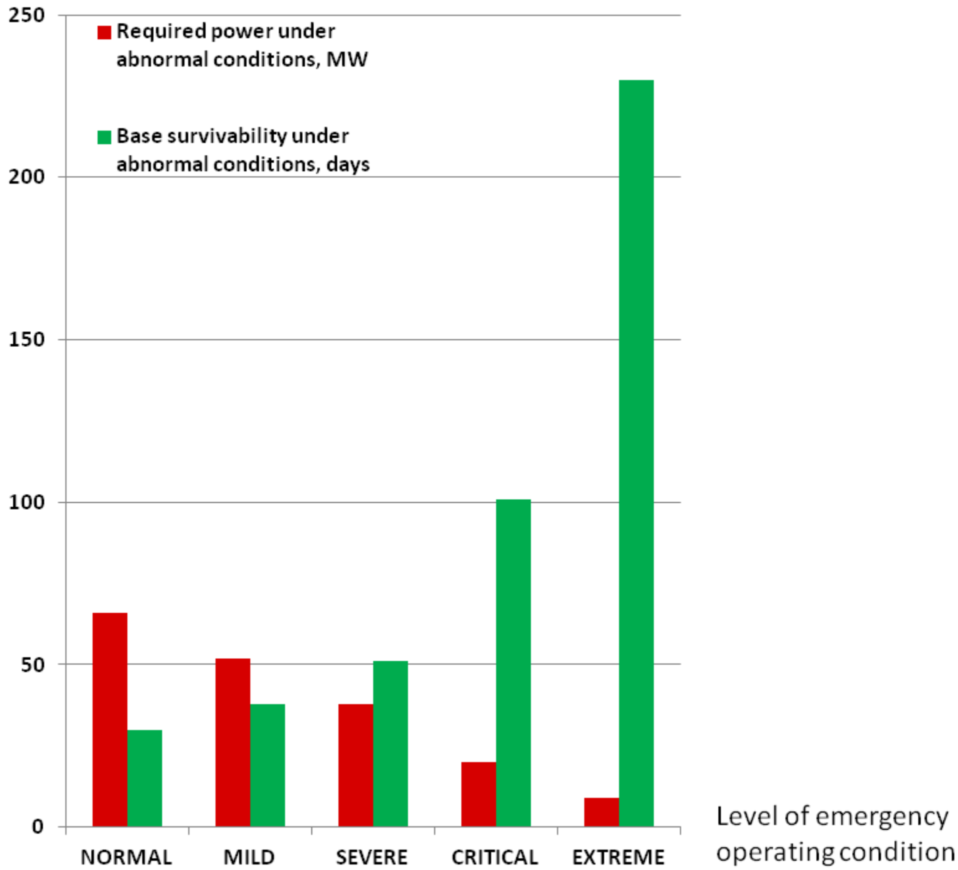


Figure 3: Typical base survivability projection in response to various levels of emergencies.

### 3.2.3 Electrical Diagram of the Notional Base

In order to proceed with the modeling of the notional base, it is necessary to decide first on a topology for the electrical system. Many different schemes have been used by utilities, but the special nature of the system in question and the criticality of its mission demand that reliability of service and redundancy take precedence over other considerations, including cost. Therefore, it can be assumed that some form of distribution architecture based on a double circuit be used, as shown schematically with its major distribution lines in Figure 4. It is further assumed that these circuits and their service feeds and loads are interconnected according to the so-called breaker-and-a-half scheme. This is justified on the basis that, whereas a comparison of various configurations is complex, system and mission specific, and with figures of merit giving only general guidance, the breaker-and-a-half scheme is one of the most practical and reliable ones [18], [19].

This topology is illustrated schematically for convenience in Figure 5: it consists of two separate buses at the same voltage and to which all loads are tied via local breakers. Additionally, connections between the two rails are possible at regular intervals by means of cross-over breakers that are normally open but can close if needed to reroute power. Thus, this distribution scheme resembles a step ladder where the sides of the ladder are the two main buses and the rungs are the load breakers plus the cross-over breakers.

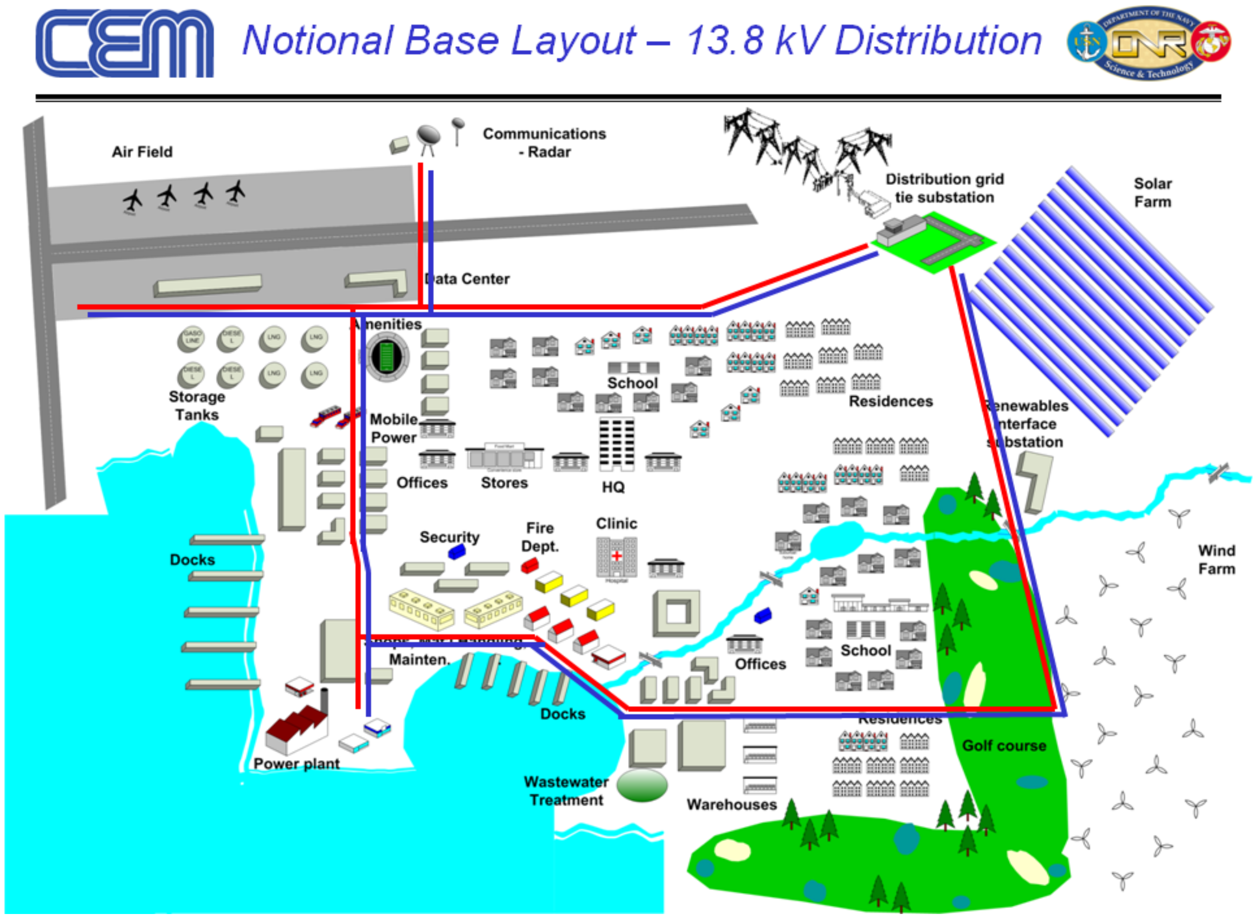


Figure 4: Layout in a double circuit topology for the major distribution lines (red and blue).

Power from the local utility providing electric service to the base is assumed to be at 34.5 kV. This voltage is transformed down to a 13.8 kV distribution voltage by two transformers (Transformer 1 and Transformer 2 in subsequent diagrams), each handling the loads on one of the two rails of the breaker-and-a-half topology.

Thus, keeping in mind the layout of Figure 4, where the major loads are identified, and the topology of Figure 5, one can derive the one-line electrical diagram shown for clarity in two sections in Figure 6 and Figure 7. This and all subsequent models shown in this report are available in electronic form as part of the deliverables package of this project. Although difficult to read, they are included here as figures within the narrative for ease of reference in the use of the software.

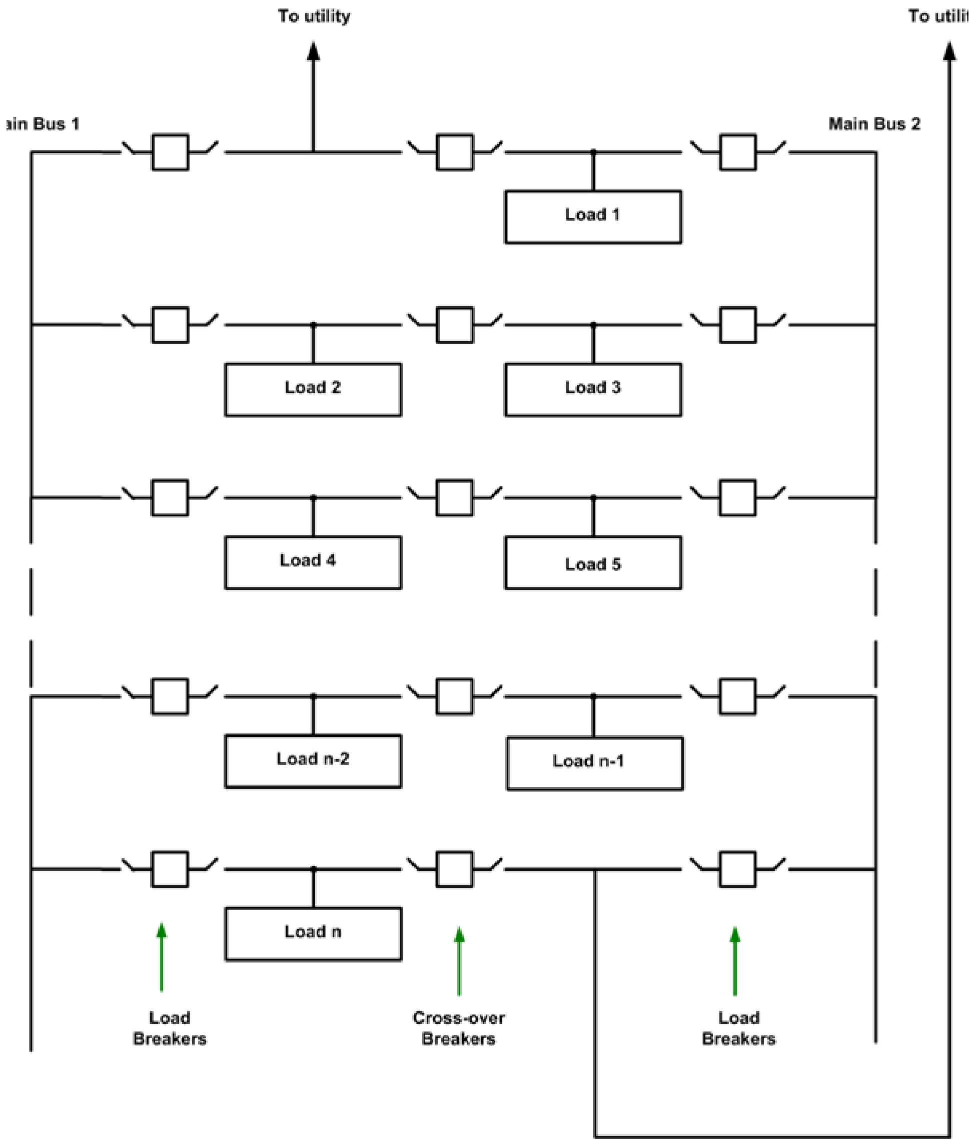


Figure 5: Schematic diagram of the breaker-and-a-half topology used for the notional base.

Even as shown implemented at the distribution level, the system is composed of several elements as listed in Table 2, some of which are themselves the aggregate of many others.

With the model of the base implemented with Paladin's DesignBase, several calculations can now be performed and some of them will be described in the following sections.

