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Retrofitted Power Distribution Substation Model

An Interactive Qualifying Project Report

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By

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1. System Dynamics
2. Electrical Power Distribution
3. Engineering Economics

Note:

This paper has been submitted as a partial IQP report. The project discussed herein involves the work of three students, one of which is a senior. Although the report has not been written in its entirety, the senior member of the team has completed work which has been deemed sufficient, to meet the IQP degree requirement, according the project advisor. Subsequent to the submission of this partial report, all IQP team members will continue work on the paper, which is scheduled for completion before the end of the term.

Abstract

This work involved the modeling of an electrical power distribution substation, and an energy storage / power generation subsystem employed to reduce stress on substation components by decreasing peaks in the substation load. The model was developed using a System Dynamics method, and iThink modeling software. By simulating various retrofitting options and loading scenarios, the feasibility of each option was assessed, showing that current energy storage technologies are currently too expensive, and that generation-based retrofitting options are more feasible.

Chapter 3 - Model Development

3.1 - System Boundaries

In order to observe and analyze the behavior of an electrical distribution network under typical operating conditions, and under a variety of usage and retrofitting scenarios, a model of the system has been developed using iThink (v 8.1) system dynamics modeling software. The focus of this model has been placed upon those portions of the system, which are physically located at the distribution substation. The effects of more distant portions of the system, as they relate to the load placed upon substation components, have been treated as exogenous inputs, which are the result of various undefined processes that have been designated as beyond the scope of the model.

Because this model is intended to aid in the analysis of *substation* retrofitting options, such modifications to the system will have no effect on the consumers' demand for energy, and likewise on the necessitated power flows, which exist downstream from the substation. There is ample justification for placement of the model boundary at the substation boundary. Adoption of this model boundary has allowed for attainable project goals to be selected, by limiting the scope and complexity of the model to manageable levels.

3.2 - Intended Usage Model

The system model discussed herein has been devised for use as a decision-making tool, which allows for simulation of the system's behavior under a range of scenarios. These scenarios may involve various modifications to usage trends, such as growth or decline in the demand for electrical energy, and multiple variations on retrofitting implementations involving the addition of energy storage devices and/or power generation devices, at the substation level.

Important device characteristics have been parameterized to allow the adoption of any type of storage or generation device to be assessed for technical and economic feasibility. These parameters include (but are not limited to) characteristics such as energy storage capacity, power input/output capacity, system efficiency, and device lifespan. Research has been conducted in order to obtain the actual values of these parameters, for a variety of devices, which are currently available. The result is a simulation package, which allows for rapid assessment of retrofitting strategies involving both real devices and devices that do not currently exist, but may one day become commercially available.

3.3 - Analytical Focus

In accordance with the wishes of the project sponsor, the National Grid, analyses have been centered around the main power transformer, which is responsible for stepping-down the voltage of power supplied via the high-voltage transmission lines connecting the local feeder to higher levels of the supply network. The loads placed upon this critical substation component are of utmost concern, as they must not exceed the rated limits of the device, lest it need replacement.

Using the model of the distribution network, modifications to the substation may be simulated, and the resulting changes in the transformer load may be observed. More importantly, the trade-offs between system performance and retrofitting cost may be readily examined in order to choose an investment strategy, which will maximize savings without sacrificing quality of service.

3.4 - Model Structure

The structure of the model has been broken down into various subsections, called sectors, which interact with each other via inter-sector flows. Some of the sectors deal with technical aspects of the system, such as power flows, and energy stocks, whereas other sectors have been developed in order to account for financial and economic considerations, such as retrofitting expenses, energy pricing structures, and long-term savings. Figure 3.0 shows the top-level structure of the model. As shown, the input to the model is load data; this corresponds to the demand for energy. The load data is passed to the electrical distribution sector, as well as the energy storage and power generation sectors. Within the storage and generation sectors, the load data is used to 'decide' how much energy should be stored, released, or generated. This decision affects the electrical distribution sector, by changing the source of the energy being distributed. The costs associated with equipment purchase and maintenance, are influenced by the characteristics of the energy storage and power generation sectors, and are calculated in the 'costs' sector. The cost of energy is accounted for in the energy pricing sector. Once all cost have been calculated, they are passed as input to the financial sector, which tracks the gains, or losses, associated with the chosen retrofitting scenario. The following sections of this report describe, the structure of each sector, and provide an explanation and verification of each sector's functionality.

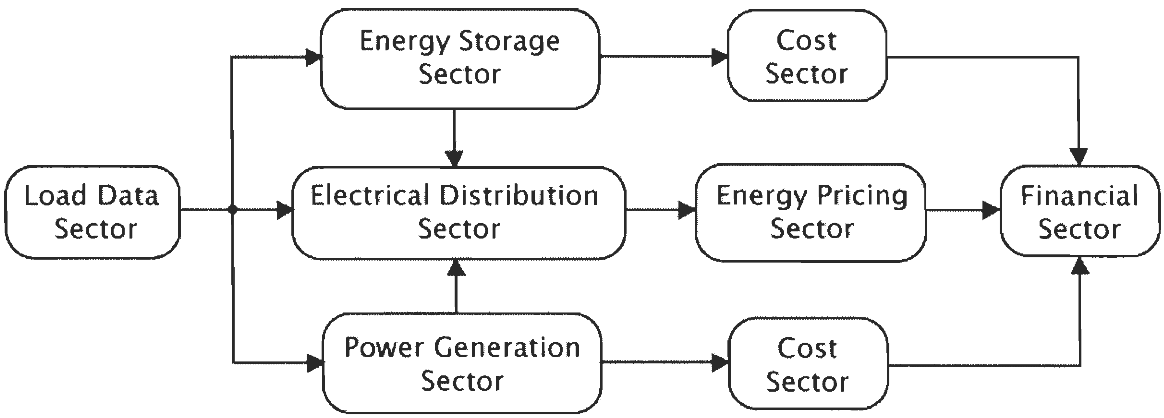

Figure 3.0 – Top-Level Model Structure

The model is comprised of multiple sectors. This 'sector map' shows (using arrows) how data is shared between the sectors. This simplified model view shows only the most important sectors; others sectors have been developed, which support the functionality these sectors, and provide a means for performing technical and financial calculations.

3.4.1 - Electrical Distribution Sector

As a test bed for the modeling and analysis process, a portion of the local electrical distribution network was chosen. The National Grid provided information about a particular feeder, known as feeder 27W2 of the Bloomingdale distribution network, including a description of its structure and one years worth of load data. Though these data originated from a specific feeder, the model itself is applicable to any system with a similar structure.

A simplified diagram of the distribution system structure is provided in Figure 3.1. At one end, the distribution network is connected to the electrical grid via a 115 kV transmission line. The system is responsible for drawing power from this line, sufficient to meet the demand of the customers, who are connected to the other end of the system via a series of power distribution lines, known as a feeder.

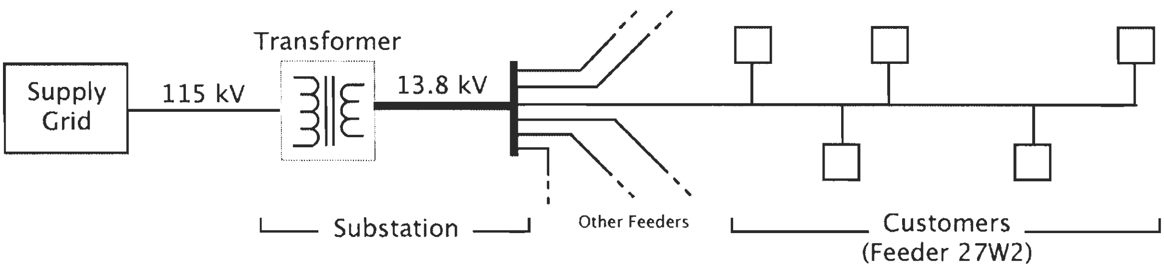

Figure 3.1 - Simplified Electrical Distribution System Structure

Power is produced by generation plants, and made available via the supply grid. This energy is transmitted over high-voltage lines to a distribution substation. At the substation, a transformer is used to reduce the line-voltage before the power is supplied to the customers over street-side power lines.

