

**Determining Load Characteristics for
Transient Performance
Volume 4: Test Results and Analysis**

**EL-850, Volume 4
Research Project 849-1**

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ABSTRACT

This study evaluated a prototype load modeling procedure developed by the University of Texas at Arlington (UTA) in EPRI project RP849-3. Tests were run on three different power systems to evaluate the procedure's accuracy in modeling the dynamic power response of loads (active and reactive) when subjected to limited excursions of voltage and frequency. In support activities, guidelines were developed for the load modeling procedure, and possible data sources for it were investigated.

The period of performance was September, 1976 to July, 1980. The work accomplished by General Electric is reported in a final report of four volumes, the contents of which are as follows:

- Volume I: Executive Summary
An overview and summary of results are presented. Recommendations are made for the research necessary to develop a production grade load modeling procedure.
- Volume II: Load Model Guidelines
Guidelines are developed for a load modeling procedure. Induction motor characteristics and their effect on system stability are examined.
- Volume III: Load Composition Data Analysis
Possible data sources for the load modeling procedure are identified and analyzed as to their potential for use in determining the composition of bus load by component. A methodology is proposed.
- Volume IV: Test Data Analysis
Test results on three power systems are reported and analyzed. An evaluation of the UTA load modeling procedure is made.

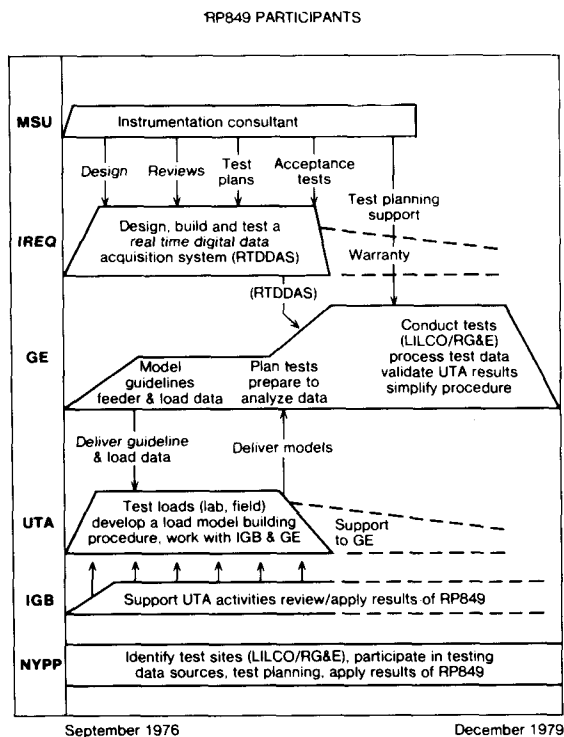


EPRI PERSPECTIVE

PROJECT DESCRIPTION

RP849 involved several participants (see figure below) including three major contractors: Institut de Recherche de l'Hydro Quebec (IREQ), General Electric Company (GE), and the University of Texas at Arlington (UTA). This research was performed to better understand and model the dynamic characteristics of power system loads particularly when they are subjected to abnormal voltage or frequency changes. This 48-month effort was the first large-scale research aimed at forming load models as accurate as those commonly used for generators and other power system components. A mobile, real-time digital data acquisition system (RTDDAS) was designed, built, and used to record load characteristics in substation tests at Long Island Lighting Company (LILCO) and Rochester Gas and Electric (RG&E).

The four volumes comprising EPRI Final Report EL-850, together with EPRI Final Reports EL-849 and EL-851, document the load-model building and testing research performed in RP849. Through this research, significant progress has been made in understanding and modeling the dynamic characteristics of load. However, as discussed in EPRI EL-850, many important problems remain to be resolved. Further research built upon the results of this project should result in a procedure through which utility engineers can significantly improve the accuracy of power system analysis.



SCOPE OF GE WORK

As shown in the figure, the work done by GE was central to the load-modeling research done in RP849. Their overall role was to evaluate the load-model building procedure developed by UTA. This was done by comparing the

responses of utility feeders during staged disturbances to the simulated responses using data describing those feeders. Specifically, the tasks were:

1. To illustrate the effect of varying the types of load models used in computer simulations of power systems
2. To identify and evaluate the utility data sources required in the load-modeling procedure
3. To plan and conduct several power system field tests
4. To use the field test results to evaluate the UTA load-modeling procedure performance and to suggest possible improvements if necessary

CONCLUSIONS

As a result of this work, it was found that a load model can be synthesized by combining the characteristics of individual components that make up the load (e.g., air conditioners, pumps, heaters). To construct this load model the user must know the number of each component that is "on" at the time of interest. Typical response characteristics of each of these components are then combined to form a composite model. This procedure is less expensive, more versatile, and more accurate than the use of field tests to measure load response.

As one part of their work, GE identified sources of data used to count what components of load are "on" at any given location and time. Up to this time, these data, which are now being collected by many utilities for load research and other studies, have not been utilized to study power system transient performance.

The discussion of the use of load models in this report, although somewhat oversimplified, does accentuate the importance of modeling loads in computer studies. The treatment of induction motor modeling, its impact on simulation results, and the computer modeling data supplied are substantial contributions to the body of knowledge of computer analysis of power systems.

The extensive work done to test and analyze the model building procedures developed by UTA has identified both the successes and shortcomings of this procedure. The comparison and analysis of predicted and recorded results demonstrate the validity of the principles of this research and emphasize

the limited validity and usefulness of the present modeling procedure. The large reservoir of unique and valuable test data collected has not yet been fully explored. The analyses and recommendations reported here can be used to plan and perform future research.

Follow-on research is needed to correct the inaccuracy that exists in the reactive power and dynamic response characteristics of the load models. The load-model building procedure must also be simplified before it is suitable for routine use by utility engineers.

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SUMMARY

The overall objective of General Electric's research in the EPRI RP849-1 project was to evaluate, through field tests, the load modeling procedure developed by the University of Texas at Arlington (UTA) in EPRI project RP849-3. The UTA load modeling procedure was used to develop load models for four different load buses on three electric utility systems for different seasons of the year. Extensive field tests at these load buses were conducted to evaluate the load models.

The philosophy implemented in the UTA load modeling procedure is to develop the load characteristics and model for a system bus based on the composition of the system load by component (air conditioning, lighting, etc.) and the voltage and frequency characteristics of those components. When the RP849 research began, it was not certain that sufficient data existed to support such a load modeling procedure. An important part of the General Electric research was to determine the availability and accuracy of data which could be used to synthesize the load composition of a system bus. Subsequently, this data was used as inputs to the UTA procedure to develop load models for the load buses to be tested. The field tests then are being used to not only evaluate the analytical techniques of the UTA load modeling procedure, but also the very load modeling philosophy being attempted.

Early in the overall RP849 project, the EPRI project manager (T. Yau) requested guidance to define the most important characteristics for inclusion in the UTA load component and composite load models. GE provided guidelines for these decisions using transient stability studies with various load models which existed before the RP849 project began. The particular concern was to demonstrate the sensitivity of system performance to various uncertainties in the load model characteristics.

The research and results are summarized here under the three main areas - load model guidelines, load composition data analysis, and load model evaluation.

LOAD MODEL GUIDELINES

Studies were made with a simple 2-machine system to demonstrate the effect of load model characteristics on system transient stability. The measure of stability used in this case was the maximum angle swing between the two machines. The system loads were modeled using models of the traditional polynomial and exponential form, the objective being to demonstrate the effect of present uncertainties in the parameters for such models. UTA, in the RP849-3 project, was to later determine the most appropriate model structures.

The system studies demonstrate the significant effect which load characteristics have on power system stability. Active power characteristics are shown to be most significant, and the nature of the effect of load characteristics on system stability is shown to be dependent on the network configuration, that is, the relationship of the major load and generation areas to one another. One study demonstrated the importance of load model representation relative to excitation system performance, an item generally carefully studied and represented in system stability studies and one representing an investment of up to one million dollars. Although transient stability was the major concern, some consideration was also given to dynamic stability.

Special attention was given to the effect of induction motor load and its dynamics because of the significant portion of the total load made up of this component. Studies were made with the same 2-generator system with induction motor load modeled at a load bus. These results demonstrated that the induction motor load can cause significantly less stable results than for the constant current load model, generally felt to incorporate a significant portion of induction motor load. Some detailed results of these simulations have been documented to indicate the effect of motor load on overall system performance. Motors ranging in size from 10 hp to 5500 hp were considered in the studies. The effects of various modeling assumptions for induction motor characteristics are shown, and the importance of data on motor size, initial loading and shaft load characteristics is demonstrated. Curves showing the steady-state voltage and frequency characteristics of motors of various ratings, initial loadings and shaft load characteristics are provided for reference purposes.

LOAD COMPOSITION DATA ANALYSIS

Fundamental to the load modeling philosophy being attempted in this project is the need for data to synthesize the composition, by component, of the load bus of

interest. The review of load data sources available to the typical US utility resulted in contacts with nearly all of the components (marketing, planning, economic research, etc.) of a present-day utility.

The data analysis has demonstrated that the load composition of a system bus can be synthesized using data sources which define the devices connected to the bus (load inventory data) and data sources which define the portion of those connected loads which are on at the time of interest (load utilization data). Sources of load inventory data are utility appliance saturation surveys, US census data, component sales data, and utility billing data. Sources of load utilization data are largely made up of load research studies conducted by the electric utilities. These studies make use of demand recorders on sample sets of devices or loads to record the demand at regular intervals (typically 30 minutes) over some period of time (typically 1 year).

Although the data sources in the commercial and industrial sectors are not as prevalent as in the residential sector, the classification by the government and utilities of establishments by Standard Industrial Classification (SIC) is tending to make this data more available as are recent government regulations which require the collection of this data. Also, many commercial and industrial establishments are metered for demand as well as energy.

The methodology of determining load composition using the data sources has been applied to four different utility substations, and an example calculation for one substation is provided. Although problems do exist in obtaining the desired data at all substations, the component method should provide utilities with a significantly more accurate load modeling procedure than exists today.

LOAD MODEL EVALUATION

The UTA load modeling procedure has been evaluated using results from extensive tests at four different substations. Two test sites were used on the Long Island Lighting Company system, and one test site was used on the Rochester Gas & Electric Company system. The fourth test site was located on the Montana-Dakota Utilities Company System. It should be noted that the UTA load modeling procedure itself does not require field tests. On the contrary, the whole thrust of the RP849 Project is to be able to develop load models from typical utility data sources without resorting to field tests.

The LILCO test sites provided mainly residential, rural load areas while the Rochester Gas & Electric Company test site, which consisted of a major portion of downtown Rochester, provided a mainly commercial load. Thus, different classes of loads were tested. Tests were run at each test site during the summer of 1978, the following winter and at one test site on the Long Island Lighting Company system during the summer of 1979. The series of tests at each test site made possible an evaluation of the ability of the UTA load modeling procedure to 'track' the seasonal changes in load composition. Many tests were run during each of these test series, lasting typically a week at each test site. The load tap-changing (LTC) transformers were used to change voltage over a maximum range of $\pm 10\%$. Significant changes in voltage were also accomplished by switching of capacitor banks. At the Southold, LILCO test site a gas turbine-generator, delivering reactive power only, was tripped off the line to produce the most significant changes in voltage. The Southold test site also provided the unique opportunity to determine the frequency response of loads. This load was isolated on the gas turbine-generator, and frequency was varied over a range from 57 to 63 Hz. Changes in voltage were also made in this isolated condition. Several such isolated tests were run during the three different seasons, providing a bank of frequency response data which is unique.

The fourth test site was provided in conjunction with a staged fault test on the Montana-Dakota Utilities Company system in November of 1978. A portion of the Bismarck, North Dakota load was monitored during this fault test, during which voltage reached a low of approximately 40%. This test provided an excellent opportunity to evaluate the capability of the UTA load modeling procedure to model load dynamics. Steady-state voltage change tests were also made at this test site.

The test data from all tests was recorded on magnetic tape with a real time digital data acquisition system (RTDDAS) developed by the Institut de Recherche de l'Hydro-Quebec (IREQ). The data recorded consists of the three phase voltages and currents sampled at rates of from 60 to 150 samples per cycle. These tapes are available for future research. Data processing programs were developed to calculate active and reactive power from the instantaneous voltages and currents.

The UTA load modeling procedure has been found to accurately model the steady-state active power voltage characteristics. Further, the procedure has been found to correctly 'track' the changes in load composition that occur from the summer to

winter seasons. Although there are differences between model and test results at some test sites, the UTA load modeling procedure provides a significant improvement over present load modeling procedures.

The tests indicate that there are significant differences between the model and test results for the steady-state reactive power voltage characteristics. The model consistently predicts a lower nominal value of reactive power, and a lower sensitivity to voltage changes than observed during the tests. The most likely sources of error in the model reactive power voltage characteristics are shown to be the component models used for induction motors, fluorescent lights, and distribution transformers. Future research in the load component area would improve the modeling of the reactive power voltage characteristics.

Although there are significant differences on a percentage basis between the model and test results for the active power frequency response, both agree that active power is quite insensitive to frequency changes for the Southold substation. There are significant differences, however, between the model and test reactive power frequency responses. In several cases, the model and test results gave changes in reactive power in opposite directions. The tests also indicated a greater sensitivity of reactive power to frequency changes at high voltages and low frequencies; the model structure is unable to match this characteristic. It may be attributable to saturation of distribution transformers. Again, future research is required.

Identification of load dynamics was aided by the use of the load admittance characteristics in preference to the active and reactive power characteristics. Load admittance allows a separation of the static and dynamic components of load and removes the compounding effect of system voltage changes during transients. As predicted by the model, the dynamic load responses were approximately exponential. However, the active and reactive power responses had different time constants, both of which were significantly greater (2 to 10 times greater) than the single time constant predicted by the UTA load modeling procedure. The UTA model does not adequately model load dynamics.

The recommended research on components should improve the capability of the UTA procedure to model the reactive power voltage and frequency characteristics. A different approach will likely be necessary to model load dynamics.

Section 1

INTRODUCTION

The overall objective of General Electric's research in the EPRI RP849-1 project was to evaluate the load modeling procedure developed by the University of Texas at Arlington (UTA) in EPRI project RP849-3. This evaluation proceeded as follows at several substations: (1) the UTA load modeling procedure was used to develop a model for the substation load; (2) field tests were conducted to determine the load characteristics (active and reactive power as functions of voltage and frequency) of the substation; (3) test results were analyzed as necessary to evaluate the load model developed by the UTA procedure; (4) when possible and necessary, the evaluation (steps 1 through 3) was repeated for different seasons of the year.

This volume describes the evaluation of the UTA load modeling procedure made using the field test results and subsequent analysis. The conclusions of the evaluation are given in Section 2 of this volume.

Section 3 describes the tests run at each test site, and Section 4 describes the evaluation in detail.

For reference purposes, the complete description of the UTA load modeling procedure is given here in Appendix A, and the load compositions for the test sites are given in Appendix B.

Section 2

CONCLUSIONS

The comparison of model and test results (Section 4) has led to the following conclusions concerning the UTA load modeling procedure. The conclusions relative to the ability of the procedure to model the steady-state voltage response, the steady-state frequency response, and the dynamic response characteristics of loads are presented separately.

STEADY-STATE VOLTAGE RESPONSE

Active Power

The modeling procedure accurately models the steady-state active power voltage characteristics. Both model and test results indicate that, for the substations considered, active power changes linearly with voltage, and there is little variation in this characteristic with time of day. Further, the modeling procedure is able to correctly 'track' the changes in load composition which occur from season to season.