Table 2: Composition of Notional Base at the distribution level

| ITEM | NUMBER |
|---|---|
| **Buses** | 58 |
| **Branches** | 63 |
| **Circuit Breakers** | 18 |
| **Major Load Points** | 12 |

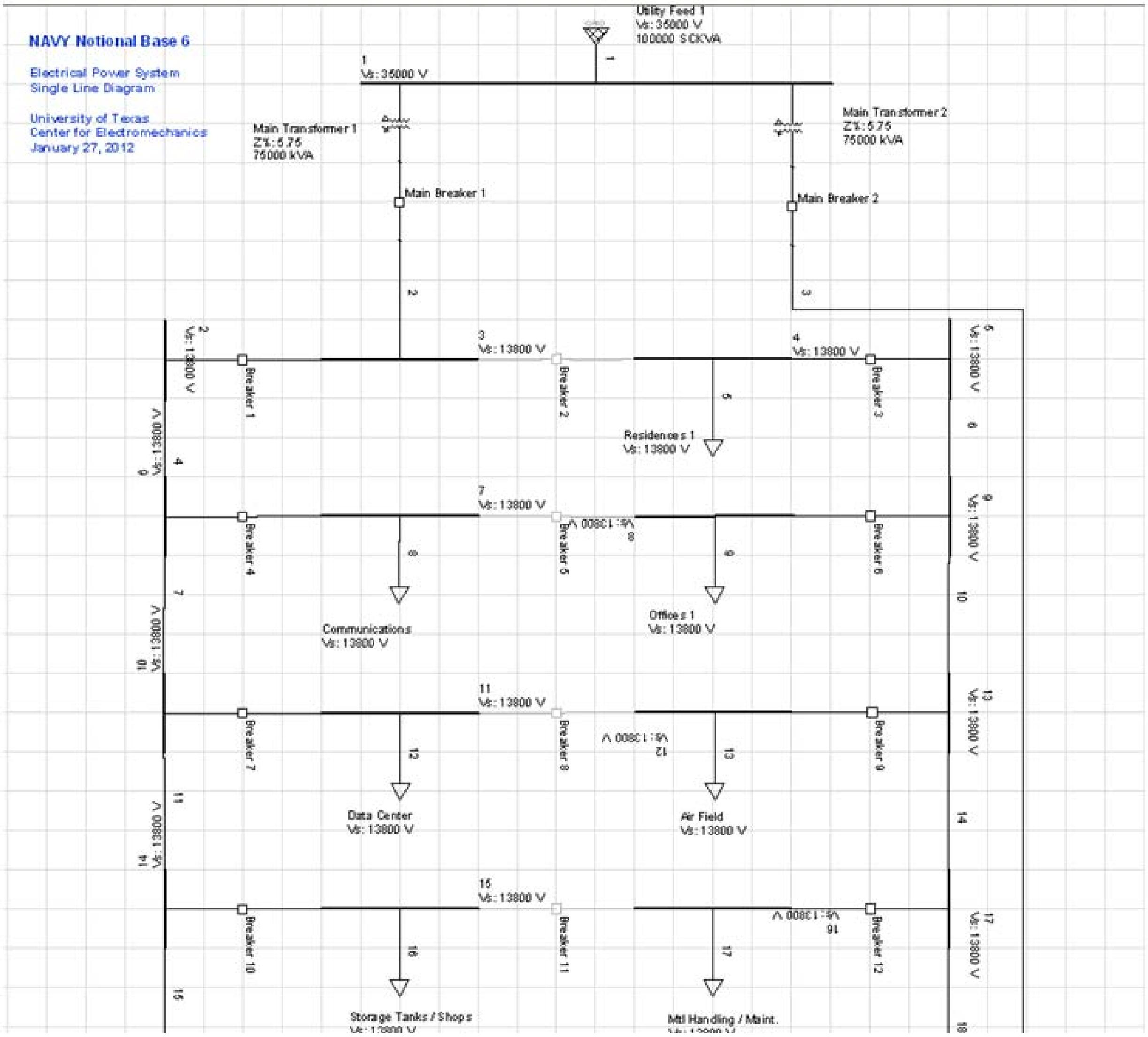

Figure 6: Upper half of the diagram of the base distribution system (breaker-and-a-half scheme).

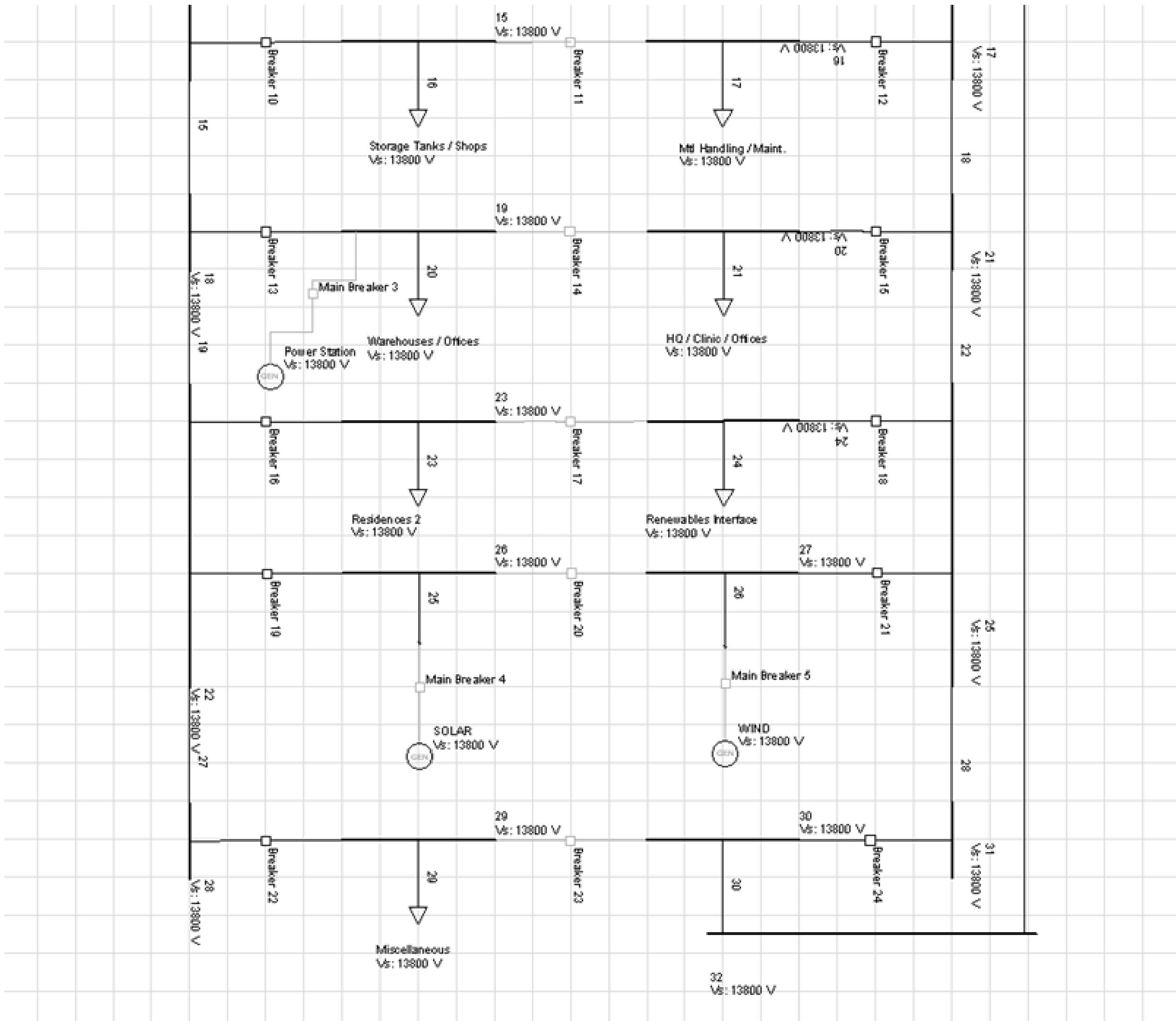


Figure 7: Lower half of the diagram of the base distribution system (breaker-and-a-half scheme).

### 3.3 Simulation Results

The modeling approach was applied to the power system of the notional base to help assess the utility of the model-based approach. The select screen shots are indicative of the available capabilities and serve as reference guides in using the software (electronic versions of all simulations are included in the deliverables package). The simulations address a variety of operating situations, including base operation with power from the external utility only, powering the base from a combination of the local utility and on-base solar and wind power, islanded operation using an on-base power station, islanded operation using an on-base power station in connection with wind and solar sources, and transient events including a transformer failure and the instabilities that may be induced during the transition to islanded operation.

Figure 8 shows a synthetic view of the power system circuit diagram identifying some of the components that will be referred to in several of the subsequent simulation runs discussed. The principal items of interest are labeled. Notice that the circuit as shown is not complete and three sections have been omitted from the figure (dotted lines).

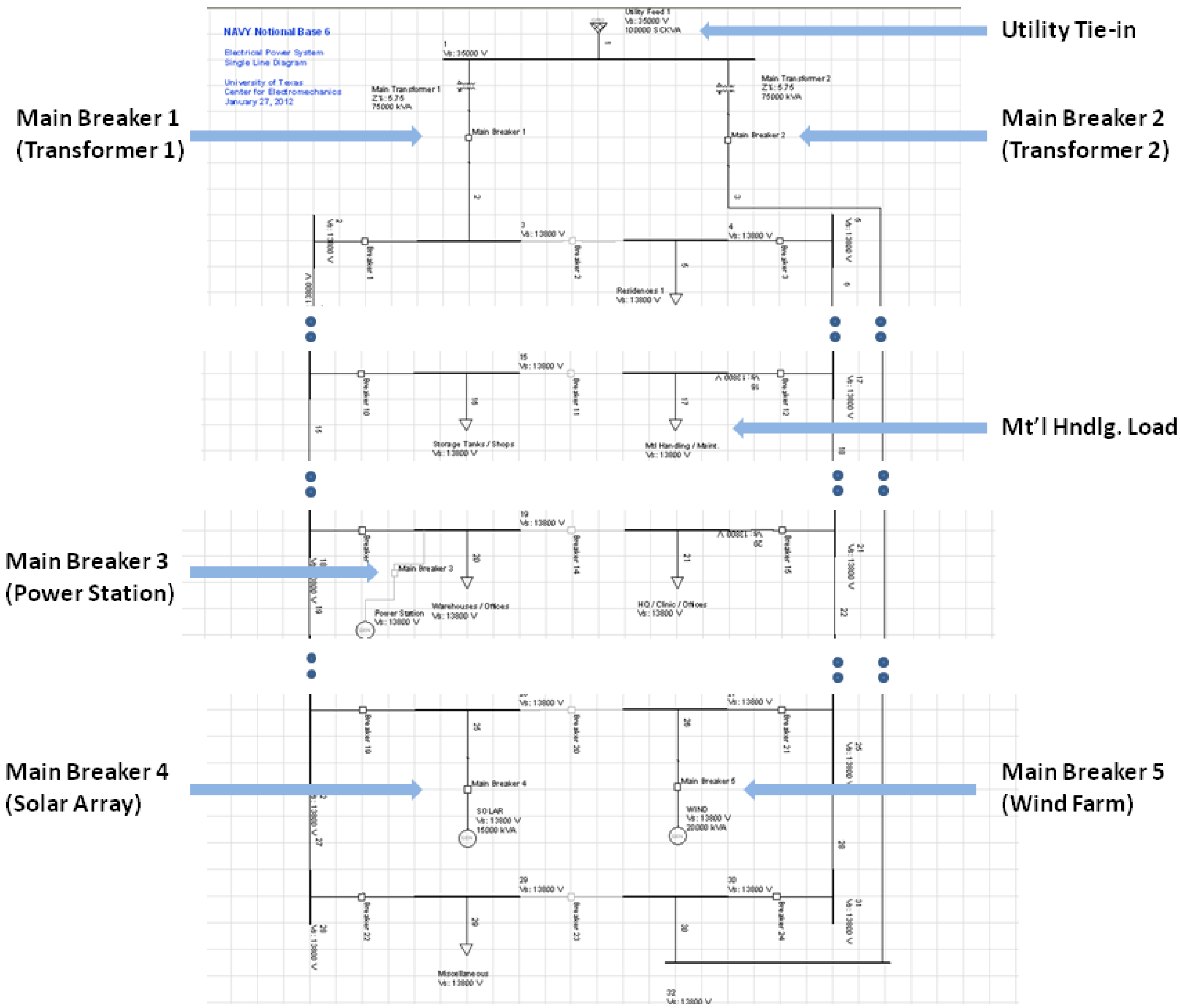


Figure 8: Baseline system.

### 3.3.1 Steady State Analyses

#### 3.3.1.1 Utility Only (Baseline System)

If Main Breakers 1 and 2 are closed in the circuit of Figure 8 and Main Breakers 3-5 are open, the base is connected to the utility supply only. This will be called the baseline system. The resulting load flow calculations show that the total base load is roughly evenly split between the two main branches, 32.9 MW from the branch powered by Transformer 1 and 25.5 MW from the branch powered by Transformer 2, for a total of 58.4 MW (Figure 9).

The point where the voltage level is lowest occurs at the Material Handling Load location. The voltage at that point is 12,460 V, down 9.71% from the rated voltage of 13,800 V. This would indicate that the present bus conductors can barely maintain the voltage within 10% of rated even under normal operating conditions. One possible explanation is that the base growth in time may have outrun the capacity of the electrical infrastructure which should, therefore, be upgraded. Figure 10 shows the readings at both the utility tie-in and at the Material Handling Load station. A complete summary of the voltages at various buses can be seen in Figure 11.

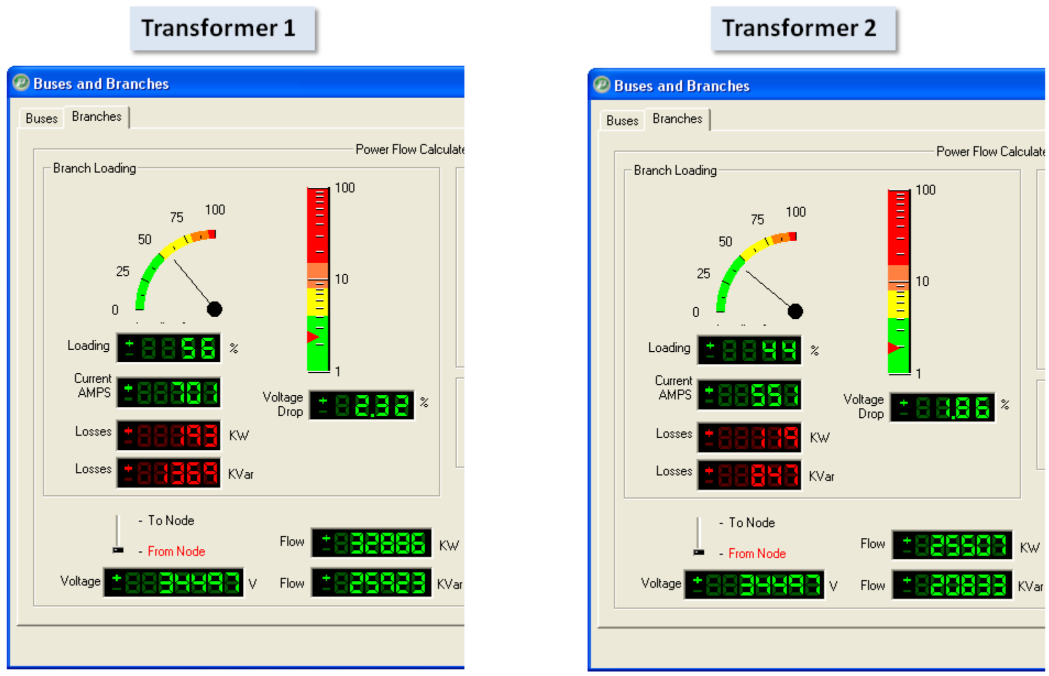


Figure 9: Baseline system Load Flow calculations.