Given the current structure, all power must pass through a transformer, which resides at the distribution substation. This transformer reduces the voltage of incoming power from 115 kV, to 13.8 kV before it passes through the remaining portions of the system, which consist of multiple distribution branches (feeders) that serve different geographic portions of the surrounding city.

3.4.1.1 - Effects of Retrofitting

Proposed retrofitting implementations would be located at the substation, and would allow power to be drawn both from the 115 kV transmission line and from the installed contingency device. Such an installation would allow the load on the transformer to be reduced when the contingency device is in supply mode, at the expense of increasing the transformer load when the device is in storage mode. That is, the load on the transformer is the sum of the consumer demand for power, and the power flowing into the contingency device. Equivalently, the load on the transformer is equal to the consumer demand for power, *minus* the power flowing *out of* the contingency device.

3.4.1.2 - Translation to a System Dynamics Model Sector

Within the devised system dynamics model, the electrical distribution sector simply serves the purpose of computing the aforementioned sum of power flows. This sector can be thought of as the top level of the model. The consumer demand and the contingency load are completely exogenous to the sector, and are generated in the load data sector, and the contingency device sector, respectively.

The electrical distribution sector consists of a single flow ('Compensated Load'), which is equal to the difference of the consumer demand, minus the contingency output (which has been disaggregated into two variables: 'Charging Power', and 'Discharging Power' of the contingency device). The compensated load flow represents the load on the main power transformer at the substation, and is thus one of the most important indicators of system performance. The structure of the electrical distribution sector is shown in the figure below.

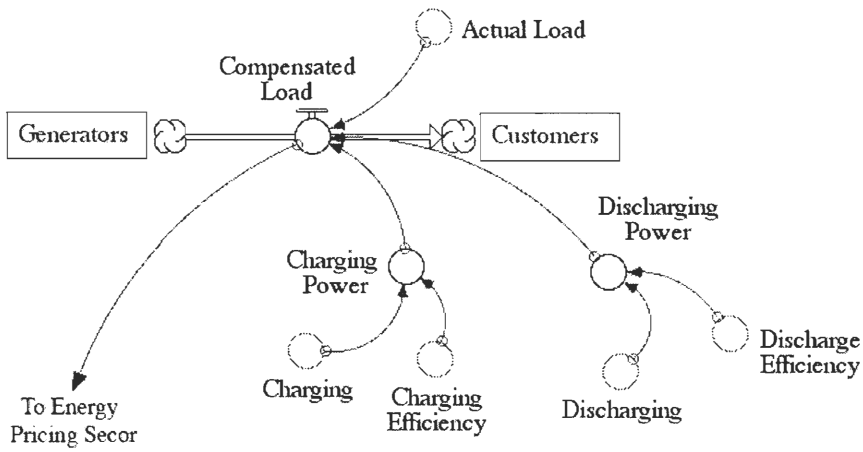

Figure 3.2 -Electrical Distribution Sector Structure

The electrical distribution sector of the model provides a means for simulating the power flows at the substation. Here, the contingency device output is subtracted from the consumer demand, or actual load, to obtain the compensated load, which is handled by the substation transformer.

The functionality of the model's electrical distribution sector can be verified by applying a set of test patterns in place of the actual sector inputs, and observing the resulting behavior within the sector. For testing purposes, the load was set to 3 MVA, with a sinusoidal fluctuation of ±1 MVA. The contingency device output was taken as a sinusoid of equal period (24 hours), but with an amplitude that was swept from 0 to 1 MVA. The following figures contain plots of the test patterns, as well as the corresponding behavior of the sector. The additive nature of the sector's structure is easily verified by viewing the shape these waveforms. As the contingency device output approaches the amplitude of the load fluctuations, the compensated transformer load approaches a straight line, corresponding to ideal load compensation.

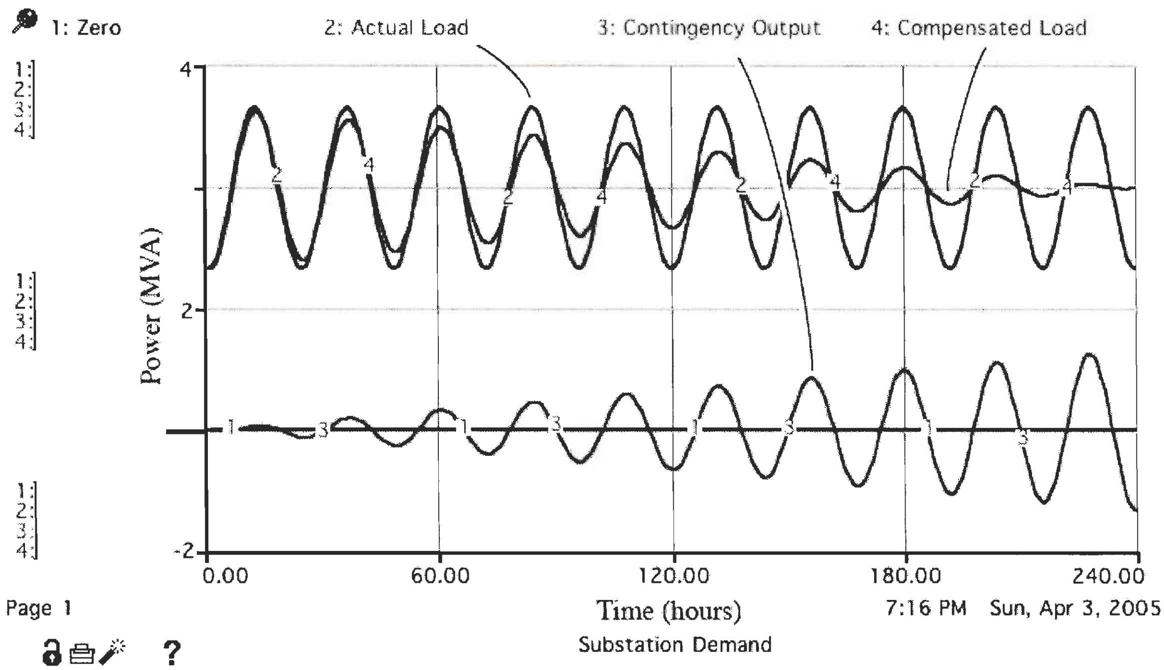

Figure 3.3 - Electrical Distribution Sector Behavior

The upper plot shows the actual demand for power, and the compensated transformer load. The lower plot shows the output of the contingency device. It can be seen that as the contingency device output increases, the load on the transformer decreases, thereby verifying the functionality of the model sector.

3.4.2 - Load Data Sector

Although the processes that result in the demand for electrical power do not lie within the model boundaries, the resulting load must be available as an input to the various model sectors. The load data sector was created to serve this purpose. Within this sector, loading patterns can either be generated mathematically, using time-dependent equations, or they can be reproduced from actual load data, which can be imported in the form of periodically sampled waveforms. Such loading pattern data was provided by the National Grid, for the inclusion in the distribution system model and analysis, and is shown in the plot below.

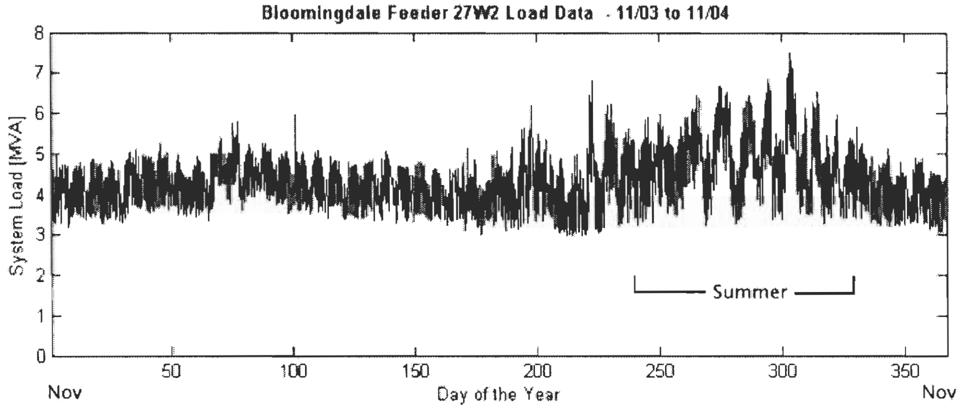

Figure 3.4 - Actual Load Data, Bloomingdale Feeder 27W2

National Grid, the project sponsor, provided actual load data from the feeder under study. This data, plotted above, shows peaks in demand occurring during the summer months.