The following observations, although not leading to firm conclusions concerning the UTA load modeling procedure, should be of use in future load modeling research: (1) significant changes in the sensitivity of active power to voltage changes were observed during the tests within short periods of time (less than 10 minutes). These changes were apparently due to load composition changes, and there was little change in the mean load characteristics with time of day. (2) The results of the GT trip tests indicate that the active power voltage characteristic may be linear over a greater range than was accomplished with the LTC tests (+10%).

The UTA load modeling procedure should provide improved accuracy in modeling the steady-state active power voltage characteristics.

Reactive Power

There are significant differences between the model and test results for the steady-state reactive power voltage characteristics. The model predicts lower values of reactive power for given values of active power, and lower sensitivities to voltage changes than observed during tests.

Likely sources of error in the model for reactive power voltage characteristics are the component models used for induction motors, fluorescent lighting, and distribution transformers. Additional data on the steady-state reactive power voltage characteristics of these components should improve this aspect of the UTA modeling procedure.

STEADY-STATE FREQUENCY RESPONSE

Some difficulty was experienced in determining the frequency sensitivity of loads from tests. Significant voltage changes were found to occur during the tests when frequency was changed, and it was necessary to fit polynomials to both of these changes. More significant changes in both frequency and voltage within a short period of time (1 minute) would have improved the accuracy of the curve fits.

Both the model and test results for the LILCO, Southold substation indicate that increases in frequency cause increases in active power. Although the model and test frequency sensitivities differ significantly on a percentage basis, they are both quite small. Both model and test results indicate a decreased frequency sensitivity with the winter composition.

There are significant differences between the model and test reactive power frequency sensitivities. In several cases, the model and test results gave changes in reactive power in opposite directions. The tests indicated a greater sensitivity of reactive power to frequency at high voltages and low frequencies; the UTA model structure is not able to match this characteristic. It may be attributable to saturation effects.

The UTA load modeling procedure does not accurately model the steady-state frequency response of loads.

DYNAMIC RESPONSE

The estimation of the parameters of the UTA model for dynamics is simplified by the use of the load admittance characteristics instead of the active and reactive power characteristics. Use of the load admittance allows the separation of the static and dynamic components of load and removes the compounding effect of system voltage changes during transients.

As predicted by the model, the dynamic load responses were approximately exponential. However, the active and reactive power responses had different time constants, both of which were significantly greater (2 to 10 times greater) than the single time constants of the dynamic models.

The UTA load modeling procedure does not accurately model load dynamics.

Section 3

DESCRIPTION OF TESTS

Tests were run at distribution substations of three different electric utility systems - Long Island Lighting Company (LILCO), Rochester Gas and Electric Company (RG&E), and Montana-Dakota Utilities Company (MDU). These tests were run at various times of the year to more fully evaluate the load modeling methodology and to make possible modifications in the load modeling procedure and tests as the project proceeded. The tests were planned for summer and winter peak load conditions because of the importance of load models for these conditions.

The LILCO tests were performed at two substations on the northeast tip of Long Island. Tests were performed on the load side of transformer bank #5 at the Riverhead substation (Figure 3-1) which feeds the Southold and Orient Point substations. The most significant tests were run at Southold. This site was of particular value because the Southold and Orient Point substations could be isolated from the rest of the system and supplied by the gas turbine-generator at Southold. This made it possible to perform frequency response tests on the Southold load. The Southold and Riverhead loads are primarily residential (including a significant percentage of summer homes) with some commercial load.

The load tap changing (LTC) transformers at Riverhead and Southold were used to produce voltage changes over their ranges ($\pm 10\%$ at Riverhead and $\pm 7.5\%$ at Southold). These voltage changes provided the data to assess the capability of the UTA load modeling procedure to model the steady-state voltage characteristics of loads. The most significant voltage changes obtained at the LILCO sites were obtained by setting the gas turbine-generator to deliver reactive power only and then tripping it off the line. Although voltage changes were induced by switching the capacitor banks at Riverhead on and off, these tests did not produce as large voltage changes as the GT trip tests; also, significant harmonics resulted which made analysis difficult.

Off-nominal frequency tests were run at the Southold site by isolating the Southold and Orient Point substations on the gas turbine-generator (only the Southold load was measured). The range covered was from 57 Hz to 63 Hz. Also, during isolated operation the gas turbine-generator's excitation system was used to cause changes in voltage. The isolated tests and associated data collection are unique and provide data not available from any other source.

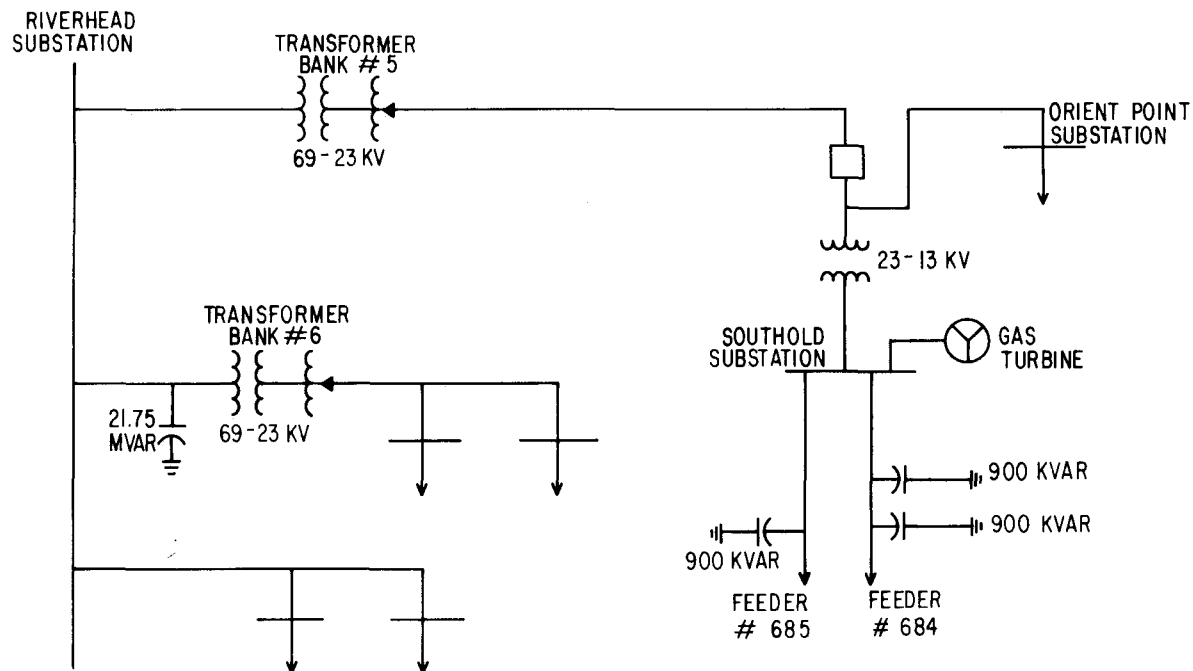


Figure 3-1. Test sites at LILCO - Riverhead and Southhold substations.

Tests were run at the Riverhead and Southhold sites during the summer of 1978 and the following winter. During the summer of 1979, tests were run at the Southhold test site only.

The RG&E tests were performed at Station 38 in Rochester, New York (Figure 3-2). This station serves approximately 30% of downtown Rochester in a distributed secondary network system, and consists primarily of commercial load. The total load of the 11 kV network was measured by summing the loads of transformers T3 and T5. The load tap changing transformers at Station 38 were used to produce voltage changes over a maximum range of $\pm 6\%$ in order to determine the steady-state voltage characteristics. Tests were run during the summer of 1978 and the following winter.

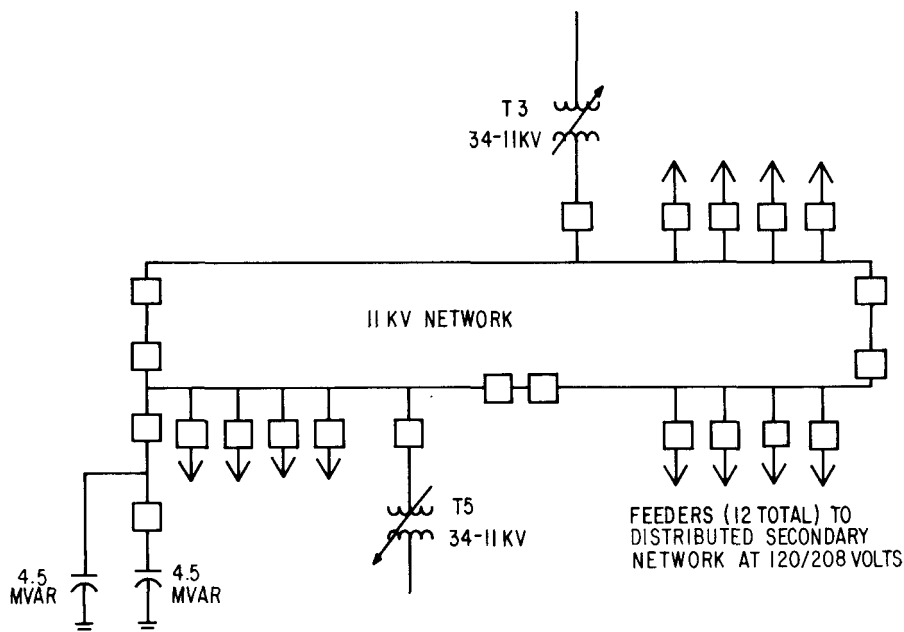


Figure 3-2. Test site at RG&E - Station 38 substation.

An additional test site became available in conjunction with a staged fault test on the Montana-Dakota Utilities Company system in November of 1978. This was an exciting opportunity to gather very valuable and detailed data during a severe system transient. The load measured was a portion of the city of Bismarck, and the 41.6 kV bus was arranged to provide a radial feed for the tests (Figure 3-3). Load was measured on the 41.6 kV side of the 115-41.6 kV transformer at the N.W. Bismarck substation. The load area was made up of approximately 9,000 homes and 35 commercial establishments. There were no industrial loads fed by the bus. In order to more fully evaluate the characteristics of the Bismarck load, the load tap changing transformer was used to produce steady-state voltage changes before and after the staged fault test.

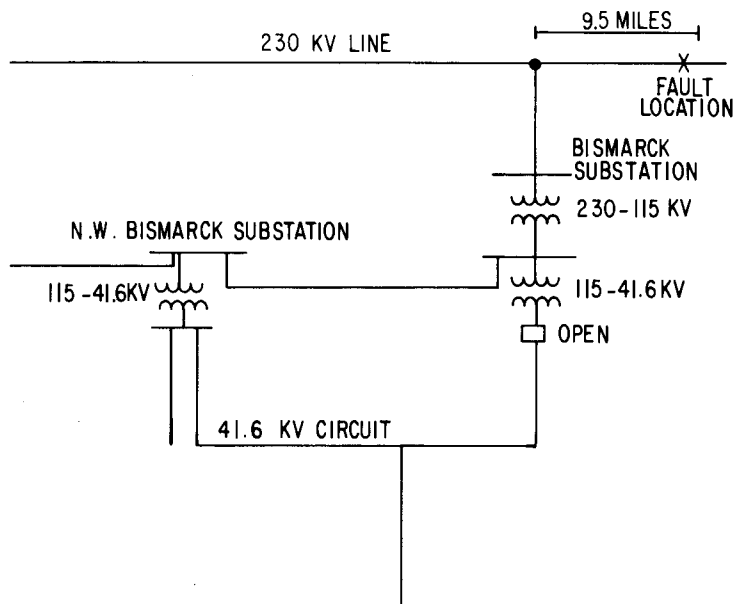


Figure 3-3. Test site at MDU - N.W. Bismarck substation.

For all tests, the instantaneous voltage and current of each phase were recorded with the RTDDAS (Real Time Digital Data Acquisition System) developed by IREQ in EPRI project RP849-2. For most tests, a sampling rate of 60 samples per cycle (3600 samples per second) was used. A sampling rate of 150 samples per cycle (9000 samples per second) was used for the gas turbine-generator tripping (GT trip) tests at Southold, for all the capacitor switching tests, and for the Bismarck fault test.

Section 4

TEST RESULTS AND ANALYSIS

The data which was recorded during the various tests at different substations and times made possible a comprehensive evaluation of the UTA load modeling procedure. Some of the tests had never before been conducted with such extensive instrumentation. Because of the serial nature of the tests and the manner in which the test data was processed, the test results and analysis are here reported in chronological order. This should give the reader an impression of the thought processes which occurred during the analysis.

The first tests of the load modeling methodology were made at test sites on the Long Island Lighting Company (LILCO) and Rochester Gas and Electric Company (RG&E) systems during the summer of 1978. The analysis of these test results is reported here in some detail. The data processing and analysis steps used for these tests were to serve as patterns for the future tests. This early analysis showed that the model gave good results for the steady-state active power voltage characteristics, but not for reactive power. The analysis explored reasons for this error. Also, significant differences were observed in the model and test results for the load frequency and dynamic responses. The tests and associated analysis conducted during the following winter concentrated on determining whether the modeling procedure was able to correctly track the changes in load composition that occur from the summer to winter seasons, and whether the same frequency and dynamic characteristics observed during the summer tests were still present. The original project plans called for a third series of tests to be conducted in the summer of 1979. Based on the results of the previous tests, the summer of 1979 tests were limited to one test site, Southold. The main purpose for these tests was to remove some inconsistencies that existed in the previous summer test results.

The fault test run on the Montana-Dakota Utilities Company system in November of 1978 provided yet another opportunity to evaluate the load modeling procedure, and these test results are presented here after those performed on the LILCO and RG&E systems. These results make a significant contribution to research in load dynamics.

SUMMER, 1978 TESTS

Steady-State Voltage Response

A complete description of the UTA modeling procedure is presented in Appendix A. The polynomial expressions of active and reactive power for steady-state conditions are (these are the expressions suggested by UTA for use in fitting the output of the DSAP program):

$$\begin{aligned}\text{Active Power, } P &= P_0(1 + p_1\Delta V + p_2(\Delta V)^2 + p_3\Delta F) \\ \text{Reactive Power, } Q &= Q_0(1 + q_1\Delta V + q_2(\Delta V)^2 + q_3\Delta F + q_4\Delta V\Delta F)\end{aligned}$$

where ΔV is the per unit voltage change from the base value, ΔF is the per unit frequency change from the base value and P_0 and Q_0 are the values of active and reactive power at base voltage and frequency. The values of P_0 and Q_0 and the coefficients for these polynomial expressions, determined for the Southold and Station 38 test sites using the UTA procedure, are presented in Table 4-1. The models were prepared for summer peak conditions, and the tests were scheduled for periods of time when this was most likely. Peak temperatures during the test periods were in the mid 80's ($^{\circ}\text{F}$). Although the test periods did not include the system summer peaks, the load levels were close to the peak levels. The load compositions used for these test sites are given in Appendix B.

The first step in the analysis of the test results was to plot and study the results of the tests of interest. Examination of these plots gave an indication of the overall nature of the load characteristics and made possible the discovery of unexpected phenomenon. Figure 4-1 is an example of such a plot for test 23, an LTC Test. In the test shown, the LTC started in the mid-tap position. The LTC was then moved up 16 taps, as rapidly as the mechanism could function (approximately three seconds per tap position), followed by 32 taps down, and 16 taps up and back to the original position. This whole sequence was then repeated.