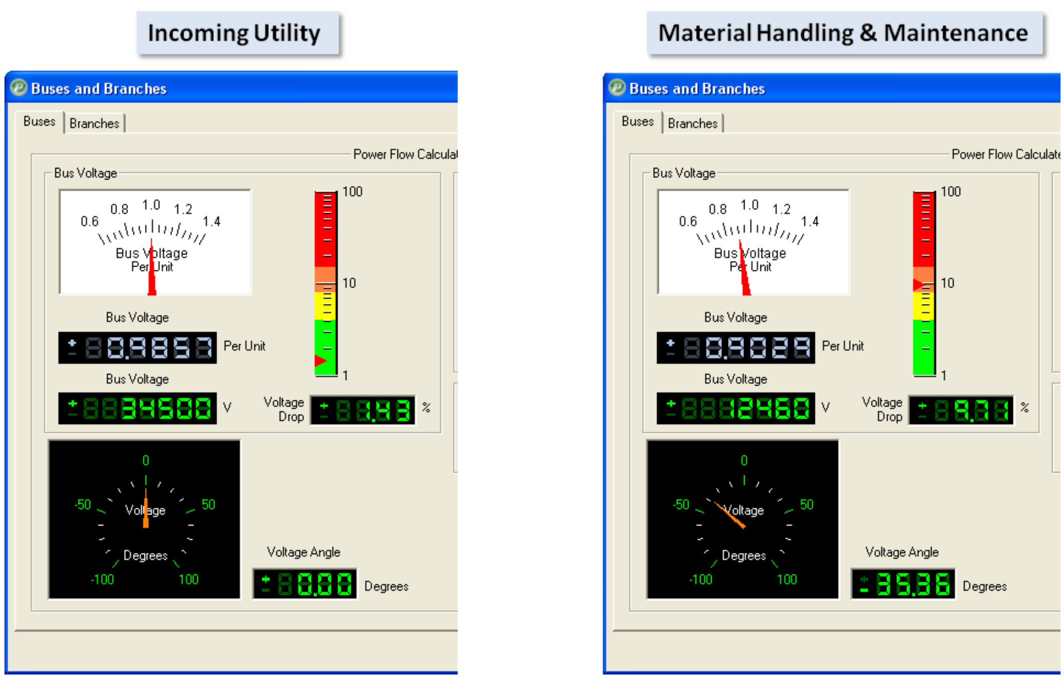


Figure 10: Voltages at the incoming utility and at the Material Handling & Maintenance load (baseline system).

### Bus Voltage Violation - Marginal ( Between 96% - 98% )

| Bus Name | Type | Calculated Bus Voltage (KV) | Voltage Drop (%) |
|---|---|---|---|
| 32 | Node/Busbar | 13.319 | 3.48 |

### Bus Voltage Violation - Under ( Below 95% )

| Bus Name | Type | Calculated Bus Voltage (KV) | Voltage Drop (%) |
|---|---|---|---|
| 18 | Node/Busbar | 12.640 | 8.41 |
| 27 | Node/Busbar | 13.077 | 5.24 |
| 26 | Node/Busbar | 12.610 | 8.62 |
| 25 | Node/Busbar | 13.077 | 5.24 |
| 24 | Node/Busbar | 13.077 | 5.24 |
| 23 | Node/Busbar | 12.610 | 8.62 |
| 22 | Node/Busbar | 12.610 | 8.62 |
| 21 | Node/Busbar | 12.778 | 7.41 |
| 10 | Node/Busbar | 12.951 | 6.16 |
| 19 | Node/Busbar | 12.639 | 8.41 |
| 17 | Node/Busbar | 12.543 | 9.11 |
| 16 | Node/Busbar | 12.543 | 9.11 |
| 15 | Node/Busbar | 12.810 | 7.18 |
| 14 | Node/Busbar | 12.810 | 7.17 |
| 13 | Node/Busbar | 12.522 | 9.26 |
| 12 | Node/Busbar | 12.522 | 9.26 |
| 11 | Node/Busbar | 12.951 | 6.16 |
| 20 | Node/Busbar | 12.777 | 7.41 |
| Communications | Functional Load | 12.970 | 6.01 |
| Storage Tanks / Shops | Functional Load | 12.749 | 7.62 |
| Residences 2 | Functional Load | 12.606 | 8.66 |
| Residences 1 | Functional Load | 12.503 | 9.40 |
| Renewables Interface | Functional Load | 13.075 | 5.25 |
| Offices 1 | Functional Load | 12.513 | 9.33 |
| Mtl Handling / Maint. | Functional Load | 12.460 | 9.71 |
| Miscellaneous | Functional Load | 12.600 | 8.70 |
| 28 | Node/Busbar | 12.604 | 8.66 |
| Data Center | Functional Load | 12.949 | 6.16 |
| 29 | Node/Busbar | 12.604 | 8.66 |
| Air Field | Functional Load | 12.518 | 9.29 |
| 9 | Node/Busbar | 12.518 | 9.29 |
| 8 | Node/Busbar | 12.518 | 9.29 |
| 7 | Node/Busbar | 12.979 | 5.95 |
| 6 | Node/Busbar | 12.979 | 5.95 |
| 5 | Node/Busbar | 12.506 | 9.38 |
| 4 | Node/Busbar | 12.506 | 9.38 |
| Warehouses / Offices | Functional Load | 12.574 | 8.88 |
| HQ / Clinic / Offices | Functional Load | 12.764 | 7.51 |

Figure 11: Summary of voltage violations at buses throughout the notional base (Baseline system).

If one assumes that information is available about the voltage level at the utility tie-in, the load power demands at the various load points, and the load power factors over a period of time, the time evolution of voltage levels at different points in the system can be traced. For example, Figure 12 shows the voltage evolution at the Material Handling and Maintenance station over a

24-hour period as a result of the utility voltage variation (shown), the variation in time of the load demand and power factor at its own load point (also shown), and the variation of power demand and power factor at all other loads (not shown).

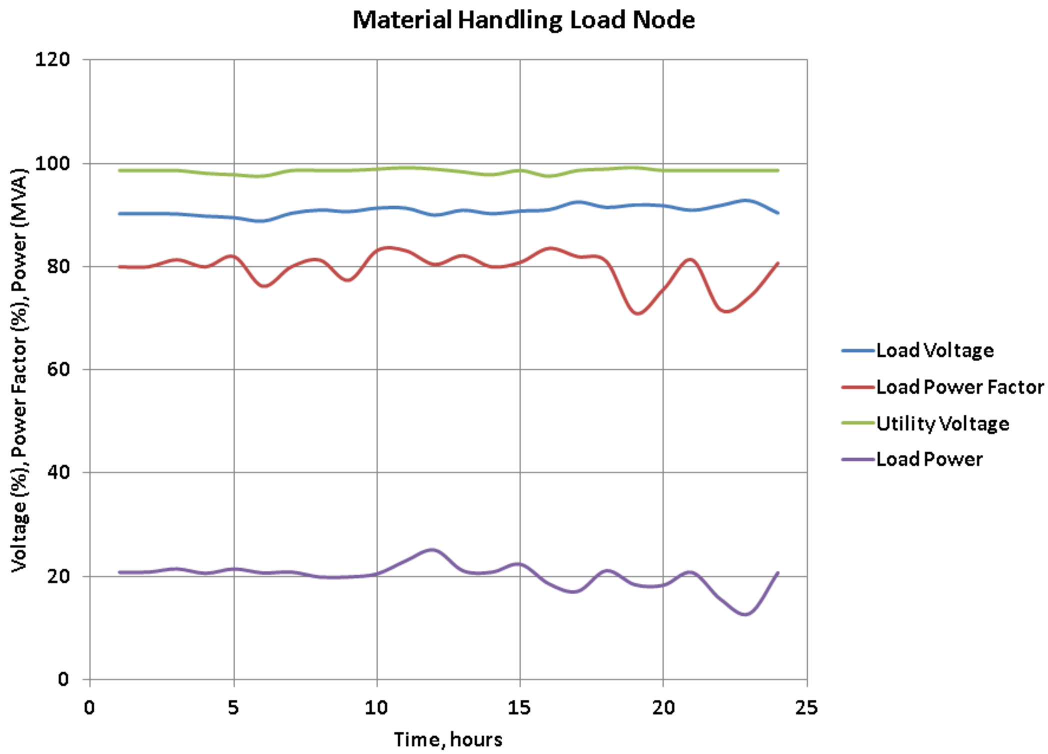


Figure 12: Voltage variation at Material Handling station over a 24 hour period (Baseline system).

### 3.3.1.2 Utility and Renewables

When Main Breakers 1, 2, 4, and 5 are closed (3 remains open), the base is connected to the local utility and the renewable sources, solar and wind. The power flow is now modified as shown in Figure 13: the utility is now supplying, through Transformers 1 and 2, 25.9 MW + 12.1 MW = 38 MW and the balance needed by the base is supplied by the renewable sources, 7.2 MW from the solar array and 13.5 MW from the wind farm, for a total base power of 58.7 MW. With the assumptions made for the available solar irradiance and wind speed at this particular time, buses 1 and 2 are now dissimilarly loaded, although both well within their capacity. It just so happens, however, that the simulation at this point also indicates a current overload for the cable connecting the wind power supply to the rest of the system, as shown by the fact that the corresponding conductor in the circuit diagram is colored in red (Figure 14). This conductor, therefore, should be upgraded immediately to a larger size.

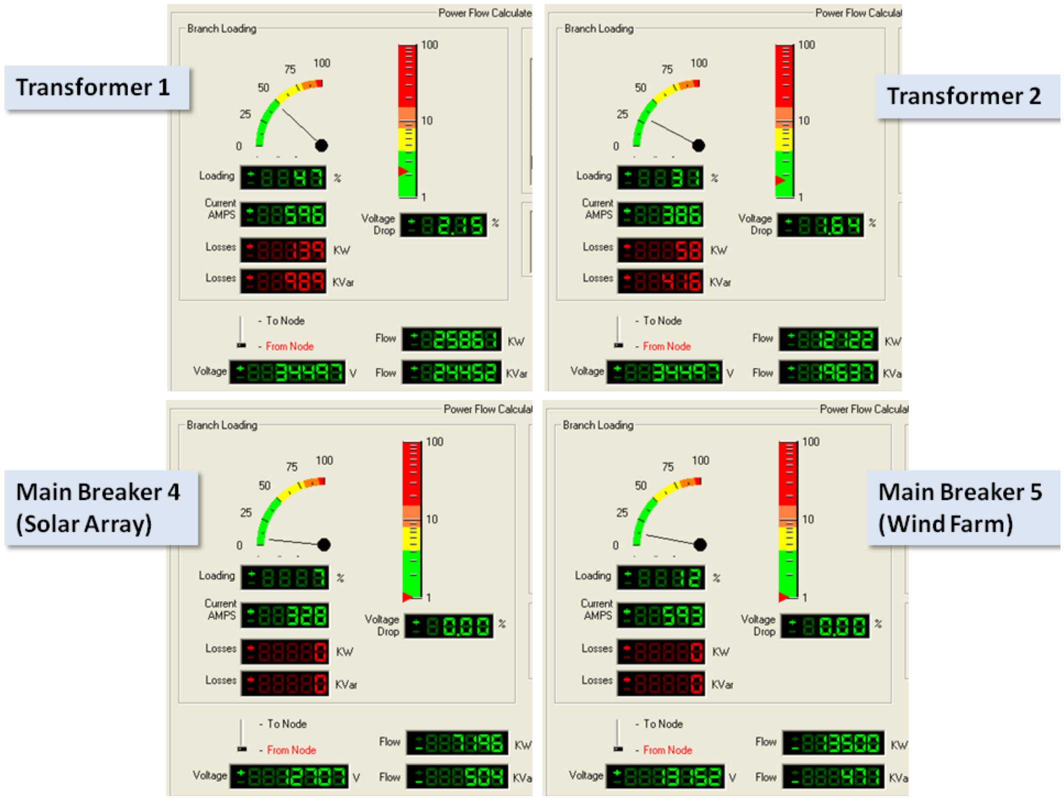


Figure 13: Base connected to utility and renewable.

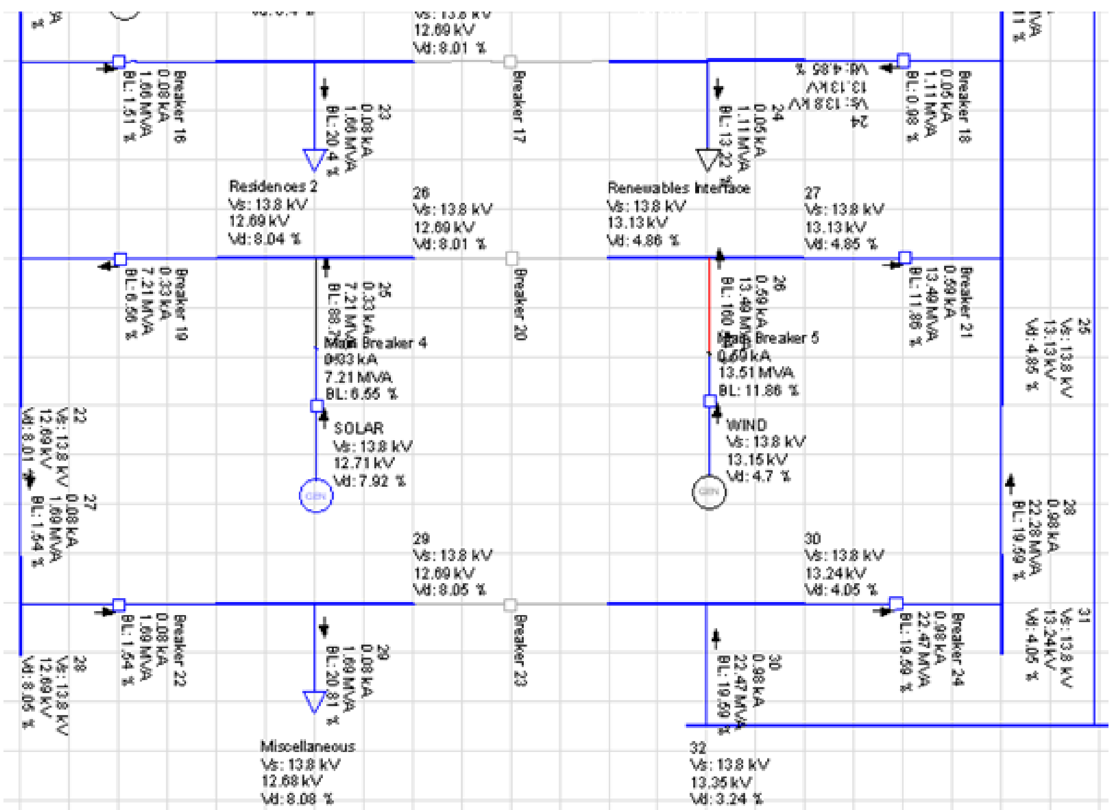


Figure 14: Overloaded conductor at wind farm shown in red (case of utility and renewables).