In order to obtain a better understanding of the characteristics of the loading pattern, a spectral analysis was conducted. Using Matlab (v 7.0) digital signal processing software, a Fourier transform was applied to the load data. The following plots contain the resulting frequency-domain data, and show varying degrees of detail. The base load, of approximately 4 MVA, has been omitted from the plots. Figure 3.5.1 shows the entire spectrum, up to the maximum measurable frequency (12 cycles/day) for the given sampling rate of one sample per hour. Figures 3.5.2 through 3.5.4 show consecutively lower frequency ranges, in order to reveal longer trends.

The frequency domain data show large fluctuations on a daily basis, indicated by a large spike at 1 cycle/day. The second largest spike (Figure 3.5.4) results from yearly fluctuations in power use, which likely occur due to the use of air conditioning during the summer months. Oscillations with periods of 1 week, 1.3 weeks, 2 weeks are also apparent, and are probably related to the cycle of business, weather, and other factors.

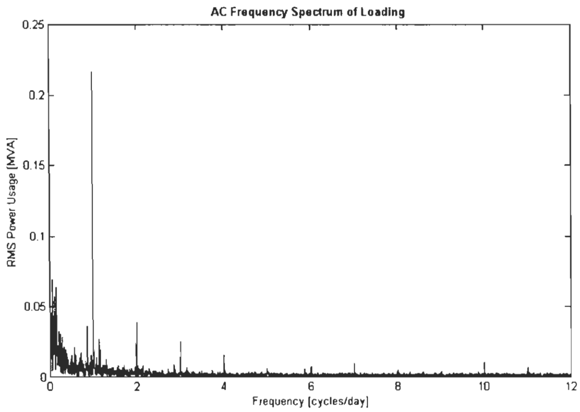

Figure 3.5.1 - Frequency Spectrum of Load
A Fourier Transform of the load data reveals large daily fluctuations.

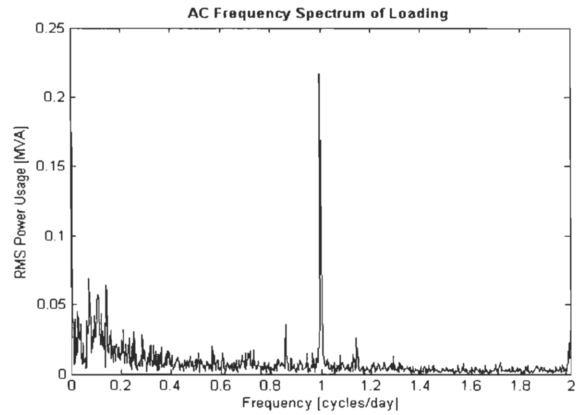

Figure 3.5.2 - Frequency Spectrum of Load (detail)
A closer look at the daily load fluctuations.

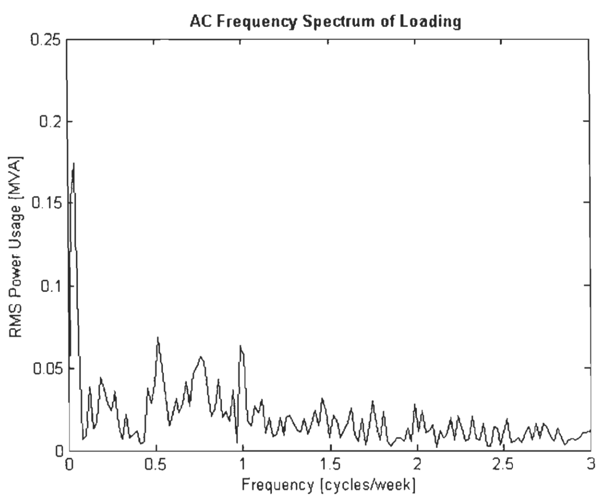

Figure 3.5.3 - Frequency Spectrum of Load (detail)
Further examination exposes weekly trends in the loading pattern, which have been attributed to weather patterns.

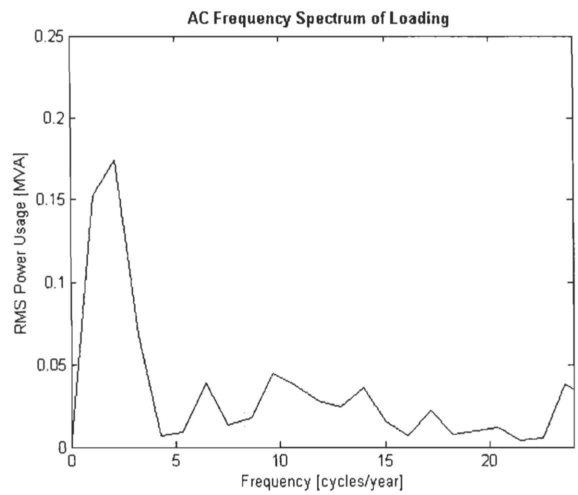

Figure 3.5.4 - Frequency Spectrum of Load (detail)
Finally, a spike corresponding to a large yearly fluctuation in the load may be seen.

3.4.2.1 - Implementation Details

Within the iThink model, the given load data are stored in graphical function objects. Six (6) of these objects (named Dat1 through Dat6) were needed to store the entire data set, due to the size limitations within the program. Each of these data subsets were given a time different offset, in order to create waveform partitions, which can be added to reproduce the full-length data set. This reconstruction by superposition is accomplished in a converter object labeled 'Real Load Data'. The necessary equation was entered as simply: 'Dat1 + Dat2 + Dat3 + Dat4 + Dat5 + Dat6'.

To better illustrate the method for constructing the aforementioned data partitions, a screen capture of the graphical function data entry window for Dat2 is shown below. The offset of 1440 hours can be seen in the number entry box below the x-axis of the plot. The load data for the partition are listed in the rightmost column of numbers, and were pasted there after being copied from a spreadsheet containing the data.

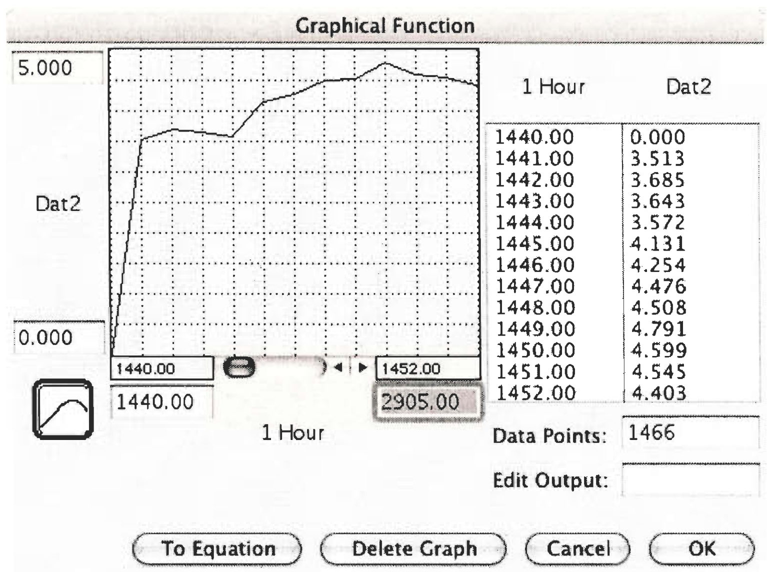

Figure 3.6 - Data Entry Interface for Dat2 Load Data Partition

The load data provided by National Grid was entered into the model using graphical function objects, which are capable of storing arrays of data.

In addition to the actual load data, two additional loading patterns are generated in the load data sector. These waveforms may be used for model testing during sector development, and for construction of unique loading patterns during scenario analysis.