The results of the LTC tests proved to be most useful in determining the steady-state voltage responses of the measured loads. Observations of this test data led to the conclusions that the steady-state voltage response of active power was a linear function of voltage, and the steady-state voltage response of reactive power was a quadratic function of voltage at all test sites. Based on these conclusions, curves were fitted to the test data in order to obtain a smooth curve through the random fluctuations of load which occurred during the tests (Figure 4-1), for comparison with the model steady-state polynomials. The curve fit polynomials were as follows:

Table 4-1
COEFFICIENTS OF STEADY STATE RESPONSE MODELS
Summer, 1978

TEST SITE	CAPACITOR BANKS	P_0 (MW)	Q_0 (MVAR)	p_1	p_2	p_3	q_1	q_2	q_3	q_4
SOUTHOLD	ALL OFF	3.541	1.359	.854	.033	.690	1.476	2.713	-.725	-6.346
"	1 ON*	3.575	.504	.873	.090	.695	2.133	11.92	-6.433	-38.85
"	2 ON	3.599	-.368	.866	-.024	.736	4.017	-5.060	7.846	33.48
"	3 ON	3.608	-1.256	.867	-.029	.742	2.599	-.767	3.038	11.20
STATION 38	ALL OFF*	24.52	10.2	.925	-2.022	1.024	2.935	6.772	-4.054	-20.74
"	ALL ON*	24.52	1.27	.925	-2.022	1.024	9.520	47.42	-39.81	-179.92

$$P = P_o (1 + p_1 \Delta V + p_2 (\Delta V)^2 + p_3 \Delta F)$$

$$Q = Q_o (1 + q_1 \Delta V + q_2 (\Delta V)^2 + q_3 \Delta F + q_4 \Delta V \Delta F)$$

* - transformer saturation modeled

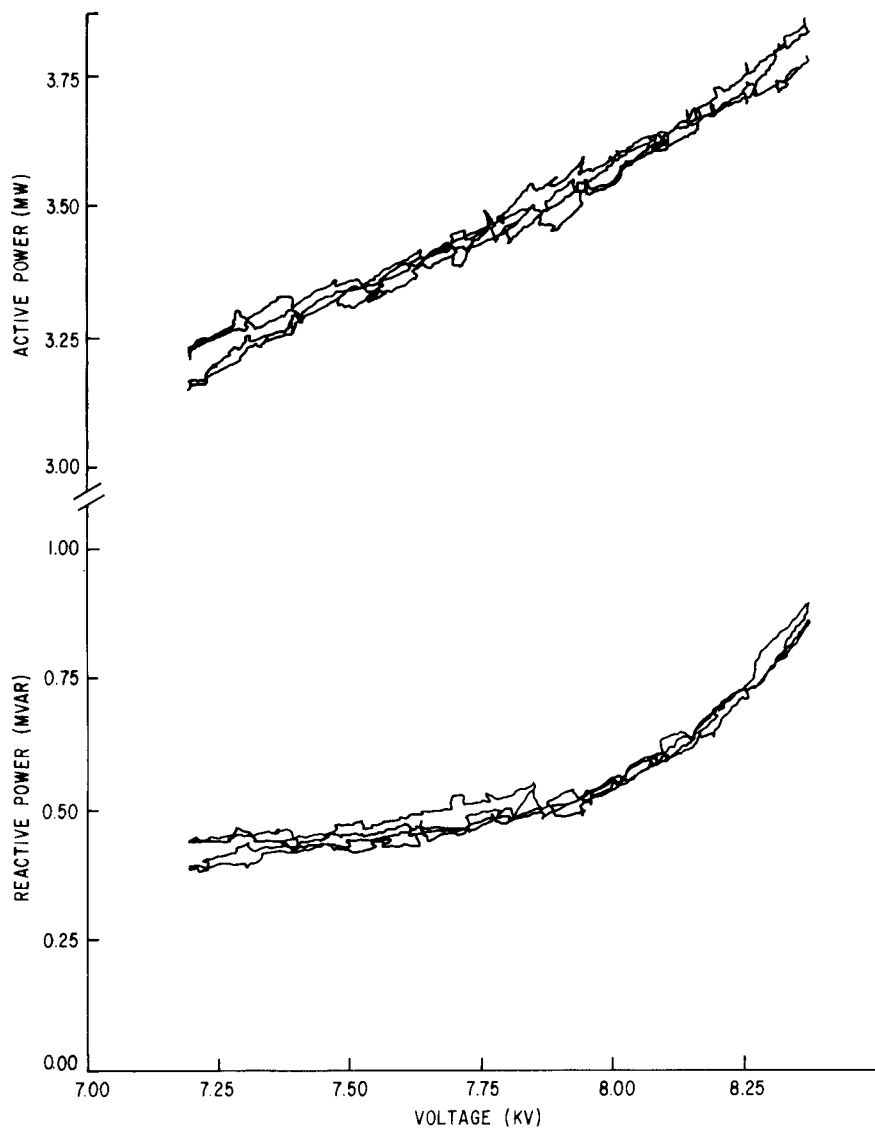


Figure 4-1. Test results of active and reactive power vs. voltage for LILCO, Southold substation, LTC Test 23, 7/1/78, 17:23.

$$P = P_0(1 + p_1\Delta V)$$

$$Q = Q_0(1 + q_1\Delta V + q_2(\Delta V)^2)$$

where P_0 and Q_0 are the active and reactive power respectively at base voltage, and ΔV is the per unit change of voltage from the base value.

Figures 4-2 through 4-5 compare the model and curve fitted test results of the steady-state voltage responses of active and reactive power for the LILCO, Southold and RG&E, Station 38 substations. Tables 4-2 and 4-3 present the coefficients of the curve fit polynomials for these and other tests. Since the Riverhead load is made up of the loads of the Southold and Orient Point substations, the Riverhead and Southold loads show similar characteristics, and only one of the two will be presented here.

The models presented in Table 4-1 were prepared after the tests to give a value of active power at rated voltage as close as possible to that observed during the tests at peak time. Since the total active power level is not an input to the program, but rather the values of active powers for the various components, and there are network losses, small differences in active power exist between the model and test values at rated voltage. Runs made with the modeling program for small changes in composition show negligible differences in load characteristics. For this reason, the characteristics shown in Figures 4-2 through 4-5 use the slopes of active power given in Table 4-1, and the values of active power at rated voltage are taken as the test values. With the active power levels so chosen, the reactive powers do not match at rated voltage, as shown.

The test data chosen for comparison with the predicted results in Figures 4-2 through 4-5 are those for the highest power levels recorded during the tests within the general peak time (4 to 8 PM). The steady-state voltage responses of active power at all three test sites agree well with the model results. The most significant differences occurred at the Southold station as shown in Figure 4-2; in this case, the difference at 1.1 per unit voltage is 2.5%.

The test results did indicate that significant changes in p_1 can occur in very short periods of time within the peak time interval. For example, note the 14% change in p_1 (from 1.18 to 1.35) for tests 24 and 25 at Southold (Table 4-2) taken within a six minute time interval, and the 11% change in p_1 (from 0.71 to 0.79) for tests 67 and 68 at Station 38 (Table 4-3) taken within a 12 minute time

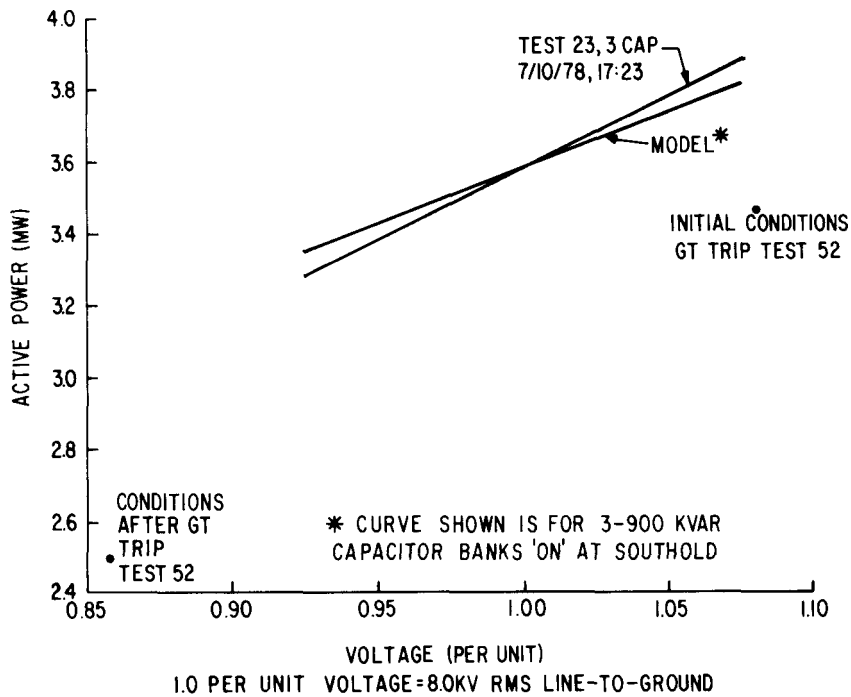


Figure 4-2. Model and curve fitted test results of active power for Test 23, at LILCO, Southold substation, 7/10/78, 17:23.

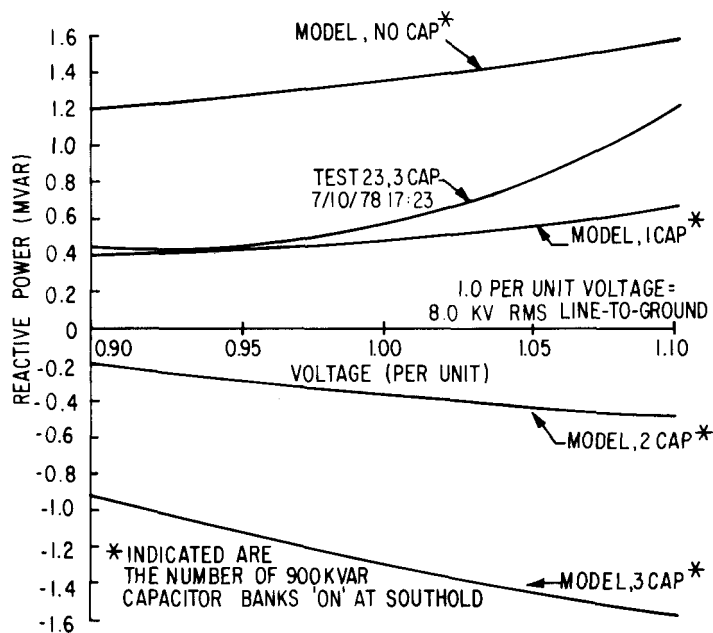


Figure 4-3. Model and curve fitted test results of reactive power for Test 23, at LILCO, Southold substation, 7/10/78, 17:23.

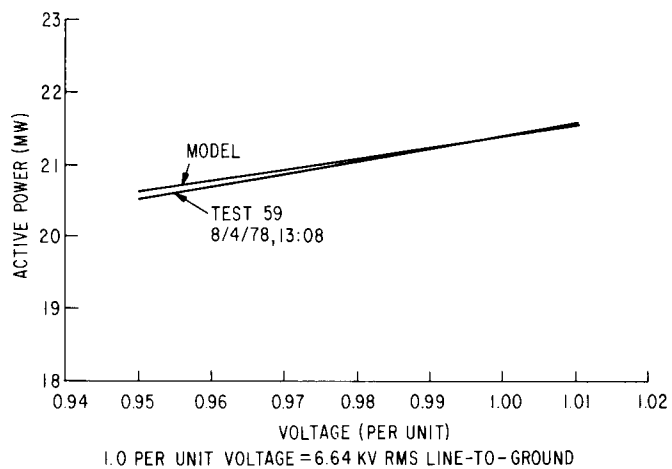


Figure 4-4. Model and curve fitted test results of active power for Test 59 at RG&E Station 38, 8/4/78, 13:08.

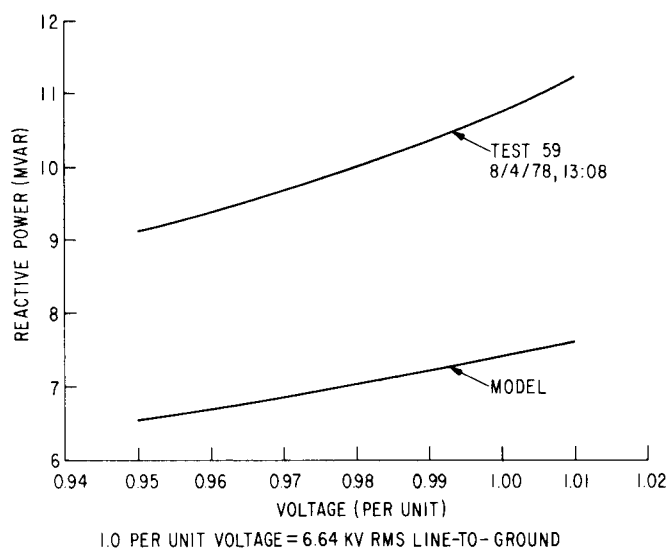


Figure 4-5. Model and curve fitted test results of reactive power for Test 59 at RG&E Station 38, 8/4/78, 13:08.

Table 4-2

COEFFICIENTS OF POLYNOMIALS FOR CURVE FITTED TEST RESULTS,
LILCO SOUTHDOLD SUBSTATION, SUMMER OF 1978 (3 CAP ON, ESTIMATED)

Test No.	Date	Day	Hour	P_o (MW)	Q_o (MVAR)	p_1	q_1	q_2
20	7/10	Mon	1121	3.39	.39	.96	7.71	107.1
21	"	"	1310	3.23	.43	1.30	7.81	100.6
23	"	"	1723	3.58	.56	1.11	7.09	50.8
24	"	"	1929	3.49	.56	1.18	6.89	70.8
25	"	"	1935	3.47	.54	1.35	7.23	75.3
31	7/11	Tue	1194	3.07	.39	1.47	3.24	96.6

$$P = P_o (1 + p_1 \Delta V) \quad Q = Q_o (1 + q_1 \Delta V + q_2 (\Delta V)^2)$$

Table 4-3

COEFFICIENTS OF POLYNOMIALS FOR CURVE FITTED TEST RESULTS,
RG&E STATION 38, SUMMER OF 1978

Test No.	Date	Day	Hour	P_o (MW)	Q_o (MVAR)	p_1	q_1	q_2	Cap (9MVAR)
4	8/3	Thu	1124	22.86	2.80	0.72	8.26	40.92	ON
17	"	"	1320	22.85	2.65	0.80	8.06	50.74	ON
25	8/4	Fri	0501	7.58	4.61	1.06	4.96	15.23	OFF
33	"	"	0659	11.42	6.78	0.81	3.82	7.99	OFF
34	"	"	0712	12.32	7.17	0.63	4.17	15.58	OFF
43	"	"	0919	18.71	9.59	0.88	3.66	9.32	OFF
51	"	"	1110	21.21	10.62	0.88	3.44	1.16	OFF
52	"	"	1123	21.11	10.54	0.69	3.09	4.28	OFF
59	"	"	1308	21.42	10.76	0.83	3.86	15.02	OFF
60	"	"	1320	21.41	10.84	0.83	3.94	13.64	OFF
67	"	"	1459	21.14	10.70	0.71	3.37	8.19	OFF
68	"	"	1511	21.24	10.69	0.79	3.21	4.14	OFF

$$P = P_o (1 + p_1 \Delta V) \quad Q = Q_o (1 + q_1 \Delta V + q_2 (\Delta V)^2)$$

interval. Many data points (120 time points per RMS calculation and approximately 240 RMS calculations per curve fit) were used to calculate the values of p_1 ; with an expected random measurement error of 1%, these values of p_1 should be reliable. The significant changes in p_1 which have been observed are likely due to changes in load composition. Except for the changes noted above, the results at most test sites showed little variation of p_1 with the changing daily load level (P_0). For example, using the results from Table 4-3 for Station 38 for Friday, August 4, a mean of 0.81 is calculated with a standard deviation of only 0.12. Figures 4-6 and 4-7 show the active power voltage characteristics for several tests during single days at the Riverhead and Station 38 substations, respectively, and indicate no significant changes in p_1 . The small changes observed during the changing daily load levels can be explained as follows: many loads can come 'on' the system causing an increasing total load level; p_1 will change only if the mix of components with different voltage characteristics changes.