### 3.3.1.3 Islanded Operation: Base Powered by Local Power Station

If the utility connection is severed, by plan or by accident, power to the base is provided by the local power station. In this case, in our circuit Main Breakers 1, 2, 4, and 5 are open and 3 is closed. We notice (Figure 15) that the voltage drop in the system is much less, *e.g.*, the voltage at the Material Handling Load is only 2.16% down compared to 9.71% in the case of the baseline system, mostly because the power station is located at the base and not remotely like the utility tie point. The larger bus voltage results in larger power consumption from the fixed impedance loads in the system (*e.g.*, lighting), thus the total real power used is 66.9 MW. Considering that also 46.8 MVAR of reactive power are generated, the power generating station is working at a power factor of about 82%. This also implies that the generator would have to be rated at least at 85 MVA.

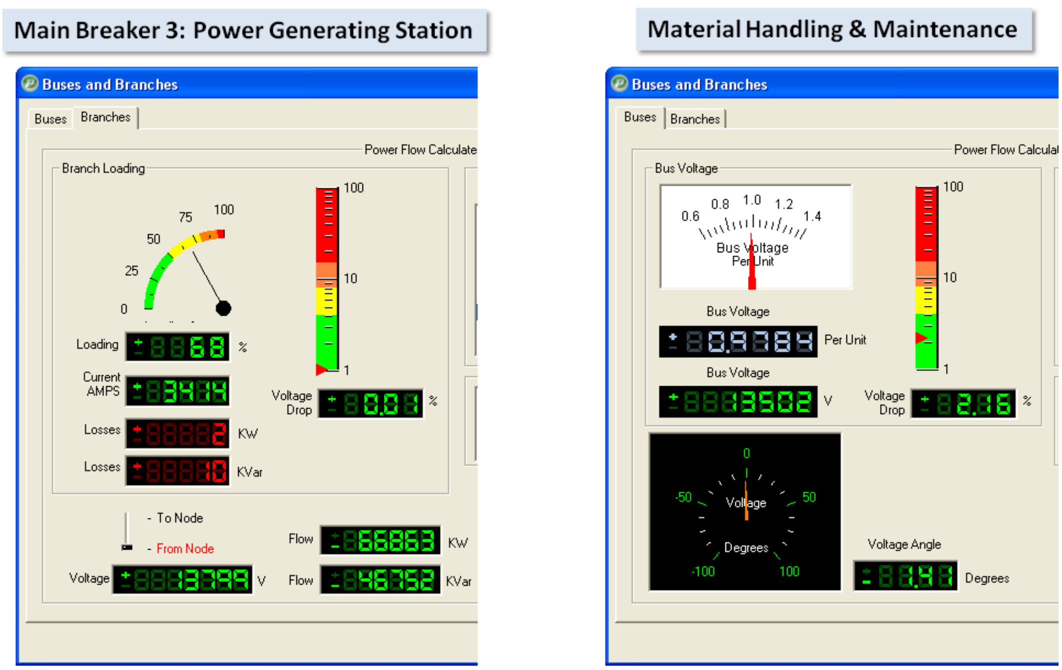


Figure 15: Operation with Power Generating Station only.

### 3.3.1.4 Islanded Operation: Base Powered by Local Power Station and Renewables

This case is realized by keeping Main Breakers 1 and 2 open, but 3-5 closed. The main results are summarized in Figure 16: the generating station still provides essentially all reactive power, but its real power output is reduced to 55.6 MW, being assisted by 7.2 MW of solar power and 4.0 MW of wind power. As expected, albeit somewhat ironically, the presence of renewable resources forces the power station to operate now at a lower power factor of 77% (down from 82%). The same effect took place when renewables were added to the utility supply: the total power factor as seen by the utility went from 78% to 65%.

An investigation can also be made of the effect a potential increase in load has on bus voltage: *e.g.*, if the load at the Material Handling and Maintenance station were to rise from 1.0 per unit (p.u.) to 1.3 p.u., namely, a 30% increase. This is shown in this particular case in Figure 17, where it can be seen that the voltage changes from 2.2% below rated to 2.8% below rated for such load change. Close inspection of the full data output would also reveal, however, that in this condition the cable connecting the solar array to the system would be carrying a 5% current in excess of its rating.

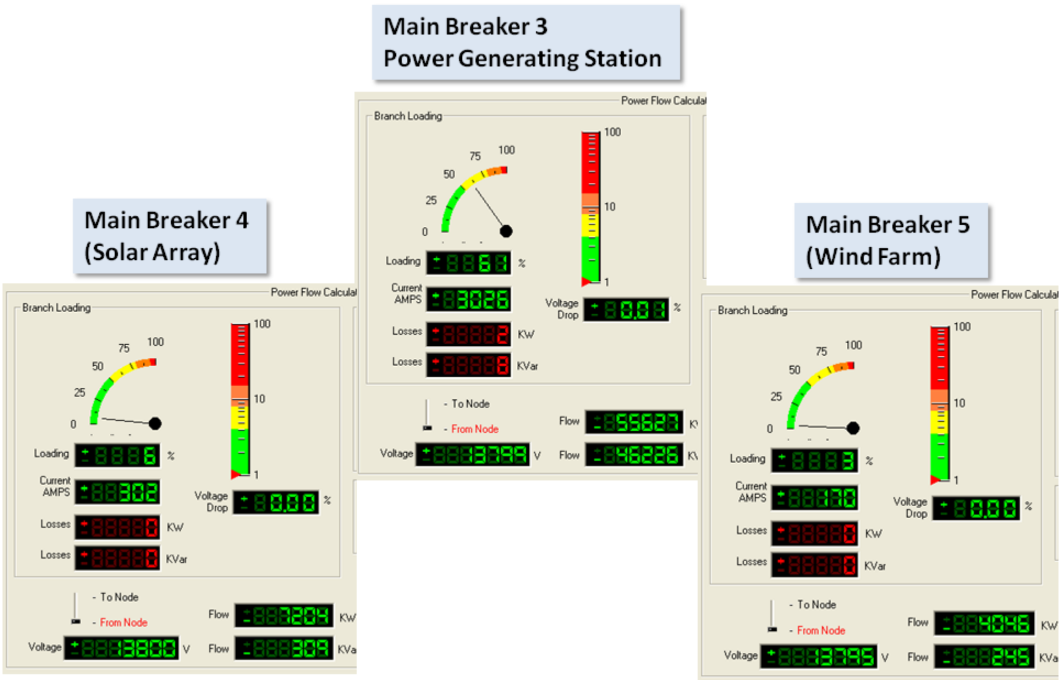


Figure 16: Operation with local generating station and renewables.

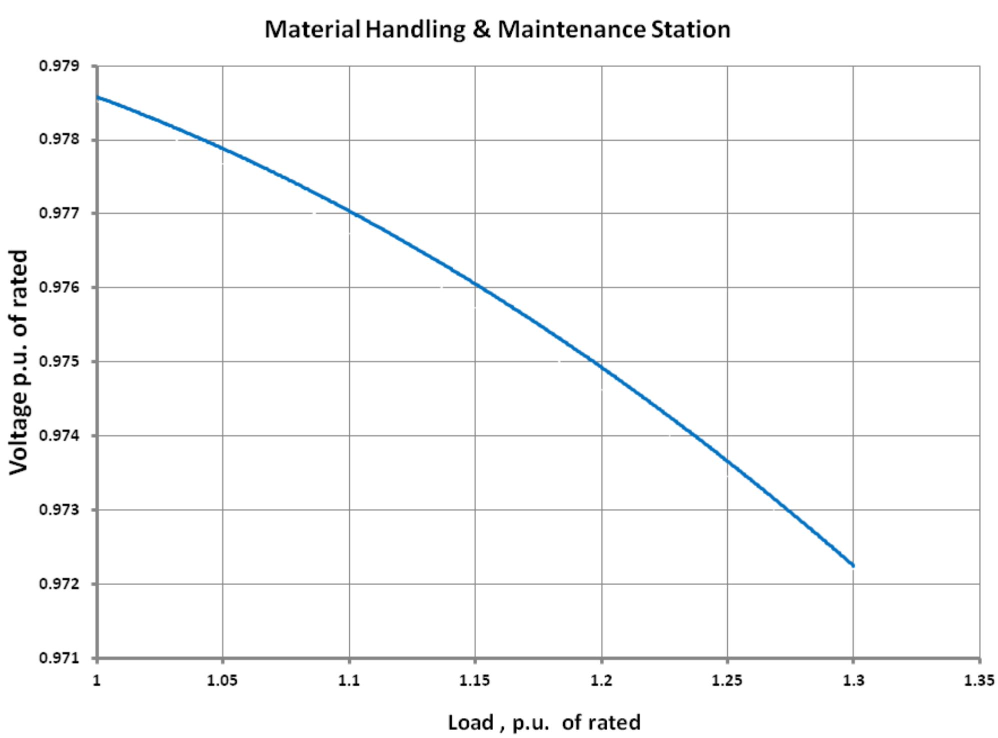


Figure 17: Voltage stability at the Material Handling & Maintenance station as a function of load (Operation with power generating station and renewables).

### 3.3.2 Transient Analyses

#### 3.3.2.1 Operation with Faulted Main Transformer 2

As an example of transient analysis, one can consider the behavior of the base grid when one of the main transformers feeding it, *e.g.* Transformer 2, fails and Main Breaker 2 opens. The grid controls are expected at this point to reroute all power through Transformer 1, according to the breaker-and-a-half protection scheme. These events are shown in Figure 18 through Figure 20. The progression of events can be followed simply by reading the captions on and below each screen shot and keeping in mind that the following timing sequence is assumed:

Main Breaker 2 opens at t = 10 ms; Breakers number 2, 5, 8, 11, 14, 17, 20, 23 close at t = 25, 26, 27, … 32 ms respectively

It can be seen that, after the fault, the breaker-and-a-half scheme successfully reroutes all power through the remaining Transformer 1 (Figure 18) with just a momentary loss of power to the various loads (Figure 19 and Figure 20). Of course, there are other viable methods to ensure continuity of power in the base grid and the breaker-and-a-half scheme is just one possible configuration. It has been adopted here for the sake of this study because it is one of the more reliably known methods, but it is not meant to be proposed to the exclusion of others.

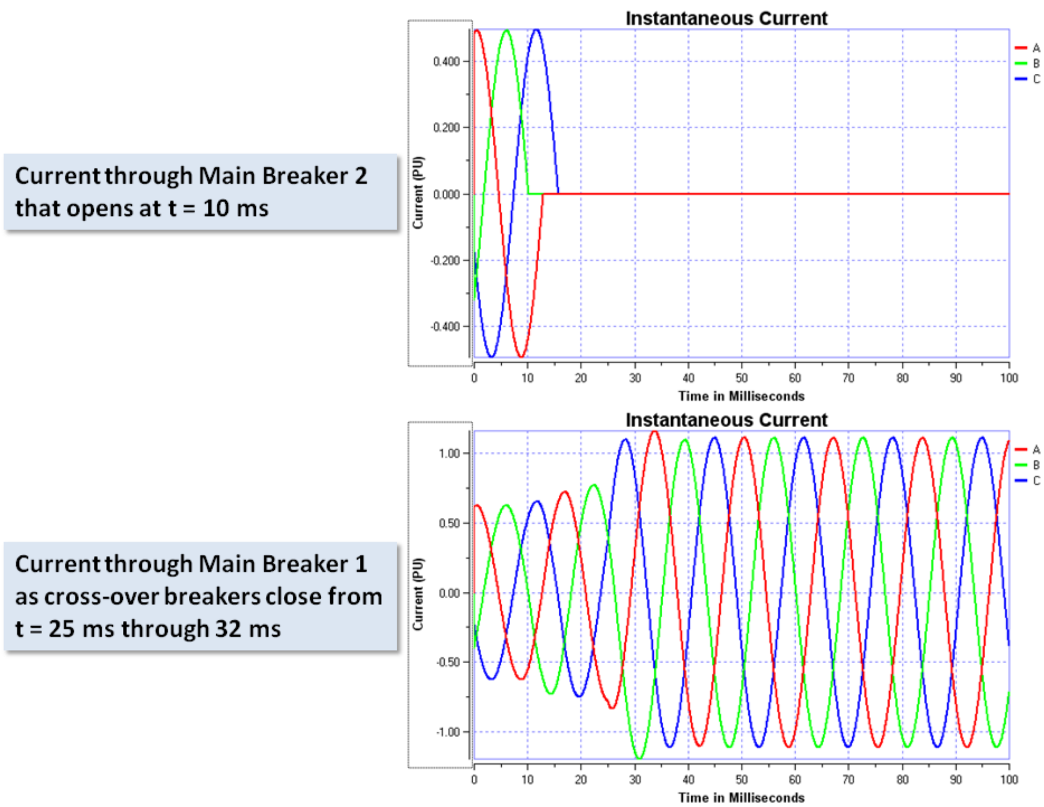


Figure 18: Transient following opening of Main Breaker 2 and reconfiguration of base grid to reroute all power through Transformer 1 and Main Breaker 1 per breaker-and-a-half scheme.