To provide a non-sporadic test pattern, with uniform amplitude and movement, which can serve as a controlled means for checking the model for behavioral inconsistencies, a simple sinusoidal waveform is used to represent daily fluctuations in the load. This pattern is easily created using a built-in iThink function, 'COSWAVE'. This function accepts two parameters, amplitude and period, which are entered in the form COSWAVE(amplitude, period). In this particular instantiation of the sinusoidal test pattern, a base-load of 4.4 MVA is added to the periodic fluctuations, and the phase of the sinusoid is rotated by 180 degrees. The exact formulation used is: - COSWAVE(0.5,24)+4.4, where 0.5 represents a 1MVA peak-to-peak fluctuation in the load, 24 specifies an oscillation period of twenty-four hours, +4.4 provides the aforementioned base load, and the negative provide the desired phase shift.

When a test pattern is need, which is more realistic than the sinusoidal waveform, a graphical function object can be switched-in, to allow any arbitrary, periodic loading pattern to be used. By default, the object contain the loading pattern for an average day. This test pattern was generated by taking each 24-hour period from the given load data, and averaging them together. The resulting waveform was inserted into a graphical function object in iThink, which can easily be modified to provide any periodic waveform.

Generated in the manner described above, the test patterns do not change over time, and the actual load data will repeat each year. In order to simulate the natural growth in demand, two scaling functions are provided. The first is a simple linear growth rate, entered as Rate*(Time)+1. The second is based on growth projection provided by the National Grid, which predicts that the demand will increase each year, but at a decreasing rate. Currently, this trend is approximated using a square-root function of the form: SQRT(0.117*(Time/8784)), which can be adjusted to place the time of system saturation at any point. The values listed will result in a simulated saturation time of five years.

Figure 3.7 shows the load data sector. The various waveforms mentioned above may be selected by altering the value of the 'Load Data Switch' object. Any loading pattern may be combined with either growth rate (or used without growth) according to Table 3.1.

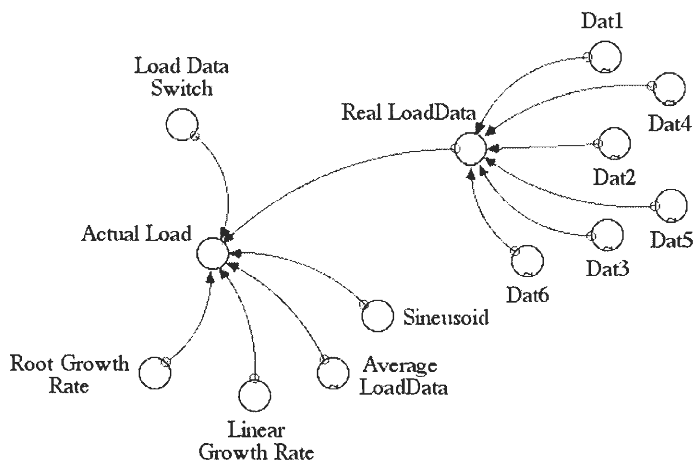

Figure 3.7 - Load Data Sector

The load data sector generates various loading patterns, which may be used for model testing, of for scenario simulation. The Load Data Switch the model user two select between: a sinusoidal loading pattern, and arbitrary or average loading pattern, or to choose actual load data. The growth of the load may be selected as a linear, or 'root' trend.

Switch Value	Loading Pattern	Growth
1	Sinusoidal	None
2	Arbitrary Periodic Function	None
3	Actual Load Data	None
11	Sinusoidal	Linear
12	Arbitrary Periodic Function	Linear
13	Actual Load Data	Linear
21	Sinusoidal	N.Grid Projection
22	Arbitrary Periodic Function	N.Grid Projection
23	Actual Load Data	N.Grid Projection

Table 3.1 – Load Data Switch Settings

This table shows the Load Data Switch setting, and which loading pattern/growth trend they correspond to.

3.4.2.2 - Functionality Verification

The following set of figures demonstrates the functionality of the load data sector. Sector output is displayed for five switch values (1, 2, 3, 11, and 12). The first three plots contain three days worth of data, and show the detail of the loading patterns. The last two plots show three years worth of data, in order to reveal the long-term shape of the load, for each growth trend.

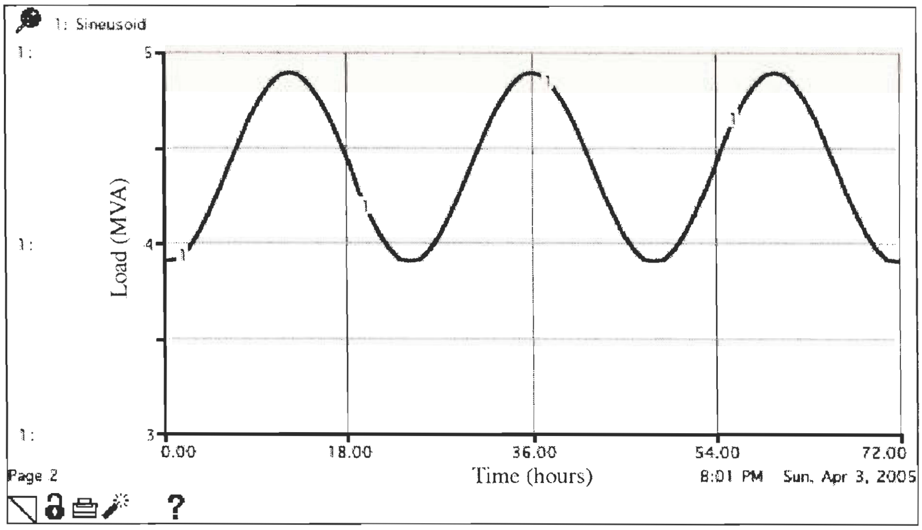

Figure 1.8 - Sinusoidal Load

This plot illustrates the sinusoidal loading pattern, and shows a three-day period.

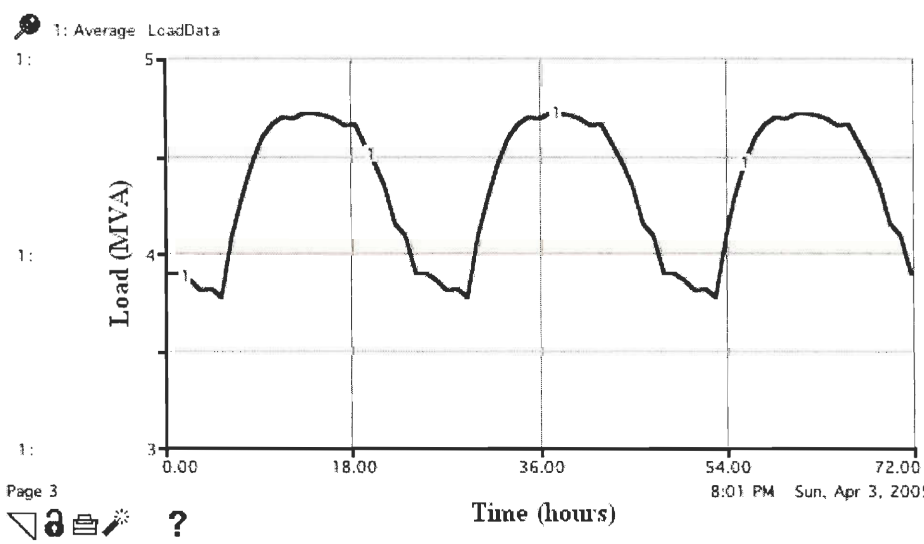

Figure 3.9 – Arbitrary Load

This plot illustrates the, graphical-function-based, arbitrary loading pattern for a three-day period. This graphical function may be edited in order to simulate and periodic loading pattern.