The gas turbine-generator trip (GT Trip) tests at Southold not only provided significant transients for evaluation of load dynamics, but also afforded an opportunity to determine the load response characteristics beyond the steady-state voltage range achieved with the load tap changer unit. These tests were run by setting the gas turbine-generator to deliver reactive power only (maximum of ten MVAR) to the system, and then tripping it off the line. The feeder voltage regulators were not blocked, and they acted to eventually bring the feeder voltage back up to the regulated value. The time delay in the voltage regulator action allowed us to get a steady-state operating point at the voltage level resulting from the trip of the gas turbine-generator. The operating points before and after the GT Trip for test 52 are shown on Figure 4-2. If a straight line were to be drawn between these two points, the slope of this line would be similar to that found during the LTC tests. The other GT Trip tests gave similar results, indicating that the linear characteristics found during the LTC tests might apply over a greater range. The GT Trip tests resulted in steady-state voltage levels from a low of 86% of nominal to a high of 115% of nominal.

Figures 4-3 and 4-5 show significant differences between the model and test voltage responses of reactive power during peak time. These differences are most significant for the Southold substation as shown in Figure 4-3. Several models are shown on this figure, each for a different number of capacitor banks (there are three - 900 KVAR capacitor banks on the Southold feeders). Although all of

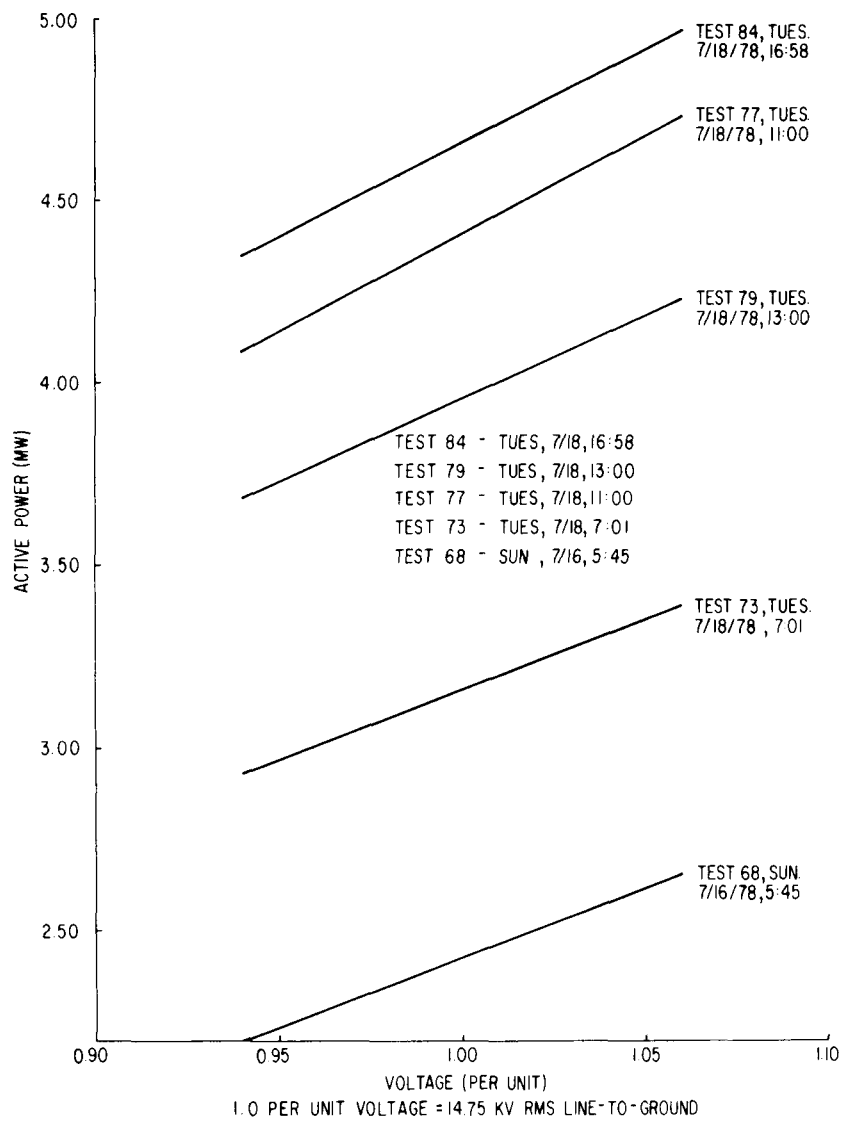


Figure 4-6. Curve fitted test results for active power at LILCO, Riverhead substation, summer of 1978.

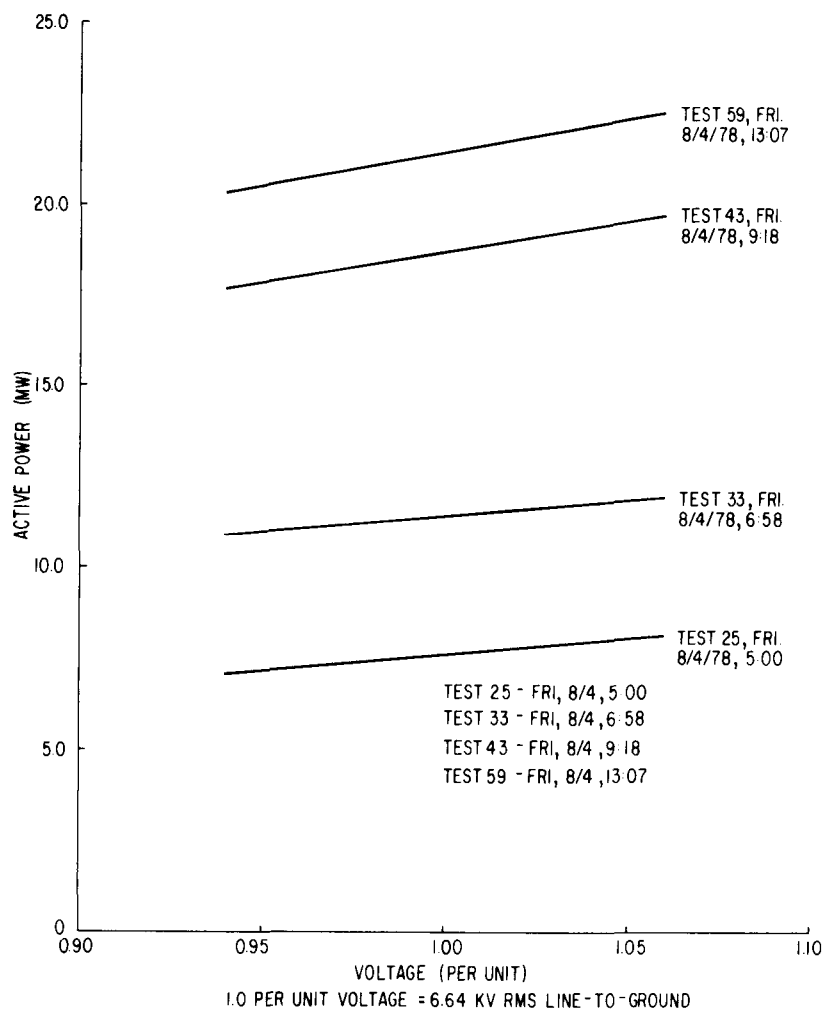


Figure 4-7. Curve fitted test results for active power at RG&E, Station 38, summer of 1978.

the capacitor banks were reported to be on during the tests, inconsistencies in some of the test results lead us to suspect otherwise (the capacitor banks were normally controlled by time clocks). In general, all of the test sites indicate a greater variation of reactive power with voltage than predicted. The closest correspondence between predicted and test results for q_1 occurred for the Station 38 substation as shown in Figure 4-5. Even this figure indicates an approximate 10% difference between the model and test values of reactive power for a 5% change of voltage from nominal.

Figures 4-8 and 4-9 show the hourly variation of reactive power voltage responses for the Riverhead and Station 38 substations. Also shown are the results for an early Sunday morning test at Riverhead. More significant changes can be seen in these characteristics than in those for active power (Figures 4-6 and 4-7). The most significant changes occurred at the LILCO substations.

As might be expected, because of the large range of reactive power characteristics, we were not able to extend the range of the reactive power voltage characteristics with the GT trip test results. This might have been possible if GT trip tests had been run immediately before or after the LTC tests; this was not possible because of the amount of time necessary to set up the GT trip tests.

Analysis of Model-Test Differences. The data used to determine load composition for the models was of limited accuracy (see Volume 3, Load Composition Data Analysis), and it was questioned whether errors in this load composition could be causing the differences in the reactive power voltage responses. An attempt was made to determine whether a load composition could be found for the RG&E test station (where the closest match was observed between test and model results) that would result in a load model which matched tests. DSAP, the UTA load modeling program, was used to construct models for various load compositions, chosen to minimize the differences between models and tests. The objective function to be minimized was chosen as follows:

$$J = \left(\frac{P_o - P'_o}{P'_o} \right)^2 + \left(\frac{Q_o - Q'_o}{Q'_o} \right)^2 + \left(\frac{P_1 - P'_1}{P'_1} \right)^2 + \left(\frac{q_1 - q'_1}{q'_1} \right)^2$$

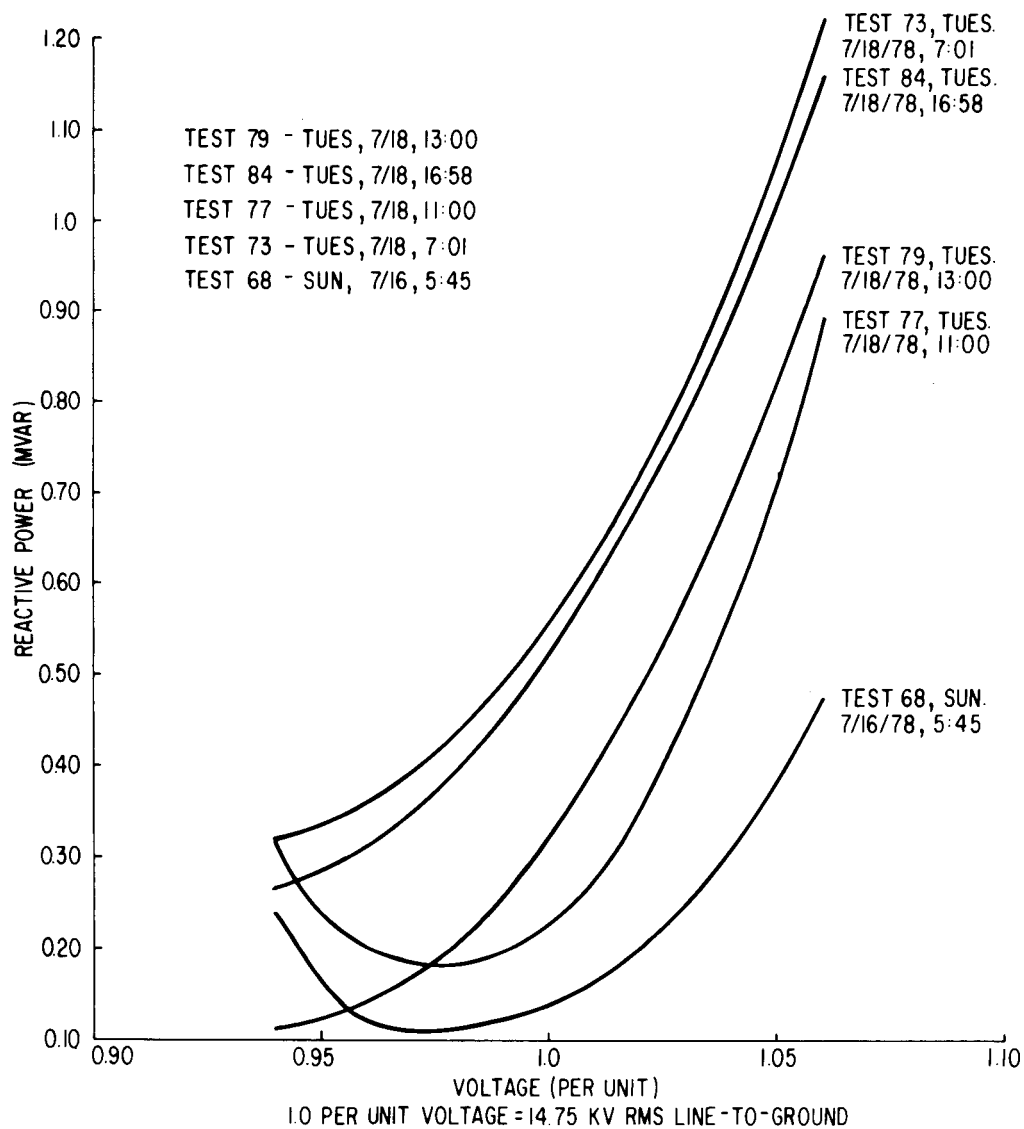


Figure 4-8. Curve fitted test results for reactive power at LILCO, Riverhead substation, summer of 1978.