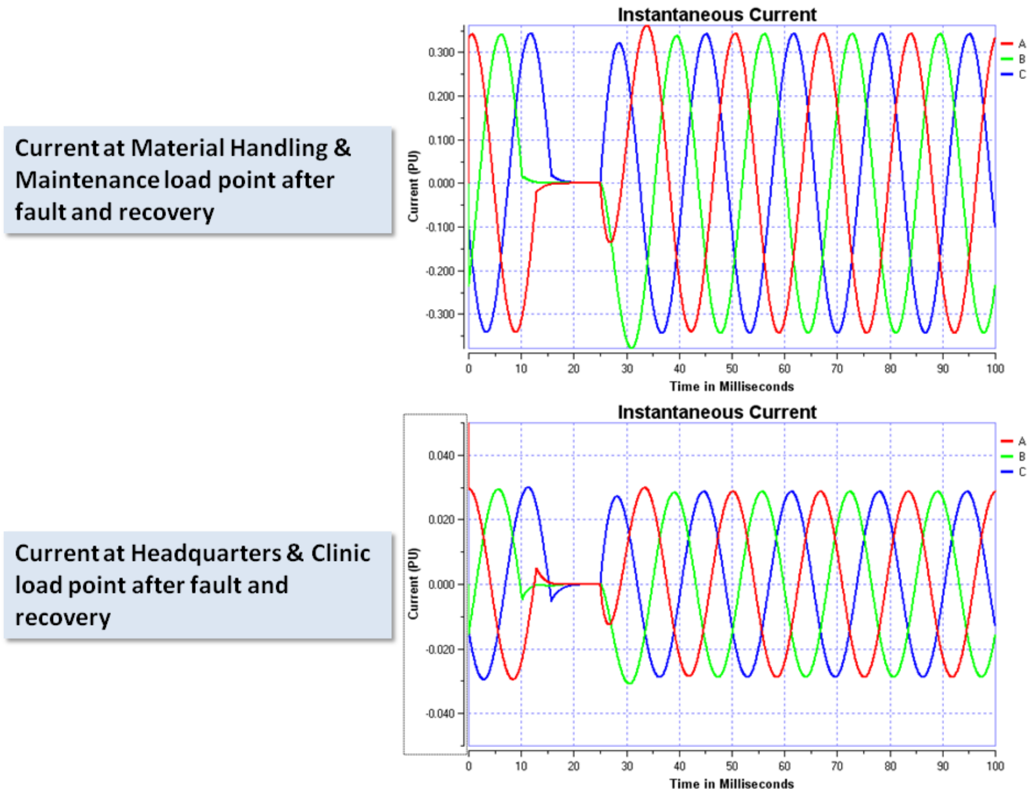


Figure 19: Transient currents at the load points indicated due to the same fault as in Figure 18.

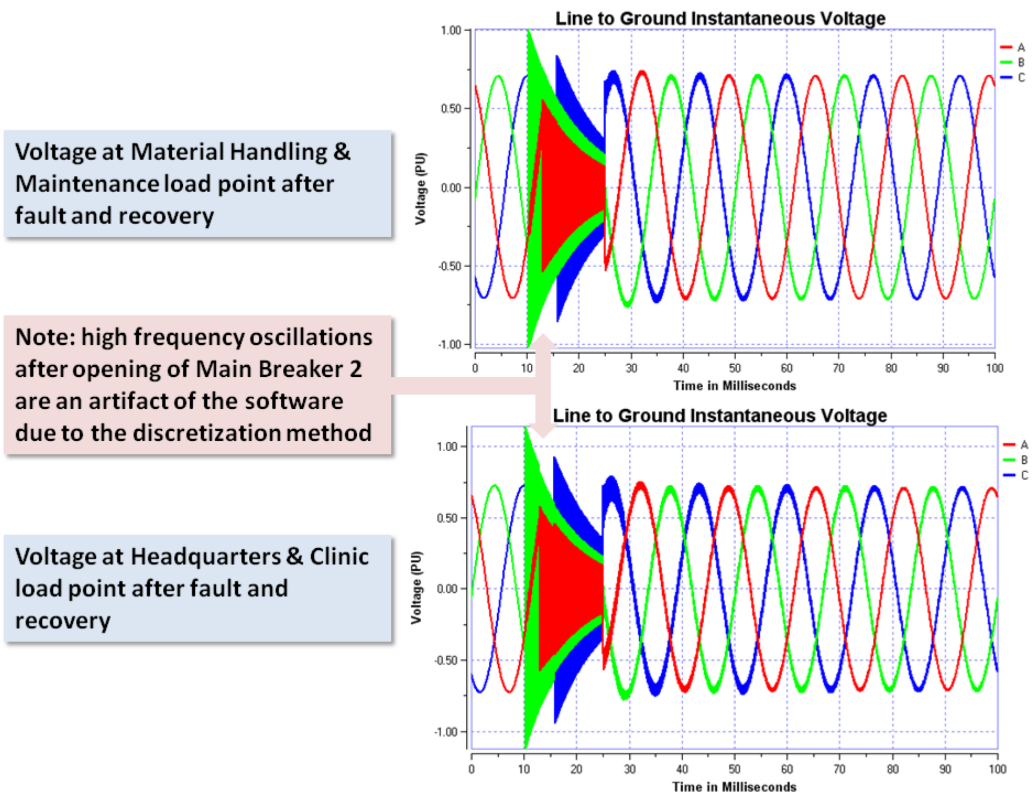


Figure 20: Transient voltages at the load points indicated due to the same fault as in Figure 18.

### 3.3.2.2 Transition to Islanded Operation

As a second example of transient analysis, one can use the transition from normal, utility-tied operation to that of fully islanded operation. This can be the result of a planned reconnection or be triggered by an emergency. In either case, the system will open both Main Breakers 1 and 2 and close Main Breaker 3. Furthermore, in an established sequence, the grid controls will close all the cross-over breakers in the breaker-and-a-half scheme configuration. Some typical events in this operation are shown in Figure 21 through Figure 23. Once again, one can follow the progression simply by reading the captions on and below each screen shot, obtained on the basis of the following timing sequence:

Main Breaker 1 opens at t = 10 ms; Main Breaker 2 opens at t = 13 ms; Main Breaker 3 closes at t = 50 ms; Breakers number 2, 5, 8, 11, 14, 17, 20, 23 close at t = 55, 60, 65, … 90 ms respectively

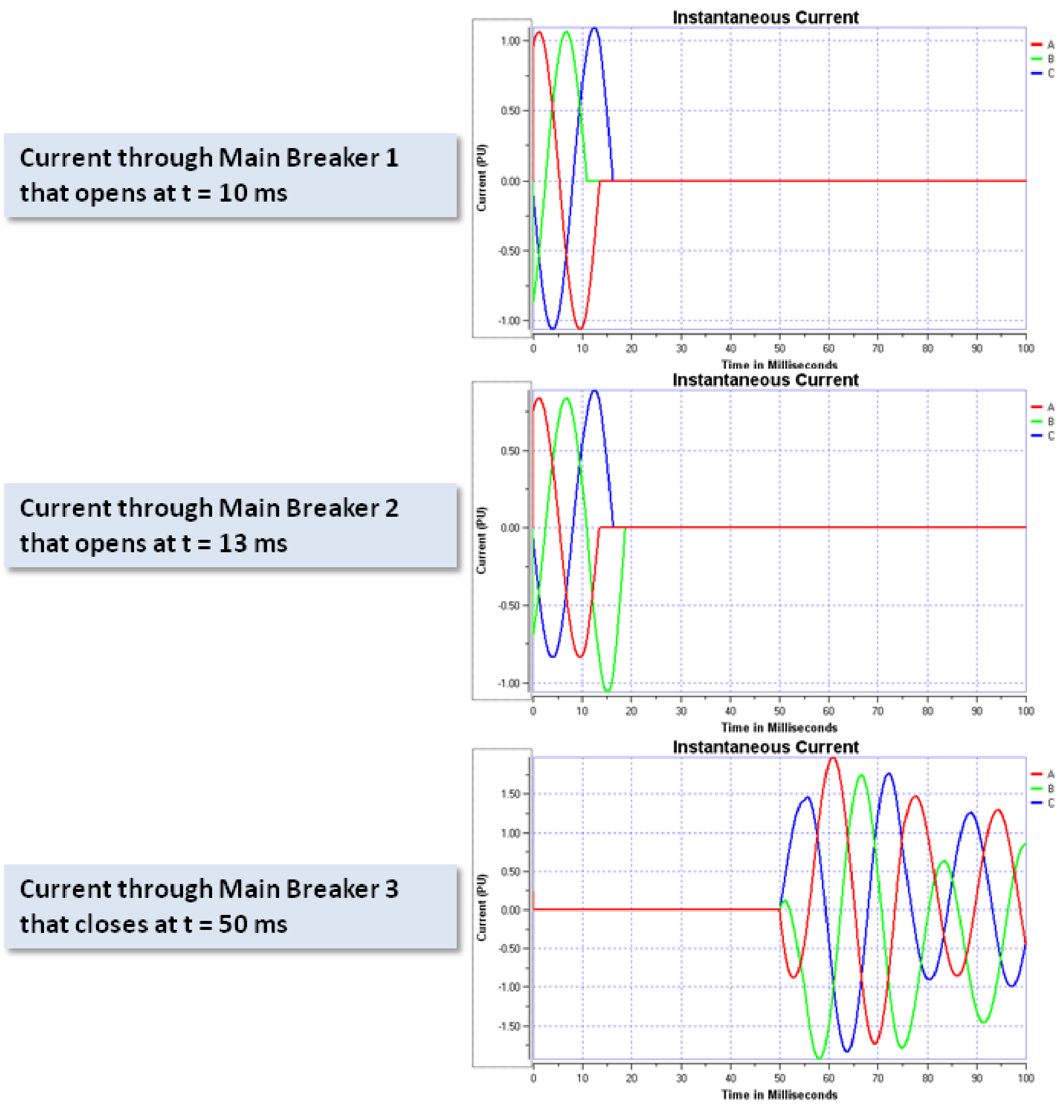


Figure 21: Transient following opening of Main Breakers 1 and 2 and closing of Main Breaker 3 and all cross-over breakers to reconfigure the base grid for islanded operation.

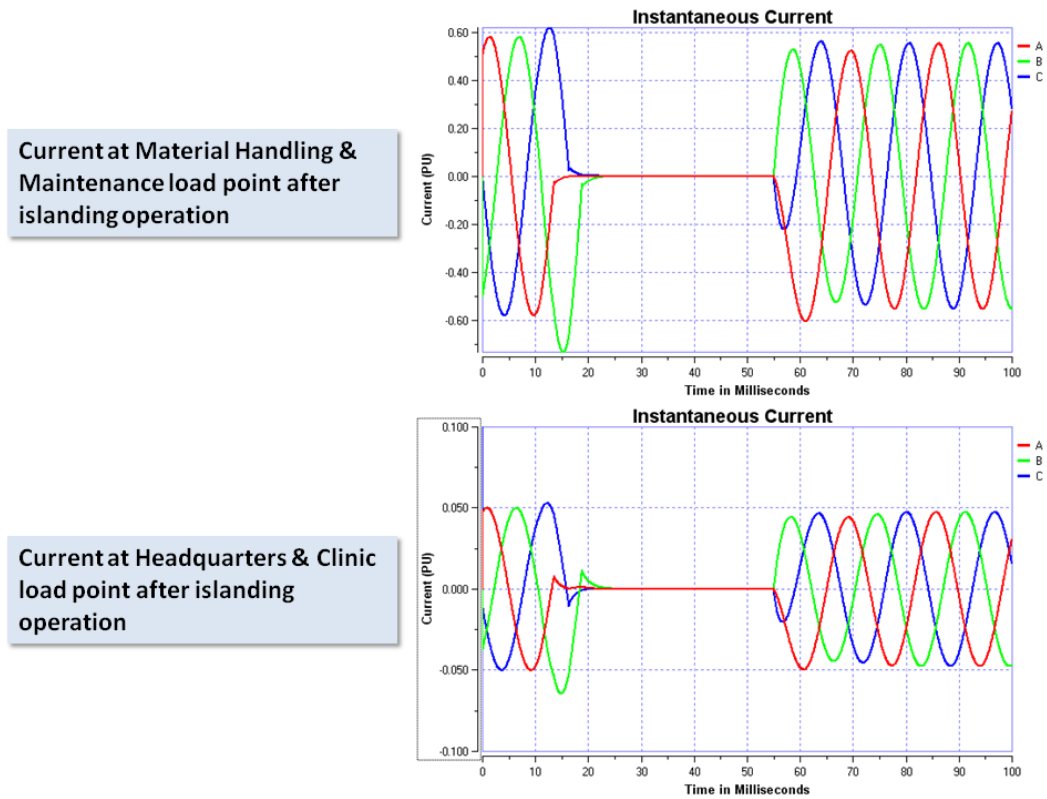


Figure 22: Transient currents at the load points indicated due to same transition as in Figure 21.

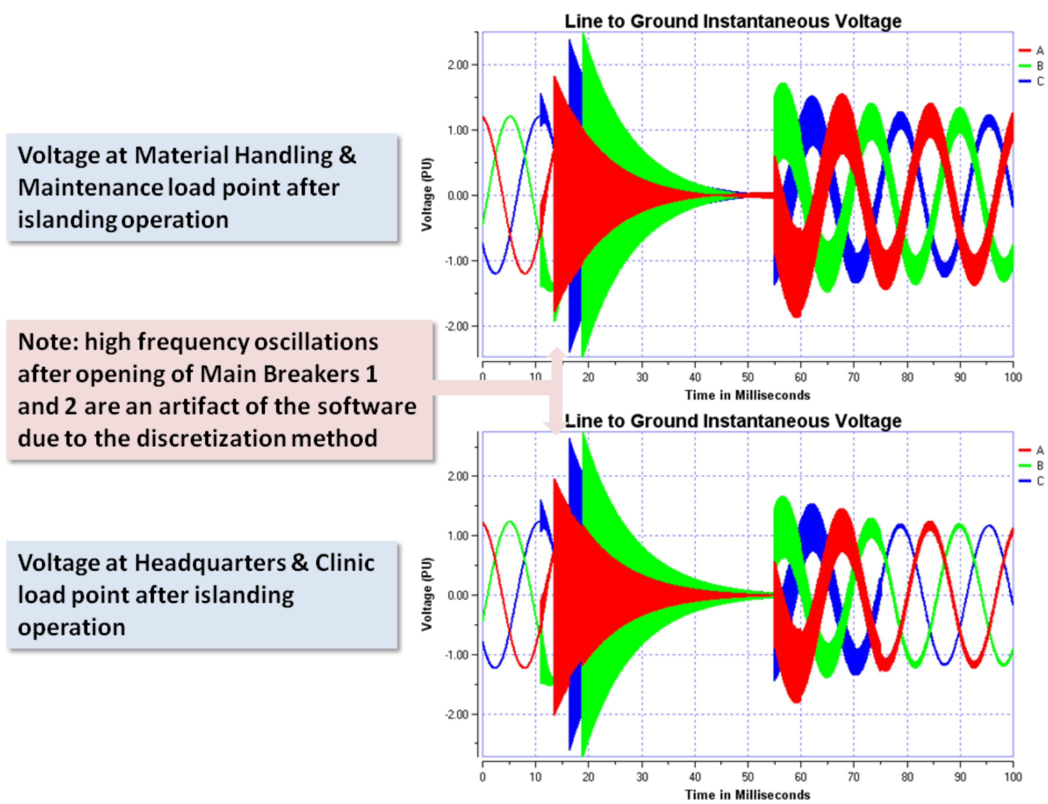


Figure 23: Transient voltages at the load points indicated due to same transition as in Figure 21.