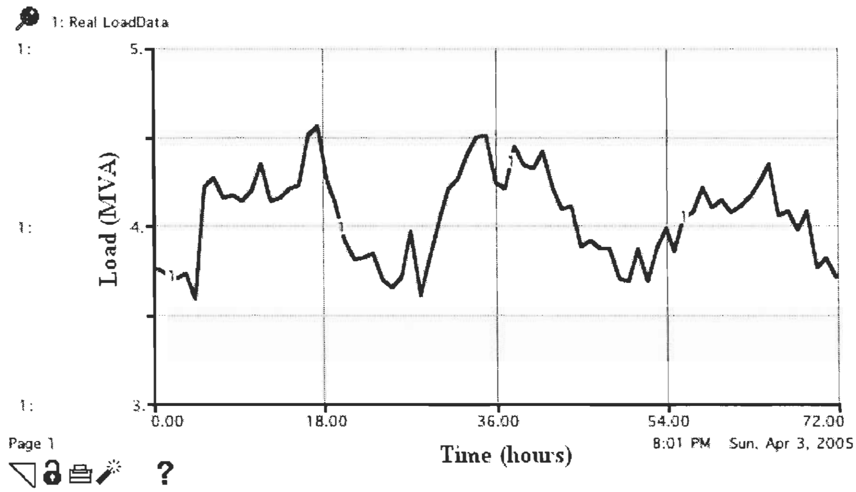

Figure 3.10 - Actual Load

This plot shows actual load data, which was provided by National Grid. This data may be used as input to the model when an accurate simulation is desired.

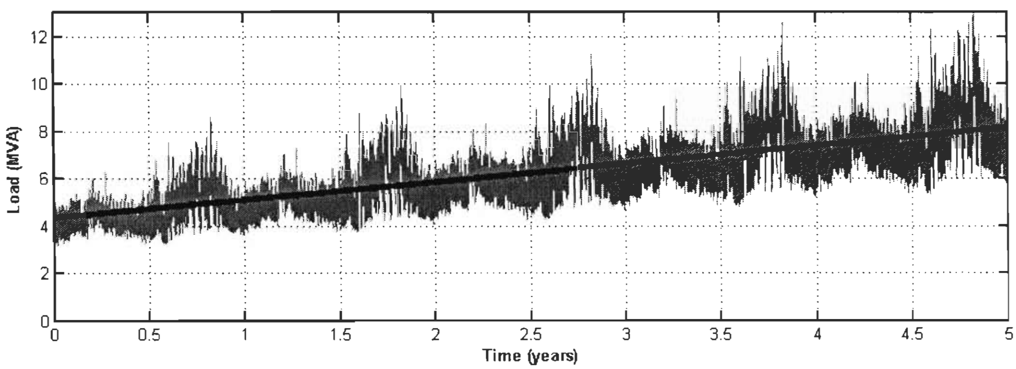

Figure 3.11 - Actual Load with Linear Growth

This plot shows a linear growth in demand over a period of five years.

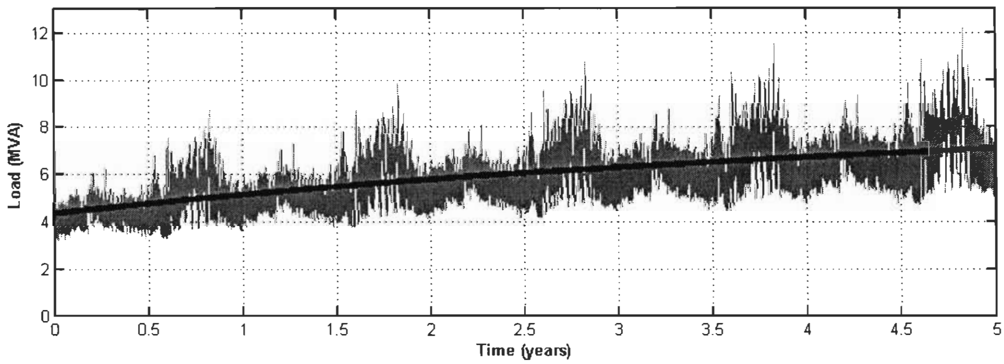

Figure 3.12 - Actual Load with Linear Growth

This plot shows a 'root' growth trend period of five years, the demand increased over time, but at a decreasing rate

3.4.3 - Energy Pricing Sector

In order to simulate the economic aspects of substation retrofitting, a model sector was developed, which calculates the cost of energy purchased by the National Grid, for distribution via the feeder. Currently, the National Grid operates on a yearly contract with those who generate the power they distribute. However, through discussion with N.Grid, it was decided that a three-tiered pricing structure is an accurate method for modeling the true cost of energy production. This pricing structure is based of the assumption that it is appropriate to disaggregate the price of energy into: one price for energy consumed at a power which is considered part of the consistent 'base-load', a second price for additional power necessitated by daily fluctuations in demand (the ‘cycling-load’), and a third price for the 'peaking-load', comprised by large spikes in demand. Given this pricing structure, the model must be capable of decomposing the demand, according to pre-set tier thresholds.

3.4.3.1 - Implementation Details

The input to the energy pricing sector is the current load on the transformer, i.e. the amount of power being drawn from the 115kV supply lines. This value undergoes a series of threshold operations, during which it is compared to the chosen tier-levels. Figure 3.13 shows the sector structure, as in appears in the iThink model.

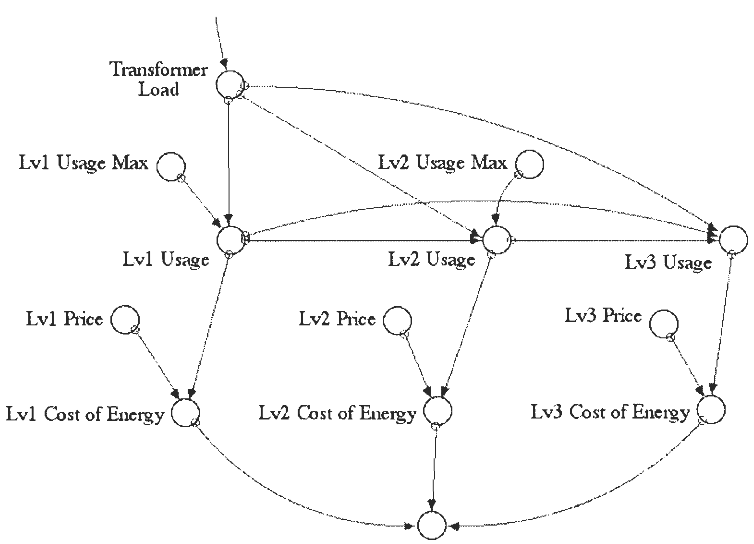

Figure 3.13 - Energy Pricing Sector

The figure shows the energy pricing sector, which computes the cost of the energy being consumed, given the current level of demand (entering at the top of the sector). A three tiered pricing structure is implemented using a set of comparison operations.

At the top of the diagram, the transformer load can be seen entering the sector as an exogenous input, and echoed by the 'Transformer Load' object. Within the 'Lv1 Usage' object, the load is compared to the tier-1 threshold (stored in 'Lv1 Usage Max'). This comparison, calculated as the minimum of the two values, results in a value equal to the amount of power used in tier-1; this is commonly referred to as the 'base load'. A similar comparison is done in the 'Lv2 Usage' object. But in this case, the tier-1 usage is subtracted from the result, to obtain the value of the 'cycling load'. Finally, the 1st and 2nd tier usage levels are subtracted from the total transformer load, to give the peaking load, or tier-3 usage ('Lv3 Usage'). The amount of power used in each tier is multiplied by the corresponding tier price (stored in 'Lv1 Price' through 'Lv3 Price'). The costs of energy from the three tiers are summed to obtain the total cost of the energy being purchased, given the current rate of consumption.

3.4.3.2 - Functionality Verification

To demonstrate the behavior of the energy pricing sector, a sinusoidal test pattern was applied as the transformer load. The average load was set to 3 MVA, and the amplitude of the daily sinusoidal fluctuation was set to 2 MVA peak-to-peak. The tier thresholds were set to 2.5 MVA, 3 MVA, and 3.5 MVA for tiers 1, 2, and 3 respectively. The following plots illustrate the resulting behavior of the sector. The first plot demonstrates how the transformer load is broken down into three portions --according to the threshold values-- by showing the transformer load, and the load in each tier. The second plot shows the costs associated with energy consumption, given tier 1, 2, and 3 energy-prices of $80, $95, and $120, respectively. The cost for each tier is shown, along with the total cost. To illustrate the effect of the tier-based pricing structure, a third plot is provided, which compares tier-based cost to the cost which would result from a single-tiered pricing structure. The distortion of the sinusoid is apparent, and corresponds to the increased expense associated with demand above the base load.