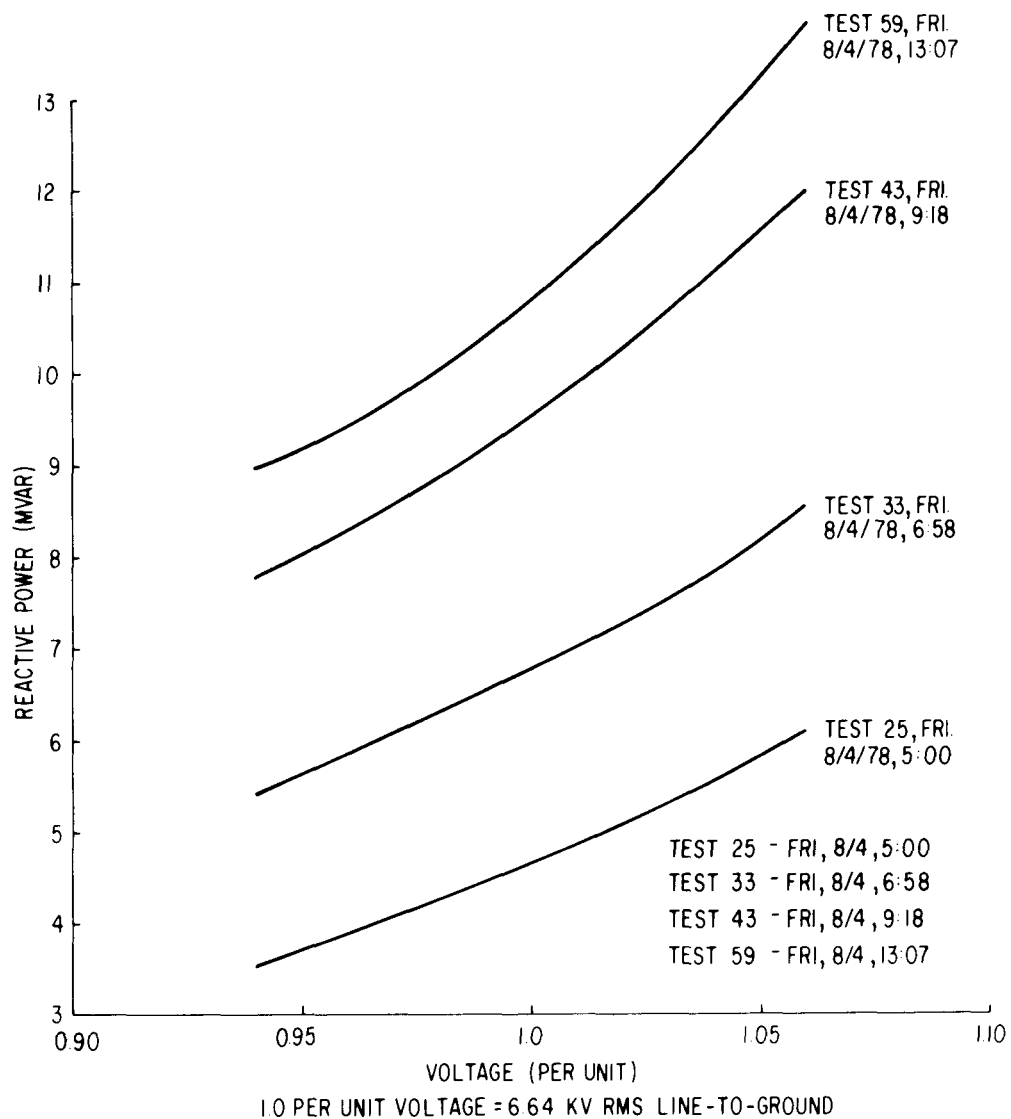


Figure 4-9. Curve fitted test results for reactive power at RG&E, Station 38 substation, summer of 1978.

where the primed quantities are the test observations. Note that the objective was to achieve agreement between test and model results not only for the slopes of their steady-state voltage response curves, but also for their nominal active and reactive power values. The analysis was conducted using the model produced before the tests, assuming that summer peak conditions would be realized. The parameters of this model were: $P_o = 27.09$ MW, $Q_o = 11.06$ MVAR, $p_1 = 0.99$, $q_1 = 1.73$, and $q_2 = 3.96$.

Table 4-4 gives the nominal reactive power (k) for various components in per unit of the nominal active power, and the slopes (p_1 , q_1) of active and reactive power with voltage, evaluated at nominal voltage, all for the components stored in DSAP. Since the peak-time tests gave slopes of reactive power of approximately 3.5, the data in the table would suggest a large percentage of fluorescent lighting; this was the case. However, if the model is adjusted to include an even higher percentage of fluorescent lighting, a sufficiently high nominal value of reactive power would not result (note the low value of k for fluorescent lights). As shown in Figure 4-5, the model already predicted a considerably lower value of reactive power than occurred during the tests. With the load component models in DSAP, no load composition could be found that would result in the load characteristics found during tests.

Table 4-4
LOAD COMPONENT CHARACTERISTICS

COMPONENT	PER UNIT REACTIVE POWER (k)	(p_1)	(q_1)
Heater	--	2.0	--
Fluorescent Light	0.061	0.984	6.8
Incandescent Light	--	1.55	--
Induction Motor (Standard)	0.712	0.044	1.59
Induction Motor (Small)	0.880	0.261	1.85
Air Conditioner (3 Phase Central)	0.527	0.088	2.59
Air Conditioner (1 Phase Central)	0.248	0.202	2.07
Air Conditioner (Window)	0.686	0.468	2.43

The load component coefficients k , p_1 , and q_1 are based on limited component test data and, in the case of induction motors, assumed initial loadings and shaft load characteristics. An analysis was made of the test results to determine what changes in the load component coefficients would make model and test results agree.

Figure 4-10 is a graphical representation of the solution under one set of assumed load component coefficients, that demonstrates the results obtained. For this analysis, the overall load characteristics were known from tests: $P_0 = 21.26$ MW, $Q_0 = 10.96$ MVAR, $p = 0.79$, $q = 3.49$. Certain load component coefficients were then taken as known: resistive load, $p=2.0$, $q=0$; fluorescent lights, $p=1.0$, $q=6.8$; incandescent lights, $p=1.6$, $q=0$; induction motors, $p=0.15$, $q=1.7$ (some of the values from Table 4-4 were rounded off, and the values for induction motors were derived by averaging the two values given in the table). With the p and q coefficients assumed known, this case determined the k coefficients for fluorescent lighting and induction motors which would give a solution, the values for resistive load and incandescent lights being zero; the region of acceptable values for the coefficients is shown. The figure shows that a higher value for the k coefficient is required for fluorescent lights (higher than 0.061, Table 4-4) and, depending on this exact value, perhaps a higher k coefficient for induction motors also. The same overall conclusions were reached for other sets of reasonable values for the load component coefficients.

Tests which Consolidated Edison has made on fluorescent lights show considerably higher values of k than used in DSAP. (This data is not published; our observations are based on phone conversations with S.A. Kalinowsky in their Electric Planning Department.) Also, lightly loaded induction motors result in higher values of k . Thus, there are further indications that the load component models used in DSAP, particularly for fluorescent lights and induction motors, may not be valid for the test sites.

A later model produced for Station 38, after the test loading was known, is given in Table 4-1. This model also included a representation of distribution transformer saturation. As displayed in Table 4-1, this model (with the capacitor banks off) resulted in a value of q_1 of 2.94, much closer to the test value of 3.49. It was uncertain whether a load composition could be found, with distribution transformer saturation modeled, that would cause the model to match test results; it was not attempted. Since it was our understanding that the saturation characteristics used in the program were based on only a few lab tests, we had little confidence in them.

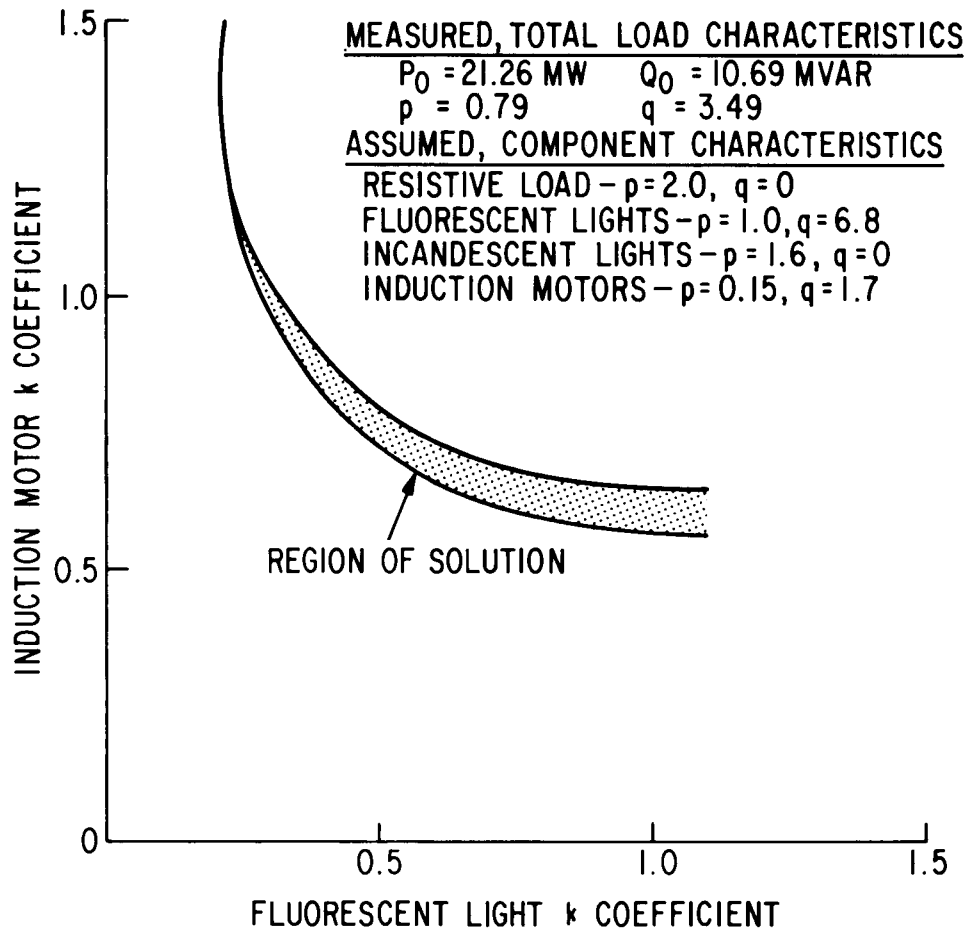


Figure 4-10. Solutions for k coefficients, RG&E Station 38, summer of 1978.

A second possible reason for differences between model and test results was thought to be the harmonics present in the measured currents. While performing the tests, it was observed on the RTDDAS oscilloscope that there was a noticeable harmonic content in the current waveforms. The harmonic content is readily apparent in the output of the DQZ data processing program, which transforms the phase voltages and currents using Park's transformation. The output of the DQZ program shows the fundamental frequency component as a DC level. Harmonics appear as oscillations about the level of the fundamental frequency component with amplitudes equal to those of the harmonics they represent. Because of Park's transformation, the frequencies of these oscillations in voltage and current is one order lower than the harmonics they represent. The harmonics in voltage were

found to be negligible. The harmonics observed in current were seventh harmonics appearing as 360 Hz terms and third harmonics appearing as 120 Hz terms.

Figures 4-11 and 4-12 show plots of the output of the DQZ program for LTC Test 4 at RG&E Station 38 at nominal and minimum voltage, respectively. Note that the magnitude of the harmonics in the reactive power is a very high percentage (approximately 20% in Figure 4-11) of the fundamental component (represented by the average level of the waveform). Since the harmonics in voltage were negligible, there are also 20% harmonics in current. The magnitude of the harmonics in the active power is a much smaller percentage of the fundamental component. Also notice that the magnitude of the harmonics is noticeably greater at nominal voltage than at minimum voltage. Two harmonics are evident in the waveforms: seventh harmonics represented by oscillations with a period of $1/360$ of a second and third harmonics represented by oscillations with a period of $1/120$ of a second.

With a purely sinusoidal voltage (this was approximately the case during the tests) the harmonics in current will not contribute to the active power. However, the magnitude of the double frequency component of instantaneous power, defined as reactive power, will vary because of the harmonics in the current. The procedures used in the RMS calculations assume that there are no harmonics present. The component models used within the DSAP program were derived for the most part from component tests run by UTA, and only the fundamental frequency values were recorded in these tests. Since most studies concern fundamental frequency values, it was decided that we should be concerned with the fundamental frequency value. The procedure used in the RMS calculations was temporarily modified so that only the fundamental frequency component of reactive power was calculated, and the programs were used to compare the results for select points and tests at each test site.

Figures 4-13 and 4-14 compare the fundamental frequency reactive power values with the previous calculations for the Southold and Station 38 substations, respectively. The differences can be seen to be significant for the Southold case although the magnitude of reactive power involved is quite small relative to the active power level. However, the harmonic effect does not account for the differences between model and test results; in fact, the differences become greater. The results for tests 4 and 59 at RG&E Station 38 substation indicate that the harmonics have little effect; in fact, the harmonics were not as significant at the RG&E substation. Thus, although the harmonics can introduce a significant error if one is interested in fundamental frequency values only, this effect does not explain the significant differences between model and test results.

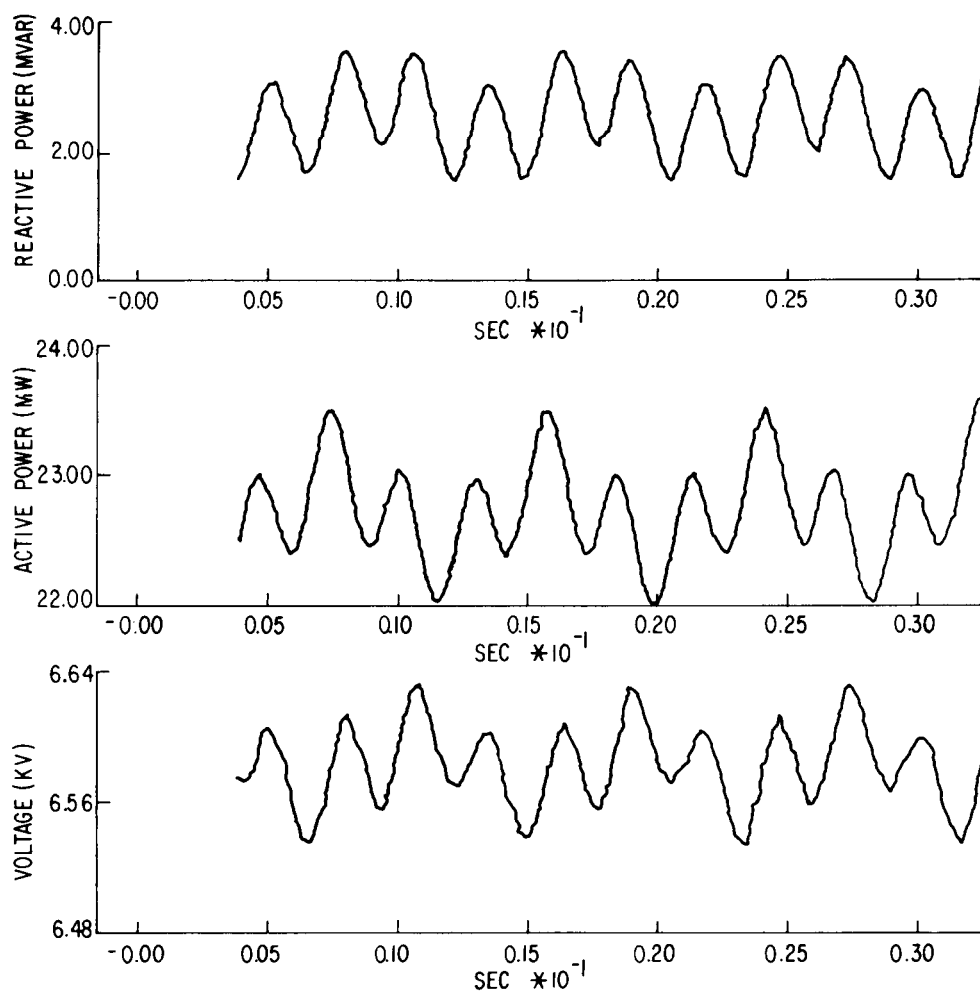


Figure 4-11. DQZ processing output for LTC Test 4 data at nominal voltage, RG&E Station 38, summer of 1978.