## 3.4 Related Civilian Data

The University of Texas at Austin Center for Electromechanics (UT-CEM) has been examining data of residential consumption and generation for a community of 735 homes. This community demands approximately 1.5 MW and generates through roof-mounted photovoltaic panels 0.5 MW (aggregate). The summary of this data and analysis is included here to highlight the type of operational information that can guide power system design. Civil sector data is used to highlight the strength of modeling of distribution power systems as appropriate military data is not yet available.

The eletrical distribution layout for the community is shown in Figure 24. This community is served from a three-phase lateral, where each phase serves between 20-40 distribution transformers. Each transformer serves between 4-11 homes, of which some have roof-mounted solar panels and/or electric vehicles (Chevy Volts), and some don't.

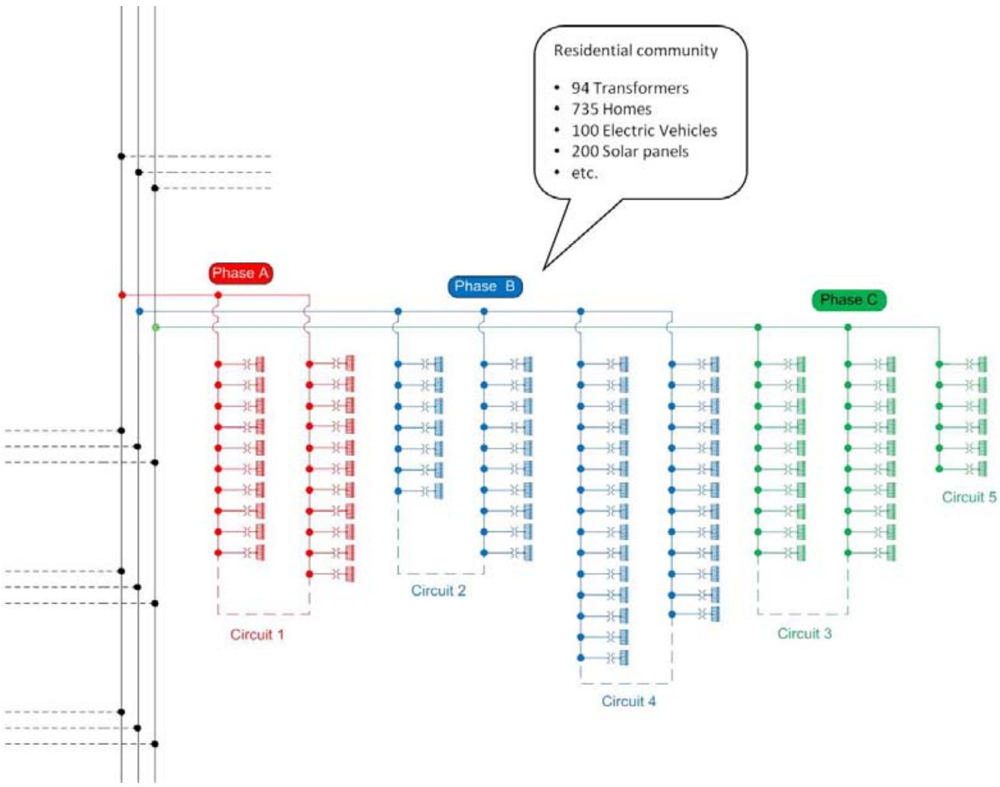


Figure 24: Residential community where data is being collected (central Austin, Texas). Each phase serves between 20-40 distribution transformers.

A chart illustrating the number of homes, solar panels, electric vehicles, cables, and transformers is shown in Figure 25. These counts are practical and assumed to be similar for the notional base under study.

In recent years, *MATLAB*/*Simulink* has made significant progress to enter the common area of overlap between load-flow and transient programs. While *MATLAB*/*Simulink* cannot perform real-time load flows as required for live energy management, it presents relevant analysis capabilities as demonstrated next.

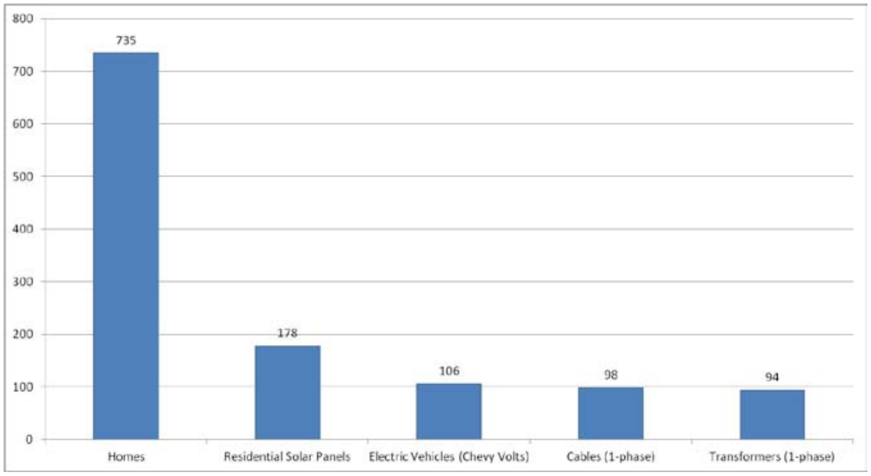


Figure 25: Load/asset counts for residential community under study. Counts assumed similar for an arbitrary naval base.

### 3.4.1 Residential Consumption

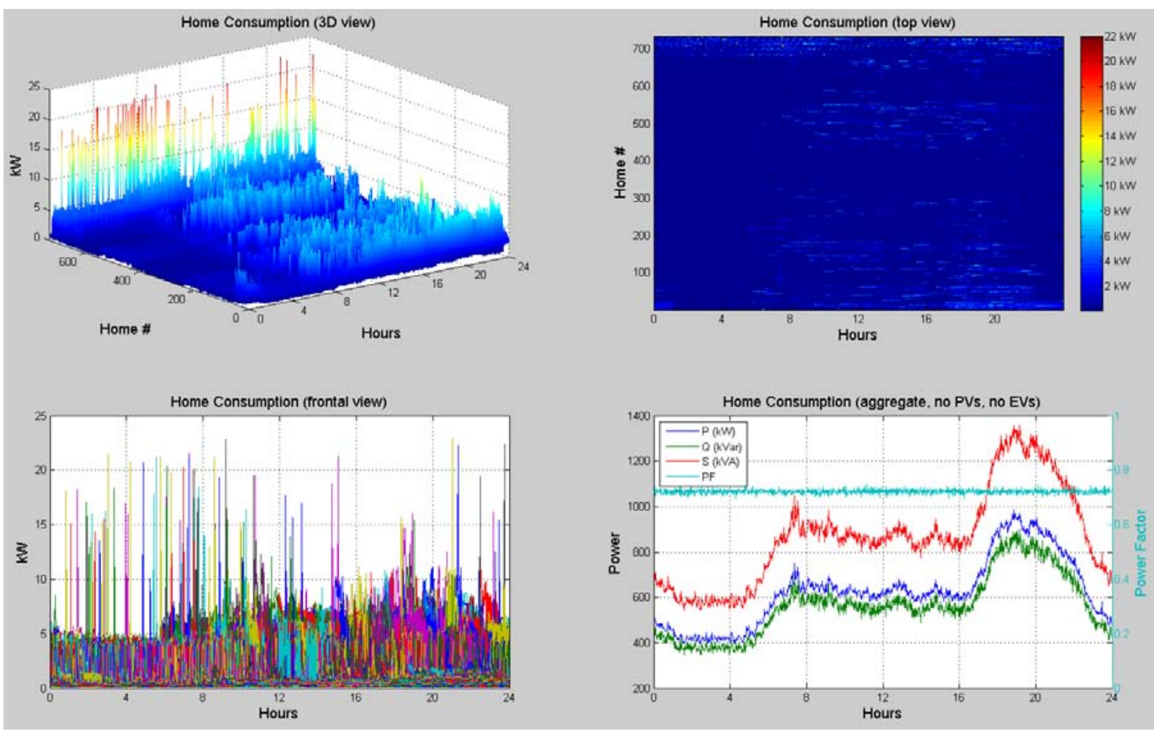


Figure 26: Residential consumption (1-min. interval) aggregated by UT-CEM (to be used in naval base model).

Top Left: shows typical residential consumption for each of the 735 homes for a 24-hour period. It is shown that after 8 AM, most of the consumption varies between 0 and 10 kW at most homes; but each home is different.

Top Right: same data as Top Left, viewed from the top. This data shows the duration of the home consumption peaks (if any). Notice that the large peaks of 20 kW (Top Left) only last 1-minute each.

Bottom Left: same data as Top Left, viewed from the side. This plot shows how uncorrelated the home consumptions are. The peaks and valleys of the home consumptions do not match. This is, partly, desirable because it hinders the load from scaling by the number of homes. On the other hand, this causes uncertainly in the load demand.

Bottom Right: same data as Top Left, shown as aggregated. This plot shows the total residential load consumption in terms of real, reactive, and total power (left axis), as well as the power factor (right axis). It is noted that the peak consumption occurs in the evening, as expected. (Solar generation from photovoltaic arrays is not considered in Figure 26.)

### 3.4.2 Solar Generation

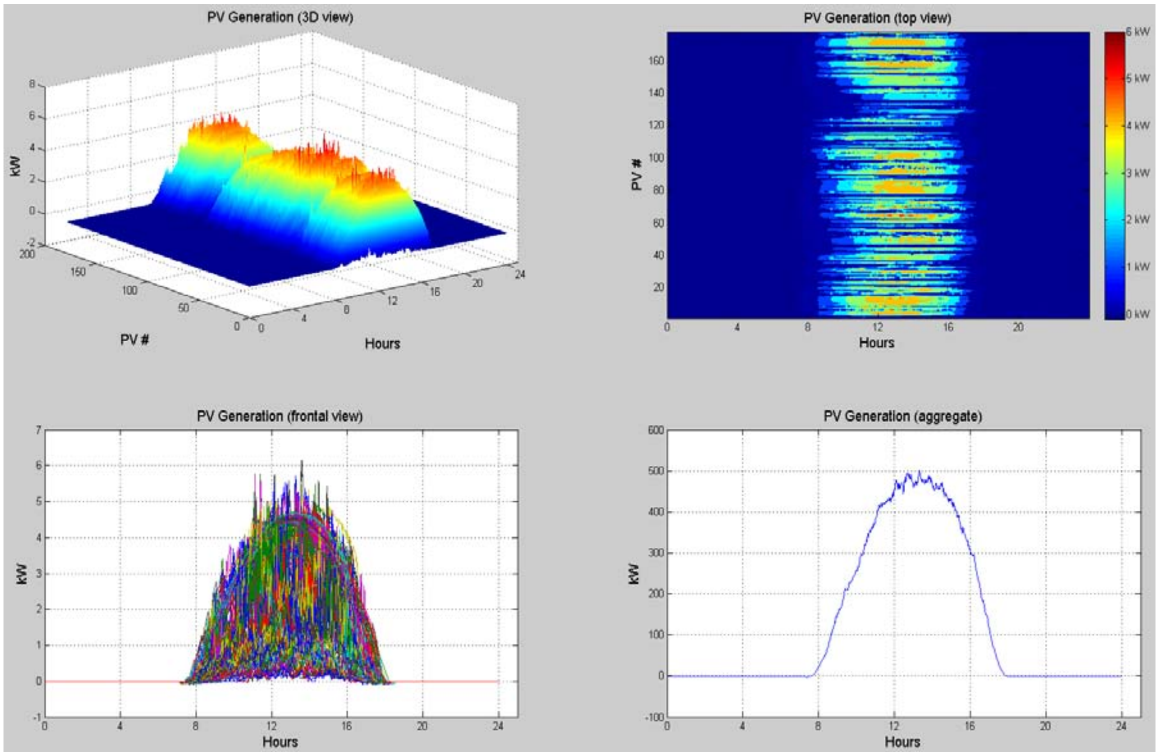


Figure 27: Solar generation (1-min. interval) aggregated by UT-CEM (to be used in naval base model).

Top Left: shows residential photovoltaic (PV) generation for all PVs for a 24-hour period. Each PV is ~5 kW. It is shown that the peak solar is different for each home, but their envelopes follow a consistent pattern.

Top Right: same data as Top Left, viewed from the top. This plot shows the difference in generation between south-facing vs. west-facing PVs: the former start earlier in the day; the latter provide power until later in the day.

Bottom Left: same data as Top Left, viewed from the side. This plot shows how uncorrelated the PV generations are, even in geographic proximity. The variability of PV output is affected by cloud patterns, which do not affect all homes equally.

Bottom Right: same data as Top Left, shown as aggregated. This plot shows the total residential generation in terms of real power. Although PV generation is uncorrelated, the aggregate generation follows a smooth envelope reaching nearly 500 kW.

### 3.4.3 Electric Vehicles

UT-CEM has collected the charging profiles for a Chevy Volt. The charging profiles, shown in Figure 28, were measured from a zero state-of-charge battery state. To predict the impact of electric vehicles on naval base energy consumption, the starting charge time, charge duration, and charging level were randomized. Similar to the residential consumption and generations, the electric vehicle load demand for all vehicles is shown in Figure 29.