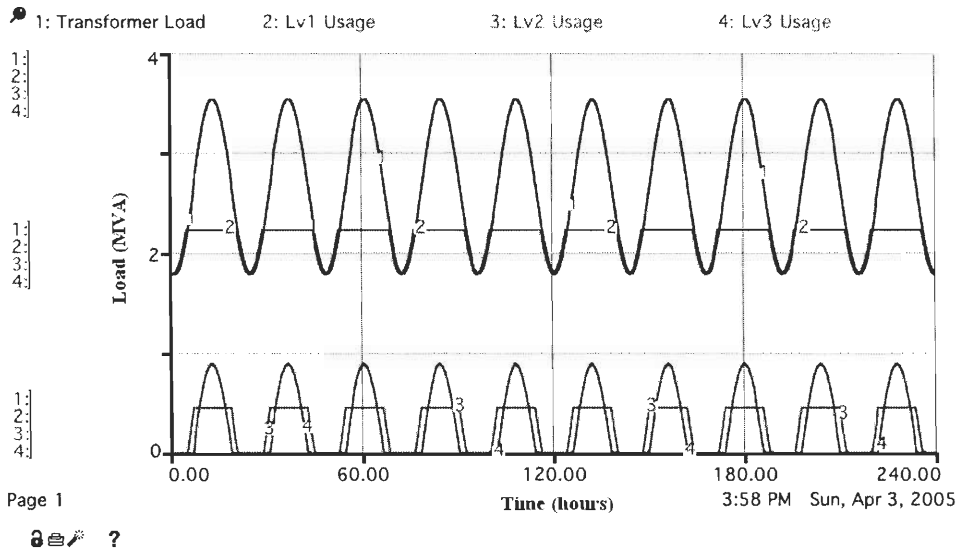

Figure 3.14 - Aggregated and Disaggregated Demand

The decomposition of the load (1) into the three pricing tiers (2, 3, & 4) may be observed in this figure.

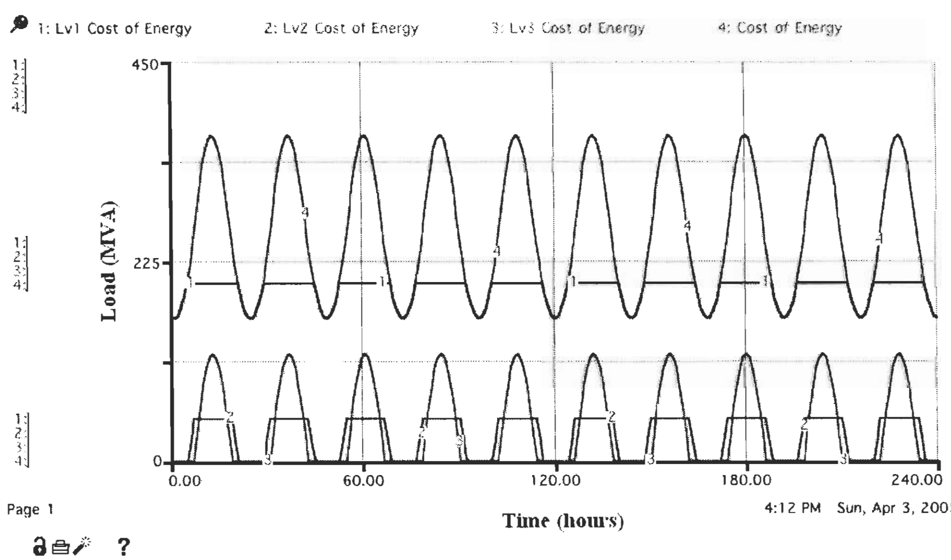

Figure 3.15 - Tier-Based Energy Costs

The cost of energy consumed at each tier is shown (2, 3, & 4). The different tier prices affect the magnitude of each plot, as compared to the magnitudes in Figure 14. The total cost of energy is shown (1). A distortion of the sinusoidal load shape is visible, and due to the increase of energy costs at higher demand levels.

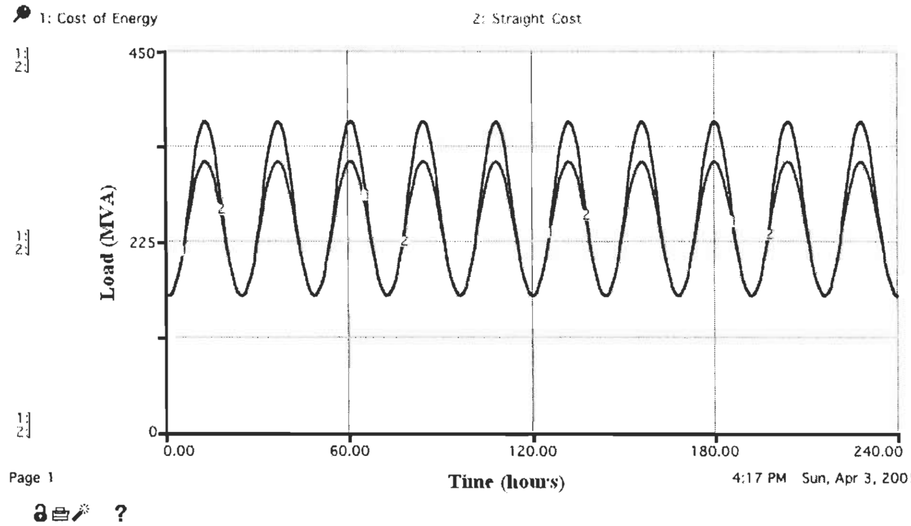

Figure 3.16 - Energy Costs Three-Tier VS Single-Tier

Figure 15 illustrates the difference between a three-tiered pricing structure, and a flat-rate structure. The distortion of the sinusoidal load shape is more visible when compared to the undistorted shape. Due to the increase of energy costs at higher demand levels, the three tiered cost is significantly greater.

3.4.4 - Energy Storage Sector

The purpose of the model described herein is to provide a tool for simulating a distribution system, with a retrofitting subsystem that allows energy to be stored at the feeder substation. The energy storage sector was designed to behave in a manner which mimics the behavior of such a subsystem, and to provide insight into the overall behavior of a retrofitted distribution system.

3.4.4.1 - Modeling Energy Storage

In order to model a device capable of storing and releasing energy, a stock object, and two flow objects are used. The value of the stock, which represents the amount of energy contained within the storage device, is equal to the stock's pre-set initial value, plus the integral of the flow of energy into the stock, minus the integral of the flow of energy out of the stock. These flows represent power drawn from the transformer for the purpose of charging the device, and power supplied to the feeder as the device is discharged. Within the iThink model, they are labeled as 'Charging' and 'Discharging', respectively. The stock itself is labeled as the 'Contingency Device Charge'.

In addition to the fundamental behavior of energy storage, the limitations of the contingency device must be accounted for. All energy storage devices have a limit to the amount of energy they can store, known as the storage capacity. Furthermore, the rate at which such devices can be charged and discharged is finite as well. For the purposes of the model described herein, these limits have been implemented as adjustable model parameters, but are assumed to be unaffected by environmental variables such as temperature, and to be constant over the lifespan of the device.

3.4.4.2 - Storage Capacity Limit

The storage capacity of the simulated contingency device is determined by the output of the ‘Implemented Storage Device Capacity’ object, and typically falls within the range of a few MVAh for the feeder under study. The value of this object is computed using the output of two other objects: ‘Storage Device Capacity’ and ‘Storage Device Implementation Switch’. Storage device capacity is a straightforward parameter (given in MVAh), which may be set by the user, to match the retrofitting solution under analysis. The storage device implementation switch structure is provided to allow flexibility in terms of the year of retrofitting implementation. The storage device implementation switch object takes on a value of either 0 or 1. A value of 1 is asserted if the current year is greater than the implementation year *and* the device age is not beyond its pre-set lifespan, otherwise, a value of 0 is asserted. Given this behavior, the storage device capacity may be multiplied by the storage device implementation switch value to obtain the system’s present energy storage capacity.