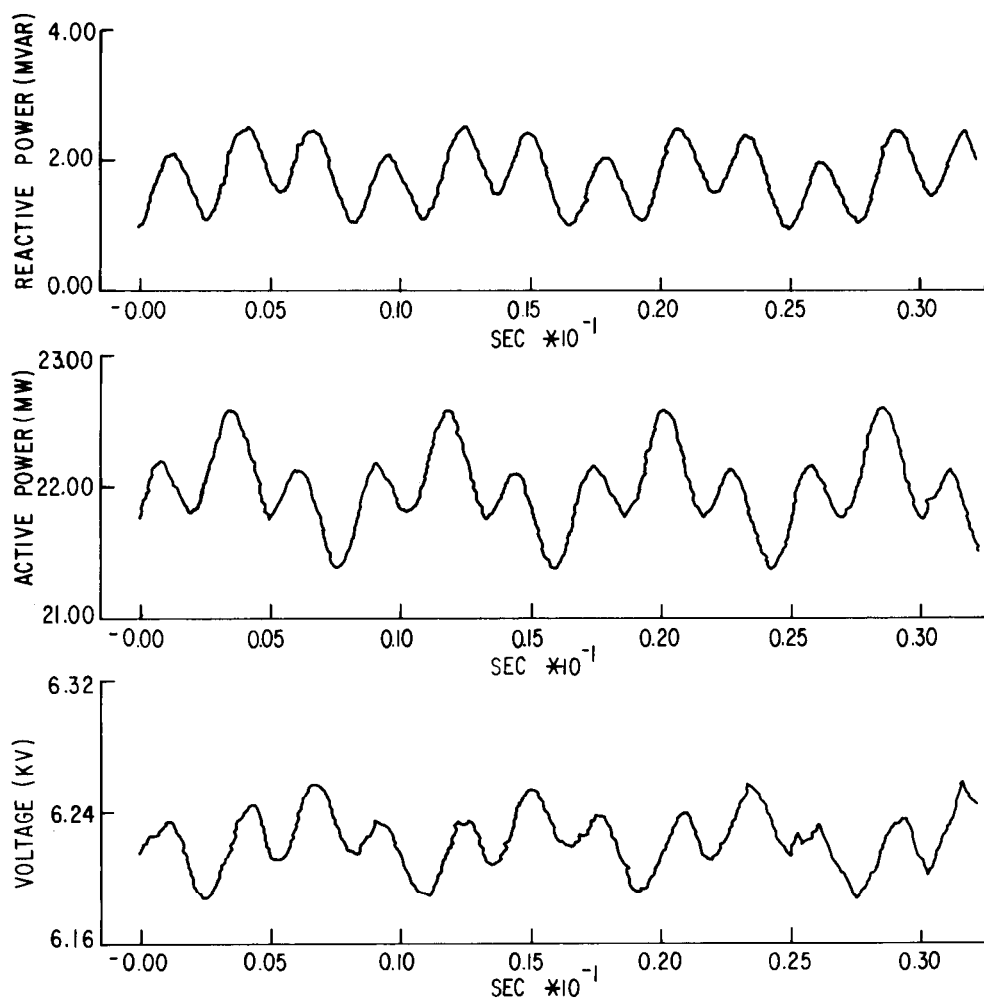
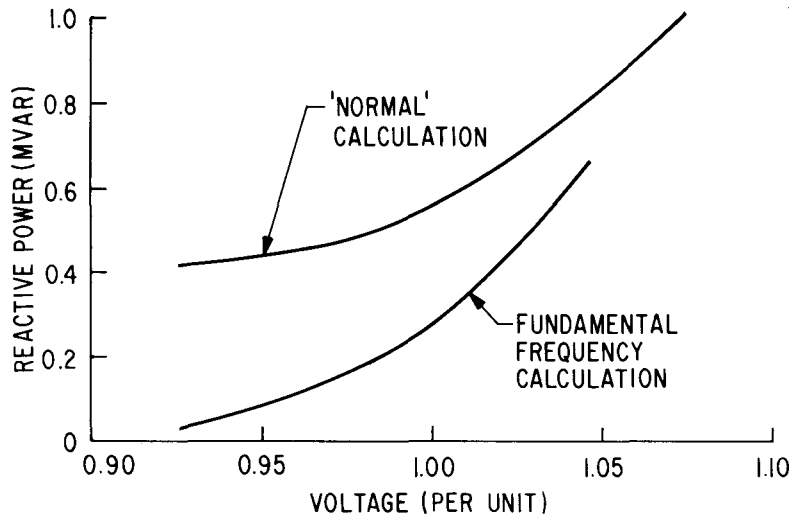
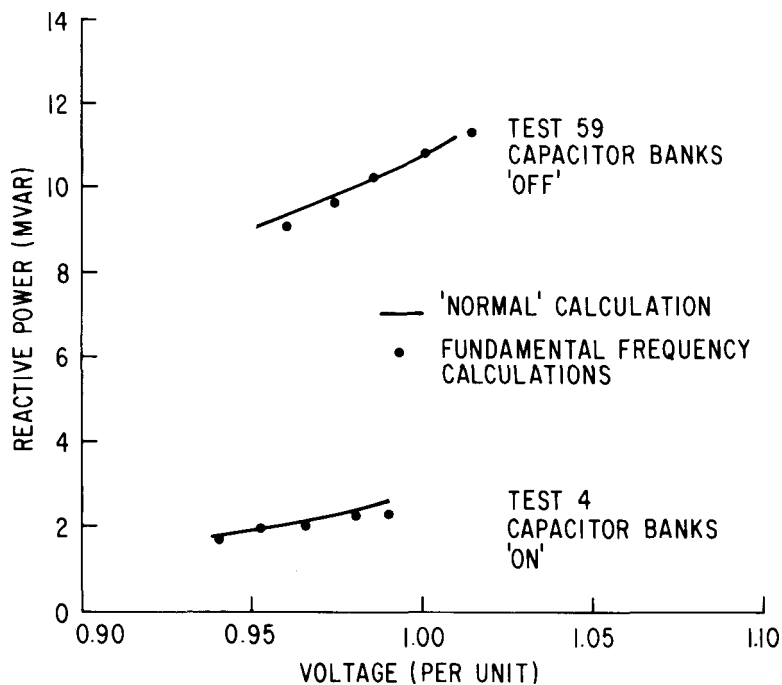


Figure 4-12. DQZ processing output for LTC Test 4 data at minimum voltage, RG&E Station 38, summer of 1978.



1.0 PER UNIT VOLTAGE=8.0KV RMS LINE-TO-GROUND

Figure 4-13. Comparison of calculated reactive power values for LTC test 23, LILCO Southold substation, summer of 1978 - 'normal' vs. fundamental frequency values only.



1.0 PER UNIT VOLTAGE=6.64KV RMS LINE-TO-GROUND

Figure 4-14. Comparisons of calculated reactive power values for LTC Tests 4 and 59, RG&E Station 38 substation, summer of 1978 - 'normal' vs. fundamental frequency values only.

Steady-State Frequency Response

The Southold substation provided us with the unique capability of isolating load and determining its characteristics as a function of frequency. In the isolated condition, the frequency was changed over a range from 57 Hz to 63 Hz. In some tests the frequency changes were combined with 10% voltage changes (voltage-frequency tests), made using the gas turbine-generator's excitation system. The voltage and frequency changes were made one at a time and were so coordinated that over-excitation of magnetic circuits could not occur.

Table 4-1 presents the coefficients of the steady-state response models, including the coefficients for those terms which involve frequency changes. The model for Southold predicts an approximate 0.7% change of active power for a 1% change in frequency. Increases in frequency cause increases in active power, and decreases in frequency cause decreases in active power. The coefficients for the reactive power terms predict a net decrease of reactive power for an increase in frequency. This is the expected result which would occur if the reactive load were made up of static capacitors and inductors.

An examination of the test results is best done by examining the overall nature of the load characteristics from plots of actual data. Figure 4-15 shows the results of a frequency test run at approximately peak time. Note that during the frequency tests the voltage regulator was only able to hold terminal voltage to within approximately $\pm 0.5\%$ of the initial value. Also, changes in voltage occur at the points when the extreme values of frequency are reached. These observations are true of all the tests involving changes of frequency.

It can be noted that active power is quite insensitive to changes in frequency. If one neglects the effect of the voltage changes on active power, an approximate 2% increase in active power occurs during the ramp of frequency from 60 to 63 Hz; an approximate 6% decrease in active power occurs during the portion of the frequency ramp from 63 to 57 Hz; an approximate 3% increase in active power occurs during the ramp of frequency from 57 to 60 Hz. These observations are approximate and also neglect the random changes in load which are occurring on the system. In general, it can be observed that active power is insensitive to frequency changes and appears to be less sensitive than predicted by the model. The model does accurately predict the directions of the changes.

Examining the overall nature of the reactive power frequency response, it can be observed that increasing frequency above 60 Hz causes an increase in reactive

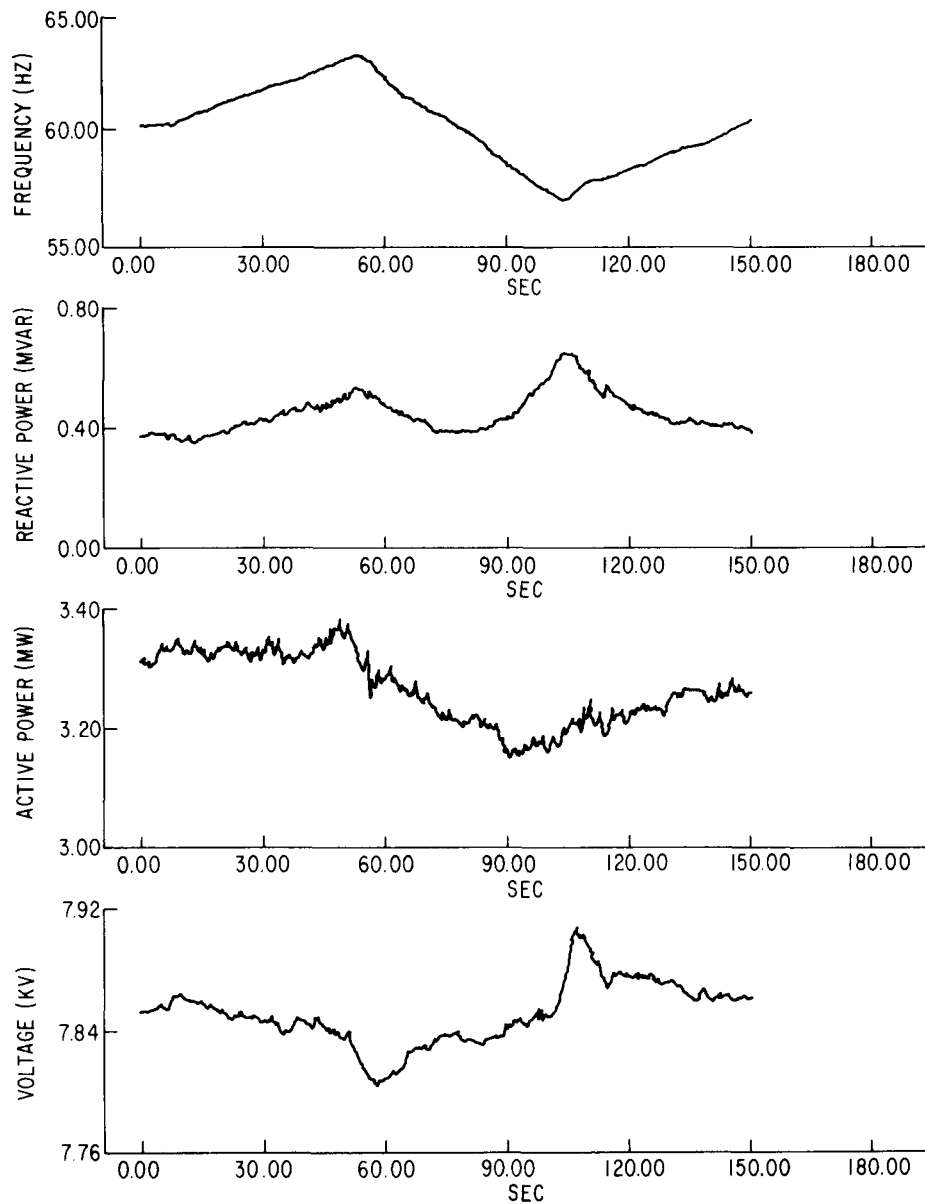


Figure 4-15. Frequency test results, LILCO, Southold substation, summer of 1978, Test 61, 7/13/78, 18:30.

power, not a decrease as predicted. Also, at the values of frequency lower than 60 Hz an increased sensitivity of reactive power to frequency is observed. The model structure is not able to produce such a characteristic.

The observations made here concerning the frequency tests were true of all frequency tests made with one exception. During those tests run with initial leading power factors, the reactive power changes were in the direction predicted by the model. The tests run with initial leading power factors were, however, not run during peak time, but during the morning hours.

Figure 4-16 presents the results of a voltage-frequency test run shortly after the frequency test shown in Figure 4-15. One can make similar observations concerning active power as made from the results of the frequency tests. Active power is quite insensitive to frequency changes. The initial increase in frequency, made from nominal voltage, again causes an increase instead of a decrease in reactive power. The decrease in frequency made from the higher voltage level causes a much more significant change in reactive power in the direction predicted by the model. Figure 4-16 is typical of all the voltage-frequency tests.

The increased sensitivity of reactive power to frequency occurs when frequency is low or voltage is high. It thus appears to be proportional to volts/hertz, leading to the conclusion that this phenomenon may be the result of saturation of magnetic circuits such as in distribution transformers.

The fitting of test data to the polynomial form used in the model was not fruitful because of the significant differences in frequency response characteristics noted above. So that some comparisons would be possible, curve fits were made of the test data to fit the following polynomial forms:

$$\begin{aligned} P &= P_0 (1 + p_1 \Delta V + p_3 \Delta F) \\ Q &= Q_0 (1 + q_1 \Delta V + q_3 \Delta F) . \end{aligned}$$

The results of these curve fits are shown in Table 4-5.

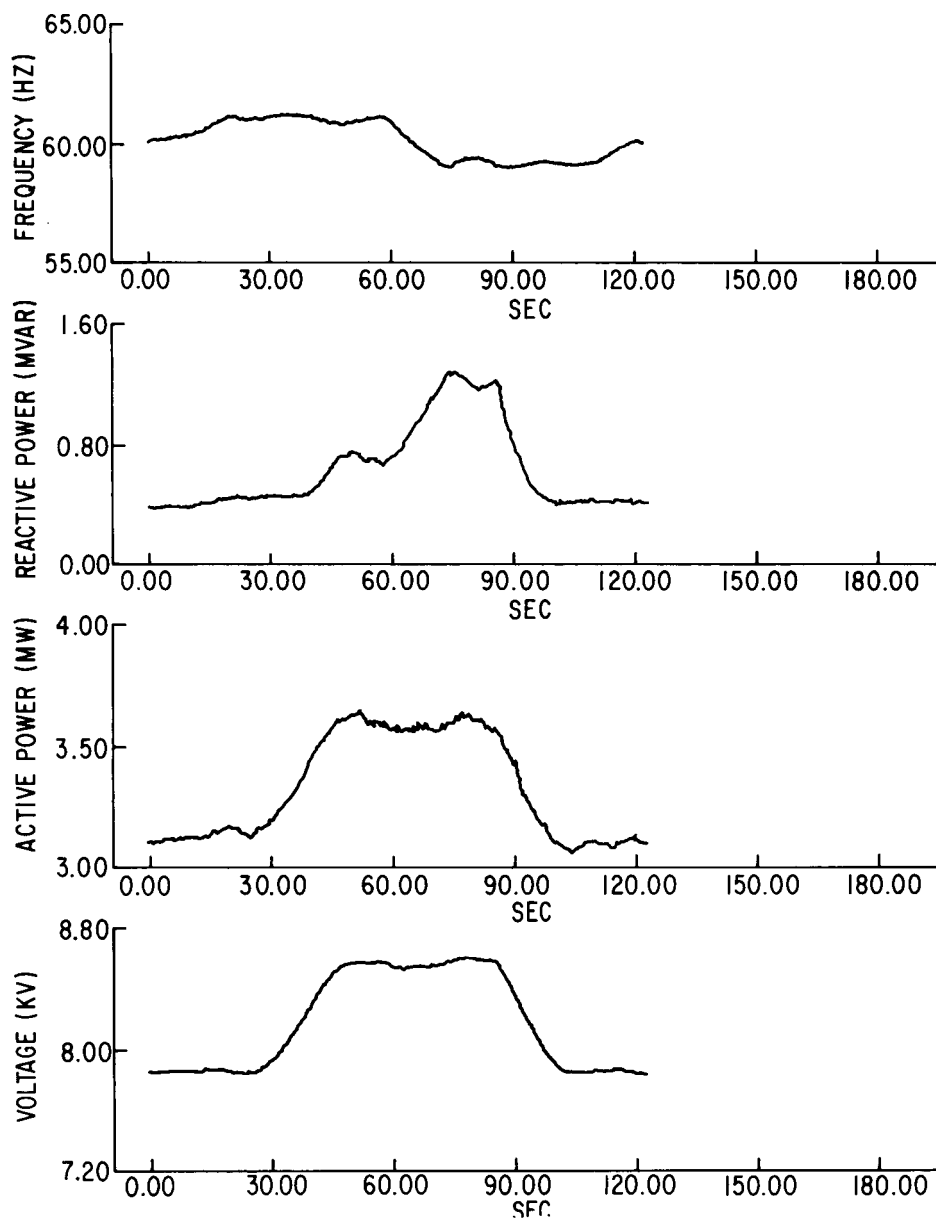


Figure 4-16. Voltage-frequency test results, LILCO, Southold substation, summer of 1978, Test 63, 7/13/78, 18:47.