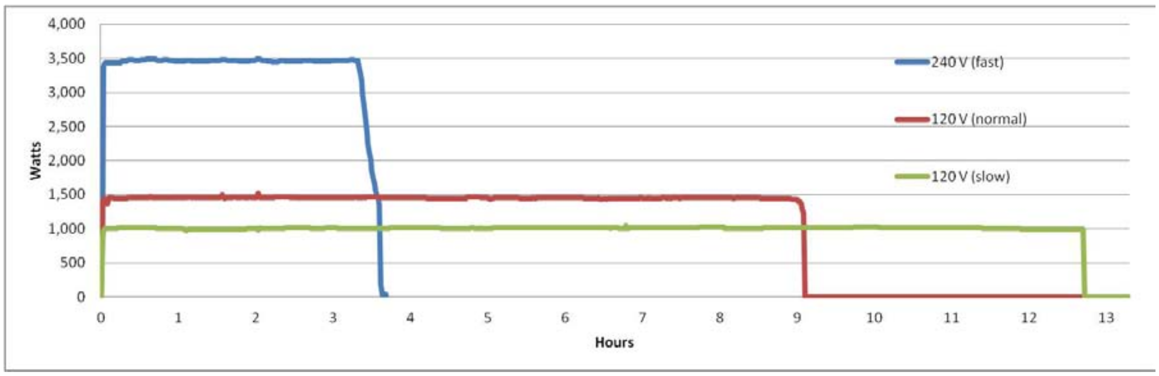


Figure 28: Chevy Volt charging profiles (1-min. interval) collected by UT-CEM (to be used in naval base model).

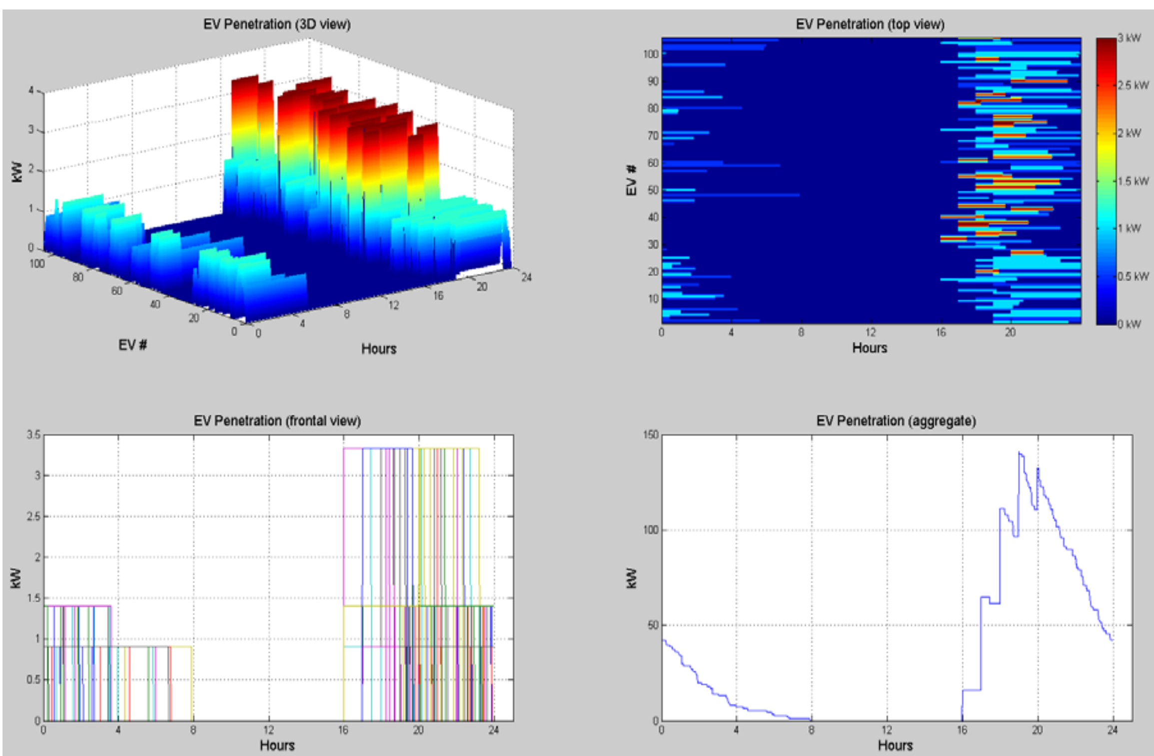


Figure 29: Electric vehicle consumption (1-min. interval) aggregated by UT-CEM (to be used in naval base model).

Top Left: shows electric vehicle (EV) load consumption for all Chevy Volts for a 24-hour period. Some vehicles charge at 240 V (red shades), but most at 120 V.

Top Right: same data as Top Left, viewed from the top. This plot shows the charging start times (after 4 PM) and charging durations. Some EVs charge in less than their maximum charge time, some utilize the full charge time. This plot also shows that some EVs charge through the night, but only those at 120 V (finishing as late as 8 AM).

Bottom Left: same data as Top Left, viewed from the side. This plot shows how uncorrelated EV charging is. Additionally, the 240 V charging is fast and does not sustain its load through its upstream transformer.

Bottom Right: same data as Top Left, shown as aggregated. This plot shows the *total* EV impact. The EV impact occurs closer to the 6-8 PM time frame, but is only 200 kW for a typical day. The risk (if any) that EV charging presents to the distribution transformers depends on the transformer size, number of EVs per transformer, and charging level.

### 3.4.4 Transformer Loading

Forthcoming fleets of electric vehicles, increasing number of residential solar panels, and new energy storage technologies concern utilities across the United States, where the concern lies in the asset management. UT-CEM has inspected the potential impact of PVs and EVs for a naval base. The results of this study are shown in Figure 30.

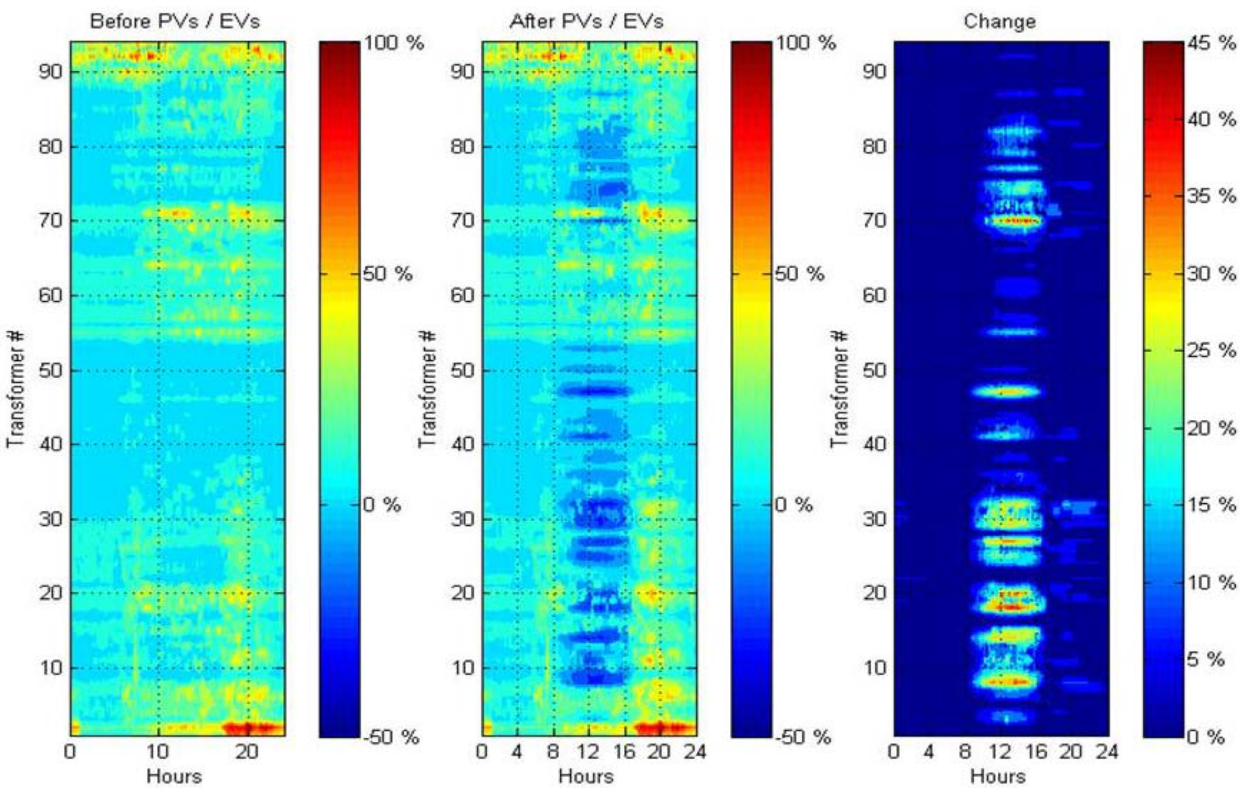


Figure 30: Transformer utilization (%-VA, 1-min. interval) aggregated by UT-CEM (to be used in naval base model).

Left: shows transformer utilization (%-VA) for all 94 transformers for a 24-hour period before connection of the PVs and EVs. As seen from the red regions, some transformers normally operate close to rated capacity (80-100%). This practice is consistent across many utilities in the United States.

Center: shows transformer utilization (%-VA) after the connection of all PVs and EVs. As seen from the blue regions (mid-day), some transformers experience diurnal reverse-flows while others do not. The amount of reverse flow depends on the ratio between PV-generation and residential consumption on *each* transformer. As noticed from the changes in the yellow regions, the EV impact is small when compared to PVs.

Right: shows the *change* in transformer utilization. While most of the utilization change is in the 0-5% region (dark blue), change does reach 30-40%. This change, however, is not due to EVs as commonly expected; it is due to PVs. Additionally, the change in consumption is either positive (increased transformer usage) or negative (reduced transformer usage).

UT-CEM is integrating this field-collected data into naval base models. Because this data is realistic, the increased confidence in results may guide decision making, safe practice, and service schedules in naval base energy management.

## 3.5 Modeling and Simulation Summary

### 3.5.1 Operator User Interface

The foremost choice in the selection of software stems from whether real-time simulation and live energy management capabilities are sought. If so, there are only two software choices: Paladin DesignBase and ETAP. Although this simplified the software selection process, the capabilities in other programs were also examined (*e.g.*, section on related civilian data).

The previous sections gave an overview of the typical capabilities of software programs belonging to the family most often used in distribution system analysis. Additionally, several examples of simulation output were given, mostly graphic. The ability to output load flow data graphically gives the programs of this family an unquestioned advantage. If the ultimate goal is real-time control, performance optimization, protection against unexpected catastrophe, and orderly recovery from unforeseen events of a CONUS Navy base, then it is imperative that the human-machine interface be designed to condense the multitude of data into an easy to use graphical panel, which can be called the electrical system dashboard.

The notional Navy base used in the course of this investigation consists of, at the distribution level, 58 buses, 63 branches, 18 breakers, and 12 load centers (Table 2). To evaluate a single scenario, the output in text/tabular format results in a printout of several hundred pages. This is impractical for real-time control. The software can output all pertinent details in the form of text and tables but these are difficult, if not altogether impossible, to analyze in a timely manner. Furthermore, the operator must be able to take action quickly, literally with few simple entries: writing out code on a command line is time consuming and prone to error.

Finally, considering that each of the macroscopic entities (*e.g.*, each load center) describing our notional base is really given by the consolidated behavior of several, perhaps even hundreds of subsystems (*e.g.*, pumping units), and that each subsystem is itself made up of many individual components (*e.g.*, variable speed drive, motor, pump), one can appreciate the fact that the actual base model, when completely detailed, will contain several thousand elements.

All these reasons provide plenty of justification for insisting on the quality of the program's graphical user interface (GUI). It has already been noted that programs of the distribution system analysis family are more likely to have an advanced GUI. Some evidence of this capability offered by the program that was used to generate the examples reported herein (DesignBase) has been given previously. More extensive illustrations could have been given; *e.g.*, one could have reported the performance of the system in more detail, analyzing perhaps that of some individual components: Figure 31 gives some typical displays of this type. This amount of detail would have been very laborious to report and examine, but if desired, more details on the performance of the system can be obtained, all in a graphical form.