3.4.4.3 - Charging and Discharging Rate Limits

The *maximum* rate at which the storage device can be charged or discharged is limited by the abilities of the inverter hardware. The *desired* rate of charging/discharging is based upon the current storage device charge and the amount of available power (or demand for additional power). In the current model instantiation, the capacity of the inverter is implemented as a user-adjustable parameter, accessible via the ‘Inverter Capacity’ iThink object. The flows into and out of the ‘Contingency Device Charge’ stock have been limited using a ‘minimum’ function with inputs of: the demand for charge/discharge, and the inverter capacity. The output of this function is always equal to the smaller of the two inputs, and thus the device will never charge or discharge at a rate which is higher than the smallest limiting factor.

3.4.4.4 - Flow-Control – Charging and Discharging

In ideal conditions, without limitations on storage device or inverter capacity, all short-term fluctuations could be eliminated from the load. In this case, the optimal threshold for controlling the charging and discharging of the storage device would be equal to the average load over the maximum period of fluctuation (in this case 1 year). This kind of ideal load-leveling would result in a steady loading pattern, with no fluctuations, apart from the overall growth of the demand for energy. Obviously, implementing a system with this kind of capability is impossible.

In order to obtain an understanding of how a more realistic retrofitting implementation would behave, a method of simulation and analysis may be employed. This can be accomplished using the devised system model, which can be used to observe the effects device limitations, and weigh the advantages and disadvantages of various retrofitting schemes.

3.4.4.5 - Implementation Details

Assuming that the inverter has sufficient capacity, the rate of charge/discharge is a function of three parameters: the current device charge (labeled as the 'Capacity/Charge Discrepancy'), the available power relative to the threshold ('Threshold Power Availability'), and the storage system efficiency ('Charging Efficiency' and 'Discharging Efficiency'). Each of these parameters involves a model sub-structure, used for calculation of the parameter value for the current simulation time step. These dynamic structures determine the behavior of the contingency device, and have been designed to allow simulation of a simplified energy storage device which conforms to the limits outlined above. The top level of the energy storage sector is shown in Figure 3.17.

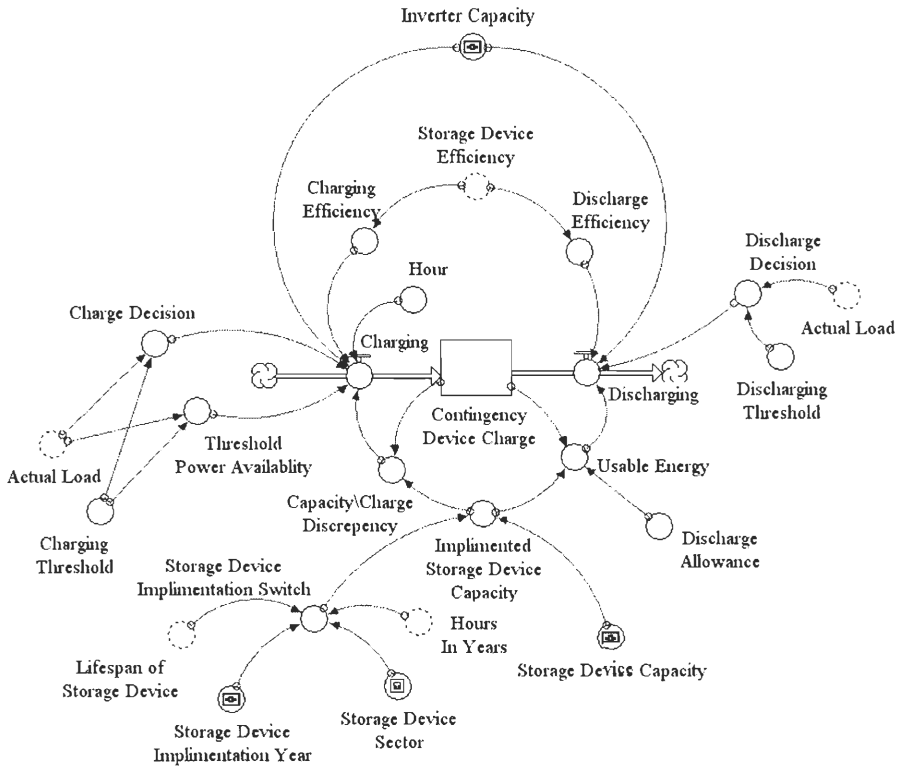

Figure 3.17 – Top-Level Structure – Energy Storage Device Sector

The structure of the energy storage device structure was designed to simulate the algorithms used to control an energy storage contingency device. The device charge is modeled as a stock. The charging and discharging rates are modeled as flows. The structures linked to theses flows control the behavior of the according to the current load on the feeder, the charging/discharging threshold, and the time of year.

3.4.4.5.0 – Charging/Discharging Threshold

Within the iThink model, charging and discharging of the energy storage device is controlled using a set of charge management and load management rules. The most important of these rules relates to the charging/discharging threshold. Given a certain instantaneous demand for power, the level of that demand is compared to the present charging/discharging threshold in order to determine how much energy should be stored or released by the contingency device during the current simulation time-step. A demand which is above the threshold warrants the release of energy, in order to compensate for the associated peak in energy consumption. A level of demand which is below the threshold indicates an opportunity to store energy.

If the proposed energy-storage-based retrofitting solution were to be designed and implemented at a real power substation, calculation of the charging/discharging threshold would be one of the most challenging aspects of the control-system development. This is primarily due to the unpredictable nature of the load. Close attention should be paid to weather forecasts, as summer temperature peaks correspond closely to the yearly peak in energy demand. Optimally, some feedback should exist between the consumer and the distributor, so that the distributor may preempt an increase or decrease in consumer demand, with a corresponding adjustment of the charging/discharging threshold.

The current model implementation takes advantage of the fact that the loading pattern is known in advance. This represents the assumption that a good method for daily load prediction can be implemented. Using this knowledge of the future load, the charging/discharging threshold is chosen based upon four factors:

- The time of year, or season
- The average load for the current day
- The current level of charge in the energy storage device
- The total capacity of the energy storage device

3.4.4.5.1 - Seasonal Threshold Variation

During the fall, winter, and spring, the distribution system does not experience its seasonal peak. Therefore, the main goal of the contingency device during these times is to level the load by reducing daily fluctuations. This can be accomplished by choosing a threshold that resides near the average load for the day. During the summer, the system experiences a large peak in demand, due to high temperatures, and the use of air conditioning equipment. For these months, the primary goal of the contingency device is to reduce the *over-all* peak in demand, in order to reduce the stress on the main substation transformer. This goal is important, and is pursued at the expense of neglecting some of the less significant daily fluctuations, which do not represent a threat to the transformer's useful lifespan. By neglecting these low-demand-level fluctuations, which might occur for example during a cooler summer week, a high level of charge may be accumulated in the contingency device. This surplus may then be reserved for the true summer peaks, at which time it may be released to the consumer, thereby reducing the burden on the substation transformer, and extending its useful lifespan. This seasonal threshold variation is illustrated in Figure 3.18.

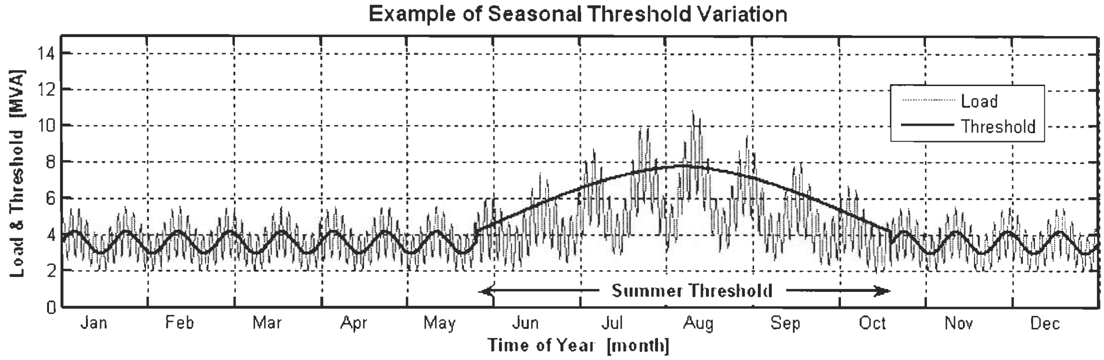

Figure 3.18 – Example of Seasonal Threshold Variation

A simplified theoretical load is shown in gray, and exhibits daily, weekly, and seasonal fluctuations. The corresponding threshold is shown in black. During the winter, early spring, and late fall, the threshold follows the mid-point of the load to provide reduction of daily fluctuations. During the peak-demand months, the threshold is raised, to insure that charge is reserved for seasonal-peak reduction. Reducing the highest yearly load will help to minimize stress on the transformer, and maximize its useful lifespan.