Table 4-5

COEFFICIENTS OF CURVE FITTED TEST RESULTS* -
 FREQUENCY (F) AND VOLTAGE-FREQUENCY (V-F) TESTS
 LILCO, SOUTHDOLD SUBSTATION, SUMMER OF 1978

TEST NO.	TEST TYPE	DATE, TIME	P_o (MW)	Q_o (MVAR)	p_1	p_3	q_1	q_3
42	F	7/12 10:05	2.64	-.53	1.36	.31	-3.90	9.27
43	F	7/12 10:10	2.74	-.57	3.46	.26	-2.73	8.16
44	V-F	7/12 10:24	2.59	.61	1.53	.43	3.51	-2.98
61	F	7/13 18:29	3.52	.45	3.86	.73	.78	-1.74
62	F	7/13 18:34	3.30	.58	1.33	.18	9.49	.47
63	V-F	7/13 18:46	3.21	.50	1.69	.48	11.7	-14.7
64	V-F	7/13 18:50	3.25	.49	1.46	.44	11.4	-14.3
65	V-F	7/13 18:59	3.16	-.45	1.30	1.04	.44	3.26

$$*P = P_o (1 + p_1 \Delta V + p_3 \Delta F)$$

$$Q = Q_o (1 + q_1 \Delta V + q_3 \Delta F)$$

Besides the difficulties in fitting the test results because of the load characteristics described earlier, other inconsistencies can be noted in the table. In general, it is felt that these difficulties resulted because of our inability to change frequency significantly without corresponding changes in voltage. Because both voltage and frequency changes occurred, it was necessary to attempt to fit the curves to changes in both. The range of voltage changes during the frequency tests was not sufficient to obtain a valid curve fit; similarly, the changes in frequency during the voltage-frequency tests were not sufficient. What would have been required were tests run within a very short period of time (1 minute) with significant changes in both frequency and voltage. This was planned for later tests.

The only fruitful observation which can generally be made from the curve fit data is to support the conclusion that the Southold active power is insensitive to changes in frequency. An average of the values of p_1 from the table gives a frequency sensitivity coefficient for active power of 0.48.

Dynamic Response

As presented in Appendix A, the UTA load modeling procedure decomposes the component loads into two categories: (1) loads which display steady-state response only, called static loads (no dynamics or dynamics not in the range of interest); (2) induction motor loads which display dynamic characteristics. (Line losses are accounted for with a third load category.) The steady-state response of the total load is then the sum of the steady-state responses of the two load categories, both expressed as polynomials in voltage and frequency. The dynamic response of the total load is that of the dynamic load category only. The dynamics which are represented are those of the induction motor inertia response. With the assumption that slip and therefore admittance cannot change instantaneously, active and reactive power can change instantaneously with changes in voltage. Also, the modeling procedure assumes that both active and reactive power respond exponentially, with the same time constant, to changes in system voltage. The time constant is determined as follows:

$$T = \frac{\sum (T_i \cdot CAP_i)}{\sum CAP_i}$$

where T_i is the time constant of the i th machine, and CAP_i is the capacity of the i th induction machine.

It was assumed that the capacitor switching and GT trip tests would produce steps in voltage of sufficient magnitude to estimate the dynamic parameters of the load model polynomials. For such step changes in voltage, the two components of the model would respond as follows and as shown in Figure 4-17: (1) the static load, active and reactive power, would change in a step; and (2) the dynamic load, active and reactive power, would change in a step followed by a decayed exponential change to a new level. Estimation of the active and reactive power dynamic terms is very difficult because of the necessity of decomposing the measured instantaneous change in power into the two components, due to the static and dynamic loads. For this reason, the dynamics were examined in terms of model representation of load admittance.

Following a step change in voltage, the two components of the model would respond as follows in terms of admittance (Figure 4-18): (1) the admittance (real and imaginary parts) of the static load would change in a step; and (2) the admittance (real and imaginary parts) of the dynamic load would not change in a step, but would instead follow a single decayed exponential response. Since only the static load component admittance changes in a step, the static load can be separated from the total response, and the time constant of the dynamic load response estimated. Thus, an analysis of the response of load admittance for step changes in voltage was to be used to estimate the dynamic load parameters.

Figure 4-19 shows the simulated response of the model dynamics to a change in voltage in terms of the conductance (RMHO) and susceptance (IMHO) (admittance can be determined from power by dividing by V^2). This simulation was made using the measured voltage change caused by the GT trip of test 52. Note that the real and imaginary parts of load admittance respond with the same time constant. Figure 4-20 shows the actual response of the admittance for this same test which can be compared with Figure 4-19, the model simulation. It can be observed that the voltage does not change instantaneously, and in fact, the time required for the change in voltage is of the same order as that required for the completion of the dynamics in the active and reactive power. Using the portion of the response which occurs after the change of voltage level (starting with the dashed line), it can be noted that contrary to the model simulation, there are two different time constants which are controlling the real and imaginary parts

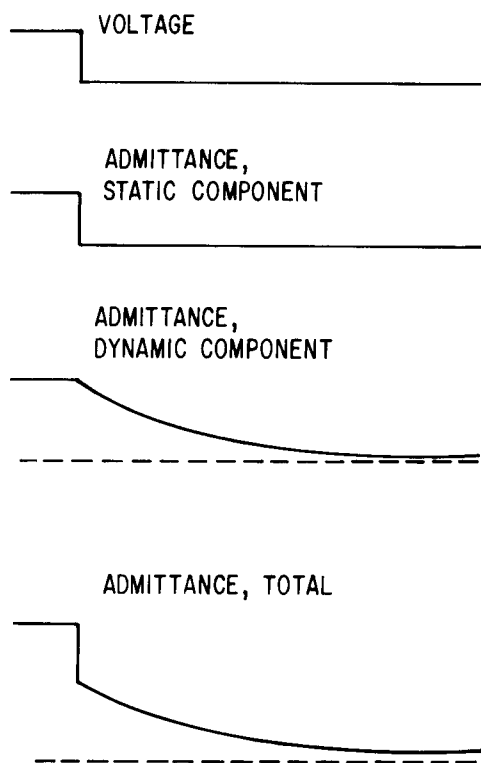


Figure 4-17. Responses of static and dynamic components of dynamic load model in terms of power.

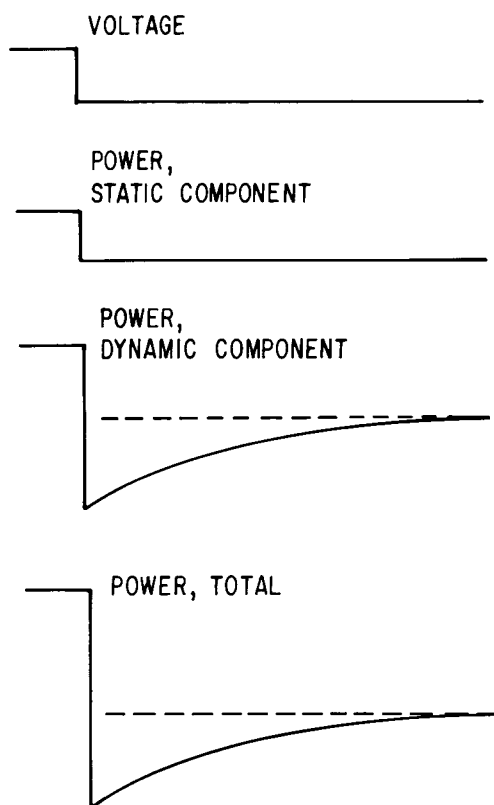


Figure 4-18. Responses of static and dynamic components of dynamic load model in terms of admittance.

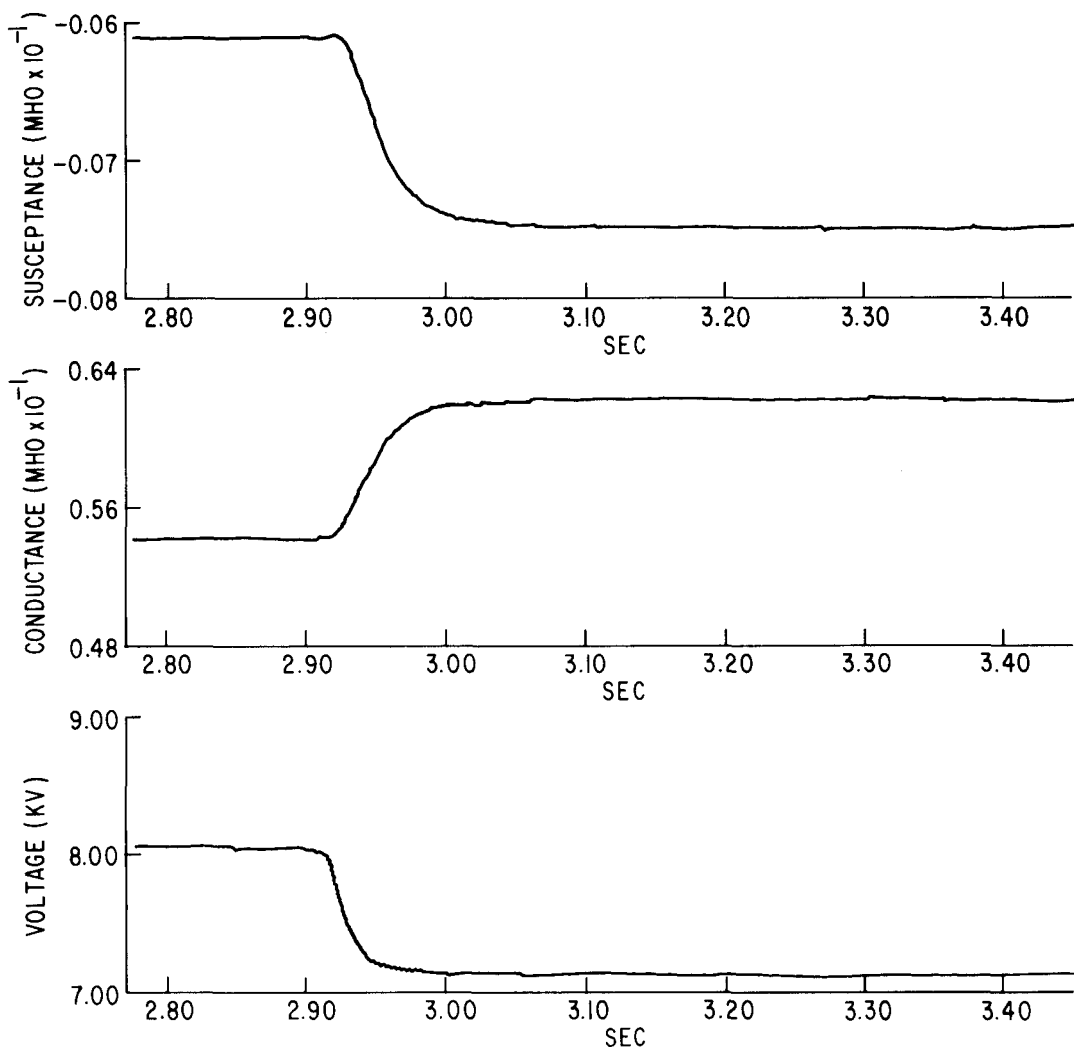


Figure 4-19. Simulated response of admittance for GT trip test 52, LILCO, Southold substation, summer of 1978, 7/12/78, 18:55.

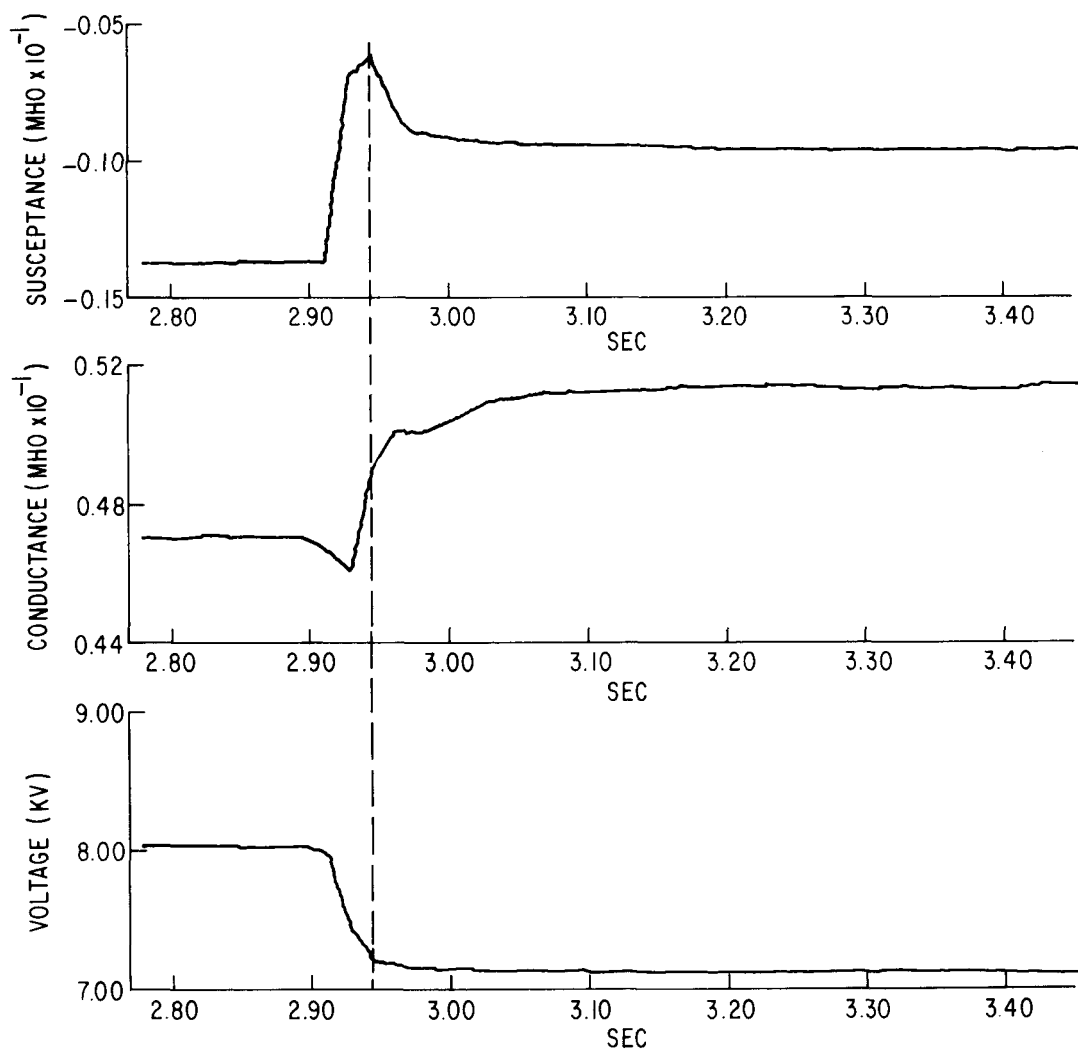


Figure 4-20. Measured response of admittance for GT trip test 52, LILCO, Southold substation, summer of 1978, 7/12/78, 18:55.

of load admittance (and therefore the active and reactive power voltage responses). The real part of admittance has an approximate 60 millisecond time constant, while the imaginary part of the admittance has an approximate 30 millisecond time constant. The single predicted time constant was approximately 16 milliseconds.