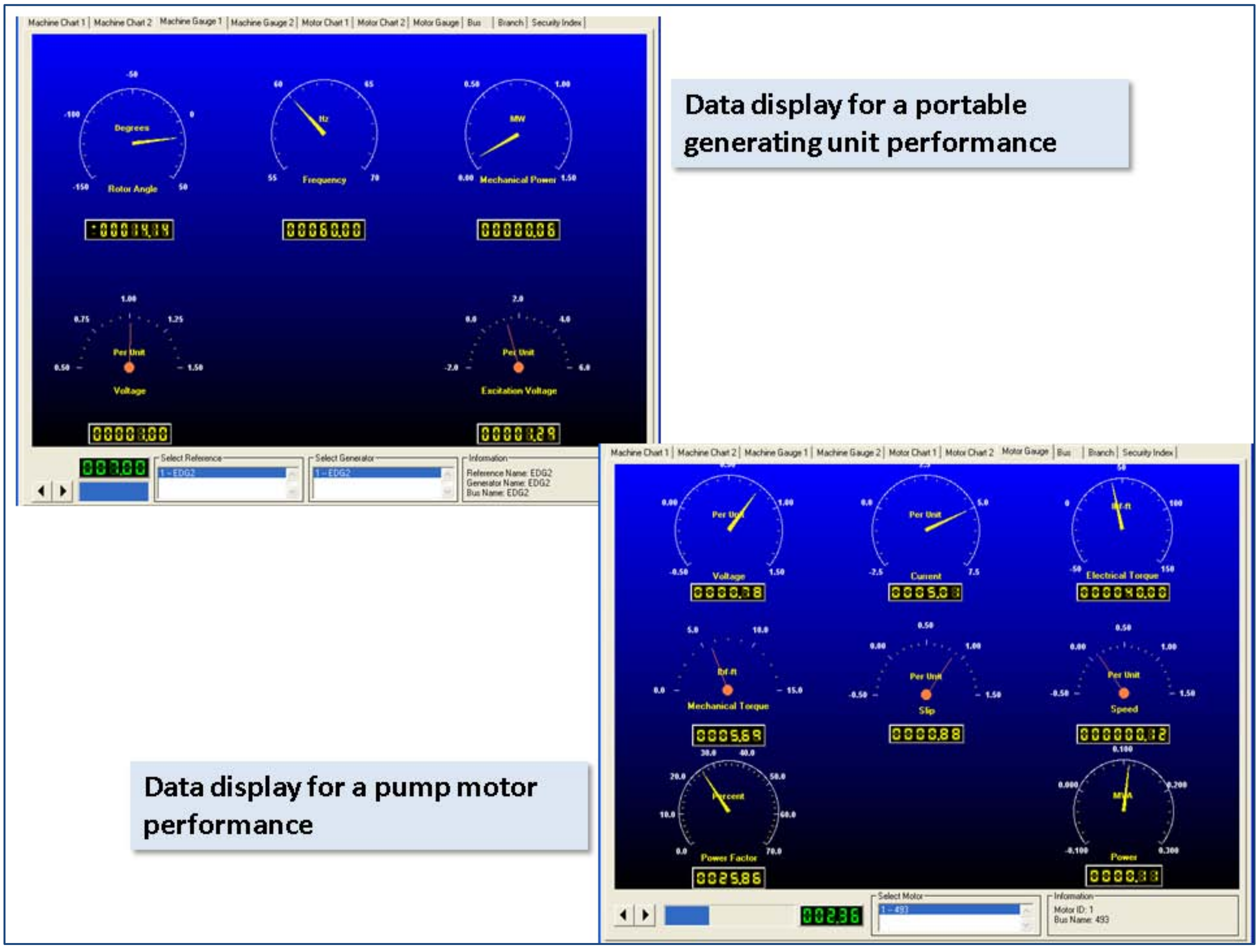


Figure 31: Examples of data displays at the component level.

This shows that the GUI can be configured to operate at different levels of detail. Thus, one can envision that a GUI for each of the levels mentioned above, namely distribution, subsystem, and component, can be designed to display the desired information. Other levels of GUI can be added as desired, and in fact, it is easy to realize that a multi-level GUI is almost a necessity for even a moderately complex real base. Proper navigational aids to move from one level to another must be provided and the points of entry for the operator's command to intervene on the system must be clearly highlighted.

The data collected by UT-CEM provides confidence that the predicted naval base energy usage is realistic. This not only permits assessing the impact of the renewable energy and electrical vehicles on military installations, but also running predictive financial simulations to determine when renewable energy sources and emerging technologies stop becoming economical or reliable.

### 3.5.2 Cyber-security

The issue of cyber-security, although mentioned, has not been developed. The subject is a very specialized discipline that involves agent identity verification, intrusion prevention and detection, cryptography, and similar matters. A fundamental tenet of the model-based control approach is that the utility's external SCADA system controls only the model, not any of the hardware on the base. When the model shows the SCADA command to be benign, the base control system implements the request. Within the scope of this project, the items addressed were 1) command authorization and 2) violation of established limits and procedures.

Both of these items will require programming a verification step to be executed before action is taken on the system to serve as a sort of policed entry point. This could be accomplished externally or internally to the modeling program.

The external implementation is believed, at the present time, to be the preferred course of action. It is true that this would entail the use of yet another software package, but it would also leverage the specialized techniques embedded in it to enhance security.

The internal implementation will have to be accomplished using the programming tools made available by the modeling and simulation software. These tools are typically in the form of logic blocks, both analog and digital, that can be combined opportunely to achieve a specific control objective. Commercial modeling and simulation packages of the types mentioned earlier in this report vary widely in the quality of their library of control functions made available to the user and in the extent to which the results of any control scheme can be interfaced with the electrical system blocks properly. Figure 32 gives some simple examples of the types of control systems that can be designed with the libraries provided.

Whether accomplished within the modeling and simulation program, with additional software external to it, or even with a combination of both methods, the desired degree of security must be weighed against the inevitable computational overhead incurred.

In this project, some checkpoints were established within some models to verify the ability to intercept unauthorized operations and potential threats. This effort remained at the preliminary stage and more complete cyber-security will be developed in the next phase of this work.

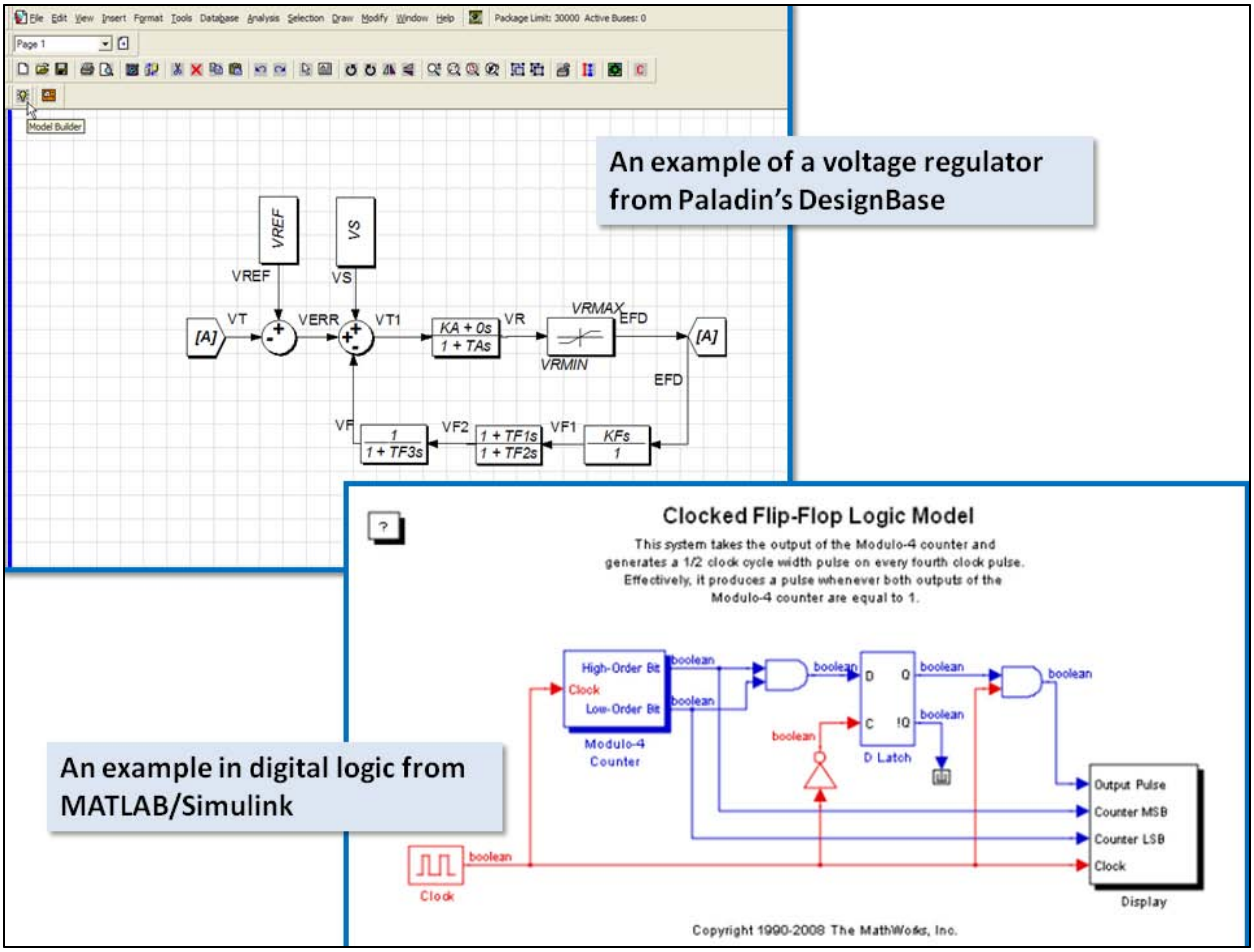


Figure 32: Control logic of programs used in modeling and simulation of electrical power system.

## 4 Roadmap to Base Energy Security

The roadmap to improving energy security in a Navy base is envisioned as being a three-step approach. (See Figure 33.)

1. Modeling and simulation validated by data on the existing system (baseline configuration) and extension to new desired configurations (system planning)

2. Gradual implementation of a new system with constant monitoring by direct feedback from deployed meters and sensors and comparison with expected data. Simulations can be run offline at each crucial point prior to implementing a new change. This step will generate a database of possible operational systems with attendant figures of merit and thus, will define a hierarchy of options available to base command.

3. Active intervention on the system via the established interface with the program to
   a. modify parameter settings of distributed hardware to achieve optimal performance (interactive control, possibly in real time)
   b. redefine the system into a different configuration based on previous simulation results (system reconfiguration)

To implement this plan, several changes are necessary, in particular regarding the base CONOPS. Following are some of the basic issues that need attention:

1. Changes to the present infrastructure will be needed. Consideration must be given to the
   a. practicality of the changes
   b. cost of the changes
   c. incremental implementation of the changes guided by the evolution in time of the system as predicted by the modeling and simulation effort

2. Changes to the electrical infrastructure must be coordinated with the existing energy infrastructure, notably the water system and the natural gas distribution system

3. The relationship with the local utility must be revised and new procedures must be mutually agreed upon in regard to
   a. disconnection from the local utility (islanding) and reconnection
   b. control of the renewable energy resources located on base (*e.g.*, typically bases cannot access their own renewables directly, but only through the mediation of the local utility)
   c. improved security procedures directed at minimizing the risk of cyber-attacks, especially through the utility SCADA network

CONOPS are difficult to establish in detail ahead of time. As a result, flexibility is required to allow for evolving needs and confront unforeseen challenges.

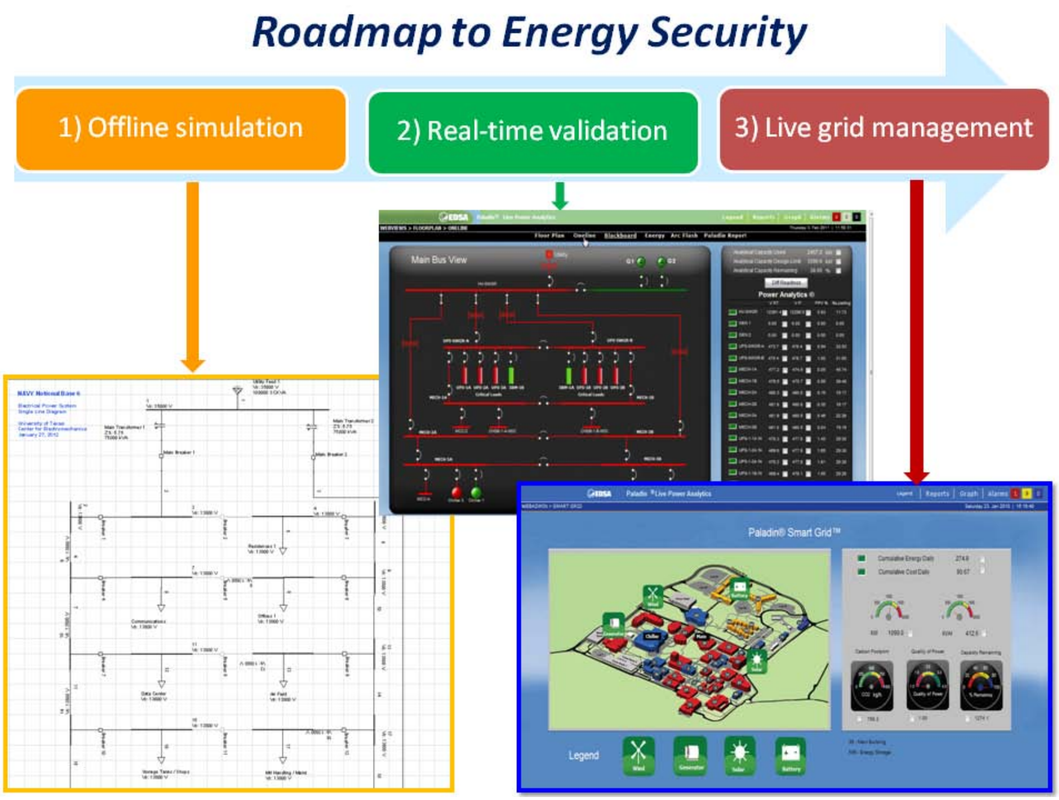


Figure 33: Three-tier approach energy security and live energy management (graphics taken from DesignBase).

# 5 Future Work

While this investigation identified a very promising approach to improved energy security for military bases, additional work is needed before its implementation. These tasks include:

1. Thoroughly evaluating the modeling software. While this work identified some key capabilities, more experience with the strengths and limitations of the selected software package, especially in regard to its GUI and its ability to interface via two-way communication with distributed control hardware, are needed.

2. Applying the control program to a small test site for verification of its functionalities (*e.g.*, a working micro-grid like the one at the University of Texas, Center for Electromechanics)

3. Acquiring representative base power usage data comparable to that available in the civilian sector

4. Applying the modeling and simulation concepts outlined in this report to an actual CONUS Navy installation or an appropriate subset that can be monitored for corroboration of the software tool developed

5. Configuring and using the software program developed for real-time validation of possible energy security enhancements on the chosen Navy test bed

6. Implementing live grid management on the previously selected Navy test bed

# 6 Conclusions

A roadmap to enhance the energy security for CONUS Navy bases has been outlined in this report. Because of the large number of variables involved and the complexity of the optimization process, this necessarily requires the use of a suitable modeling and simulation platform. Since real-time simulation and energy management is highly desirable, the processing of the body of data from field sensors and meters and its output into a readily intelligible format can only be accomplished by means of a sophisticated graphical user interface.

These requirements considerably narrowed the choices of software packages and one of the two best candidates was used to generate some sample scenarios on a notional Navy base. The notional base was defined in a format general enough to be able to be used as a template for most actual Navy installations. The preliminary sample calculations run on the notional base show that there is a very good probability that the software packages available today can fulfill the expected requirements of real-time simulation and energy management.

The study concludes giving the details of the roadmap to move forward in the process of energy security enhancement through modeling and simulation.

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