3.4.4.5.2 - Contingency Device Charge Status

A device which can store large amounts of energy will be capable of a higher degree of load-leveling than a device with a smaller capacity. Likewise, a device which is fully charged can provide more compensation than one which is only partially charged. Therefore, the threshold is also dependent upon the capacity of the chosen device, and on the amount of energy currently contained in that device. As noted, the threshold for and ideal system would be selected such that it resulted in compensation for all load fluctuations. This threshold would therefore correspond to the average system load. This ideal threshold has been used as a starting point for obtaining a realistic threshold in the devised system model.

3.4.4.5.3 – Threshold Calculation Structure

Using the provided load data, a daily load average was computed. The resulting set of averages is used as a model input, in the 'Storage Device Threshold Sector'. The charging/discharging threshold for each day is chosen using this input, and then adjusted according to the behavior of the contingency device as it provides load compensation. When the device charge is below a preset minimum, the threshold is increased, to ensure that the device is not depleted too quickly. This is accomplished using the model structure shown in Figure 3.19.

The threshold calculation is based upon the average load for the day, stored in graphical function objects 'THR Dat1' and 'THRDat2'. During the summer months, the threshold in increased, as specified using the 'threshold max' graphical function object. The contingency device charge is constantly monitored, and compared to the total storage capacity. Using a non-linear function, stored in the 'threshold movement' object, the threshold is adjusted according the level of charge. If the level is low, the threshold is increased. If the level of charge is very low, the threshold is increased more quickly. If the storage device is fully charged, the threshold is lowered. The nonlinear function used for this process, shown in Figure 3.20, was chosen through experimentation, in order to produce a feedback loop that responded quickly, but without over reacting. The 'threshold max' object is used to specify the summer threshold. This threshold was also found experimentally, and prevents charge depletion during the highest summer peak. Because testing was completed using the given load data, this threshold is specific to the loading pattern used.

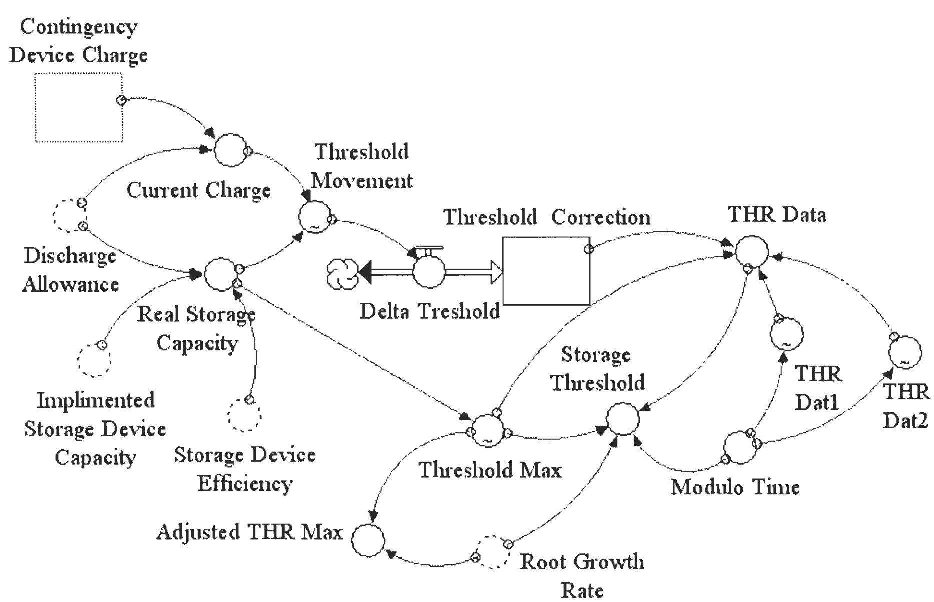

Figure 3.19 – Threshold Calculation Structure

The charging/discarding threshold is based on the average load for the day, stored in the THR graphical function objects. When the effective contingency device change is below the desired charge, the threshold is adjusted using a non linear relationship specified in the threshold movement graphical function. The current simulation time is also factored in, to allow an increase in the threshold during the summer months. This is accomplished using the 'threshold max' graphical function.

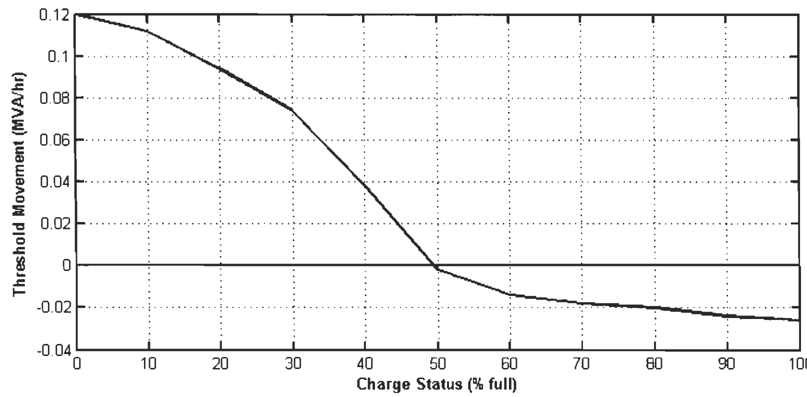

Figure 3.20 – Threshold Adjustment Rate vs. Device Charge Status

The charging and discharging threshold is adjusted according to the current charge status to prevent depletion. This curve is used to determine the movement of the threshold.

3.4.4.6 – Functionality Verification

In order to verify the functionality of the energy storage sector, test loading-patterns were applied, and the charging and discharging behaviors were observed. Figure 3.21 shows the charging behavior of the device, as tested using a sinusoidal loading pattern. It can be seen that charging occurs while the load is below the charging/discharging threshold. Figure 3.22 shows a similar discharging behavior; however, discharging occurs when the demand is above the threshold.

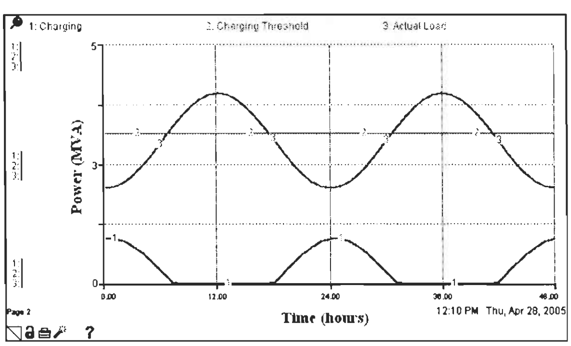

Figure 3.21 Contingency Device Charging Behavior

Charging of the contingency device occurs when the demand is below the charging/discharging threshold.

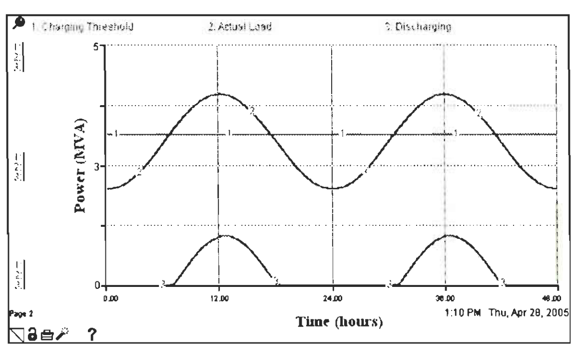

Figure 3.22 Contingency Device Discharging Behavior

Discharging of the contingency device occurs when the demand is above the charging/discharging threshold. Notice that the amount draw from the device is greater than the demand above the threshold. This is due to the efficiency of the storage device, which is less that 1.