Comparing the test with simulated results, it can be observed that the real parts of the admittances, from which active power can be derived, respond in the same direction. However, the results for reactive power respond in opposite directions. This discrepancy in the direction of the reactive power response is caused by the difference in the steady-state response of reactive power between the model and tests. The test results, for which reactive power varies at a rate greater than the square of voltage, result in admittance functions which increase with voltage. The model results, which predict that reactive power varies at a rate less than the square of voltage, result in admittance functions which decrease with voltage.

The results for Test 52 are typical of those for other GT trips and capacitor switching tests. In light of the difficulties experienced in modeling the steady-state reactive power voltage response and the significant differences between model and test dynamics, the estimation of model parameters from test data was not attempted. There are significant errors in the model dynamic response.

WINTER, 1978-79 TESTS

Steady-State Voltage Response

Tests were conducted during the 1978-79 winter at the LILCO and RG&E test sites to provide tests of the UTA load modeling procedure with changes in load compositions. These tests were essentially duplicates of those run the previous summer. Special care was taken to record the number of capacitor banks 'on' at Southold. Also, plans called for full-range LTC tests immediately before and after the isolated, off-nominal frequency tests in order to provide sufficient curve fit data.

Again, the results of the LTC tests were used to determine the steady-state voltage response characteristics of the loads for comparison with the models. Figures 4-21 through 4-24 compare the model and curve fitted test results of the steady-state voltage responses of active and reactive power for the LILCO,

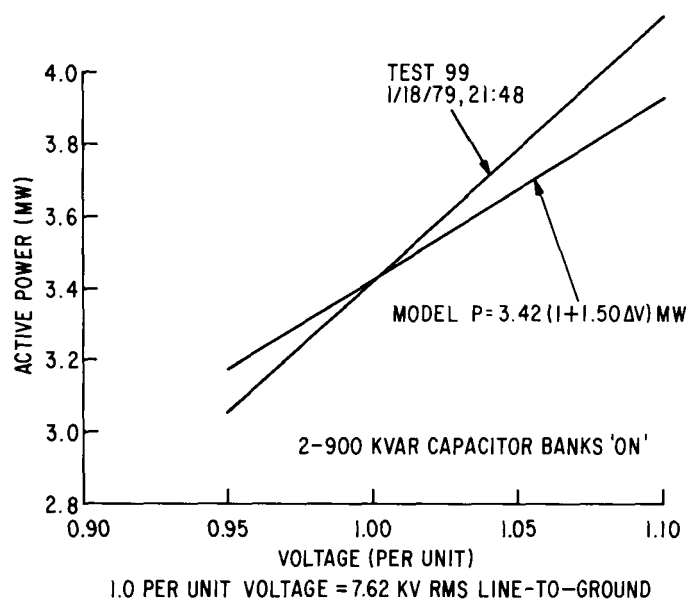


Figure 4-21. Model and curve fitted test results of active power for Test 99 at LILCO, Southold substation, 1/18/79, 21:48.

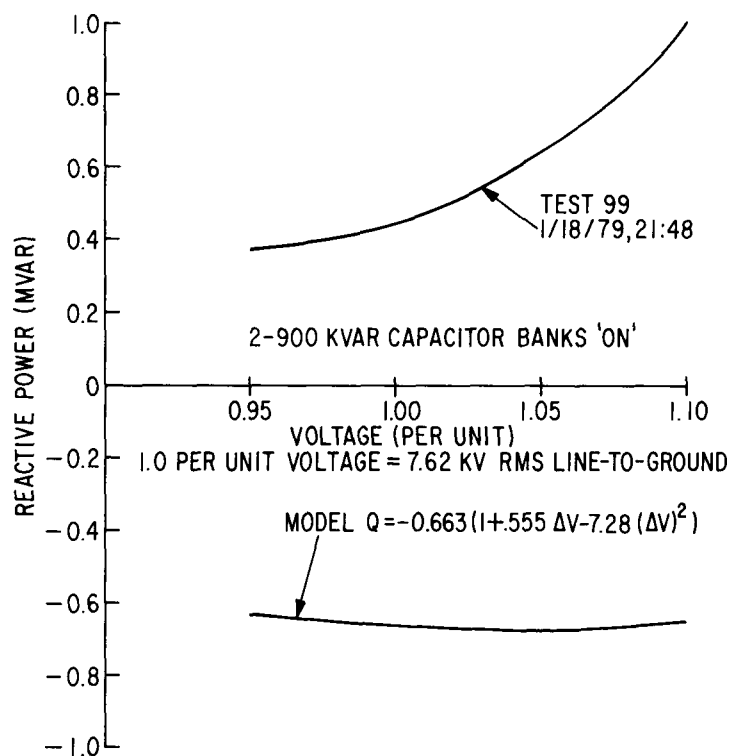
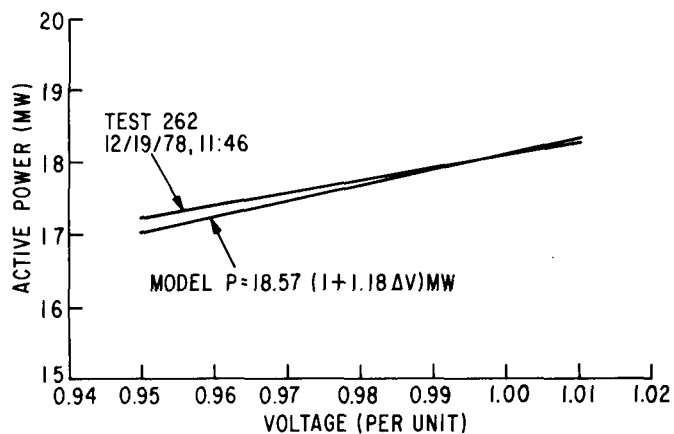
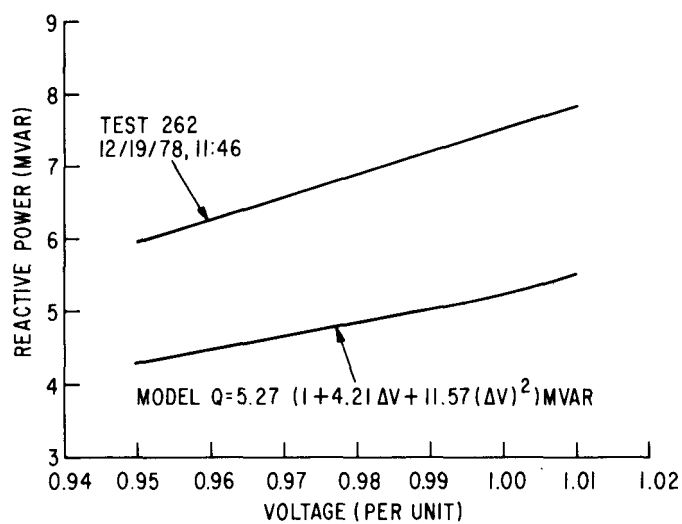


Figure 4-22. Model and curve fitted test results of reactive power for Test 99 at LILCO, Southold substation, 1/18/79, 21:48.



1.0 PER UNIT VOLTAGE = 6.64 KV RMS LINE-TO-GROUND

Figure 4-23. Model and curve fitted test results of active power for Test 262 at RG&E, Station 38 substation, 12/19/78, 11:46.



1.0 PER UNIT VOLTAGE = 6.64KV RMS LINE-TO-GROUND

Figure 4-24. Model and curve fitted test results of reactive power for Test 262 at RG&E, Station 38 substation, 12/19/78, 11:46.

Southold and RG&E, Station 38 substations. As for the summer, the test data chosen for comparison with the predicted results in Figures 4-21 through 4-24 are those for the highest power levels recorded during the tests within the general peak time. Transformer saturation was included in all models.

The steady-state voltage response of active power for Station 38 agrees very well with the model. More significant differences occur between test and model results for the Southold substation (5% error at 1.1 per unit voltage); this was the case during the summer tests. Table 4-6 presents the coefficients of the curve fit polynomials for several tests at the Southold substation. Note that all the other tests listed, many of which were taken during the peak hours for those particular days, have values of p_1 closer to that of the model. The weather was very cold, and the wind was very strong during the afternoon and evening hours of Thursday, January 18. In fact, that day did produce the winter peak for the LILCO system. Thus, test 99 had to be chosen for comparison with the model since the model was prepared for winter peak conditions.

Table 4-6

COEFFICIENTS OF POLYNOMIALS* FOR CURVE FITTED LTC TEST
RESULTS, LILCO SOUTHOLD SUBSTATION, WINTER OF 1978-79

Test No.	Date	Day	Hour	P_o (MW)	Q_o (MVAR)	p_1	q_1	q_2	Cap. on
1	1/15/79	Mon	0519	2.31	.21	2.05	4.52	144.5	0
4	1/15/79	Mon	0655	2.64	-.17	1.75	.89	-16.5	1
8	1/15/79	Mon	0903	2.81	-.74	2.11	-1.29	-10.0	1
11	1/15/79	Mon	1105	2.65	-.77	1.44	-.64	-12.7	1
14	1/15/79	Mon	1256	2.40	-.84	1.85	-.77	-6.5	1
16	1/15/79	Mon	1514	2.40	-.82	1.53	-.73	-13.3	1
19	1/15/79	Mon	1700	3.02	-1.69	1.86	.57	-14.3	2
26	1/15/79	Mon	1810	3.26	-1.62	1.69	.53	-13.5	2
28	1/15/79	Mon	1830	3.19	-1.63	1.94	.40	-14.8	2
29	1/15/79	Mon	1835	3.19	-1.68	1.95	.31	-13.2	2
32	1/15/79	Mon	1907	3.22	-1.63	1.62	.50	-11.4	2
52	1/16/79	Tue	1838	3.03	-1.72	1.89	.65	-16.2	2
78	1/17/79	Wed	1821	3.01	1.06	1.70	4.06	25.3	0
99	1/18/79	Thu	2148	3.42	.44	2.13	6.01	59.3	2

* $P = P_o (1 + p_1 \Delta V)$ $Q = Q_o (1 + q_1 \Delta V + q_2 (\Delta V)^2)$
 $V = V_o (1 + \Delta V)$ $V_o = 7.62 \text{ kV}$

A significant observation to be made concerning the active power characteristics is the ability of the model to 'track' the changes in load compositions which occurred between the summer and winter seasons. The model correctly predicted the increased sensitivity of active power to voltage for the winter load compositions at all substations. For all test sites, the minimum values calculated for p_1 for the winter were greater than the maximum values calculated for the summer. This is expected since the summer compositions have a significant portion of their load made up of air conditioning. The induction motors in these units are not very sensitive to voltage changes. Winter compositions typically have a more significant portion of their compositions made up of constant impedance type loads such as electric space and water heating.

Although changes in p_1 did occur at times within very short time periods (compare tests 26 and 28 in Table 4-6), there was little variation in the slope of the linear characteristic during the course of a whole day. The values of p_1 from Table 4-6 for Monday, January 15 have a mean of 1.80 and a standard deviation of only 0.21. The changes in load composition which occur from season to season are definitely greater than the changes which occur from hour to hour during the day - as concerns the active power load characteristics.

Figures 4-22 and 4-24 show significant differences between the model and test voltage responses of reactive power during peak time. As in the summer, the differences are most significant for the Southold substation as shown in Figure 4-22. Whereas there was uncertainty in the number of capacitor banks 'on' during the summer tests, special care was taken during Test 99 and all the winter tests to record the number of capacitor banks 'on'. Also, the reactive power characteristics were found to be consistent from test to test; that is, one could clearly see the shift in characteristics as the capacitors were switched, and the load of the capacitors could be accounted for in the characteristics. In the case of Station 38, the main difference is in the magnitude, the test and model values of q_1 being quite close.

A different voltage base (7.62 kV RMS line-to-ground) is used for Figures 4-21 and 4-22 than for the summer results shown in Figures 4-2 and 4-3. The change was made after discovering a misinterpretation of the DSAP program output. The output

of DSAP is a list of active and reactive powers (expressed in megawatts and megavars) for particular values of voltage (expressed in per unit). The difficulty arises in determining the voltage base; it is not necessarily the nominal voltage of the system. All the component data stored in DSAP is in per unit on a base of 120 volts. Thus, it is assumed that the base voltage for the DSAP output is one which is derived from the 120 volt base by the turns ratios of the intervening transformers. In the case of Southold, a base voltage of 7.62 kV RMS line-to-ground would result at the substation. (The voltage defined by LILCO as nominal is one which results in 125 volts at the customer. RG&E defines nominal voltage as the voltage which results in 120 volts at the customer; therefore, the per unit base used in the summer results for RG&E was correct.)

Calculations were made to determine the effect of this new base voltage on the summer models. The new base voltage shifts the model characteristic approximately 5%. However, the models have been prepared to give the active power determined by test at nominal voltage. Preparing new models to give these correct values would bring their characteristics very close to the ones used in making the summer analysis.

To summarize, Figure 4-25 shows both the summer and winter comparisons of test and model characteristics of active power for the Southold substation. (The summer characteristics have been corrected to the correct base voltage using the fact that small changes in composition do not cause significant changes in p_1 ; the value of p_1 has been kept constant.) Figure 4-26 shows a similar comparison of the reactive power characteristics. The resulting reactive power levels for various numbers of capacitor banks 'on' at Southold during the winter tests gave further confidence that Test 23 during the summer did have all three capacitor banks 'on'. (Test 99 during the winter had two banks 'on'.)

Figures 4-27 and 4-28 show the summer and winter comparisons of model and curve fitted test results for active and reactive power respectively for RG&E, Station 38. Model and test results agree extremely well for active power. As in the summer case, a significant error occurs with the reactive power characteristics, mainly with the overall magnitude.

Steady-State Frequency Response

The complete steady-state load model for the Southold substation at winter peak, with two 900 kvar capacitor banks on, was as follows:

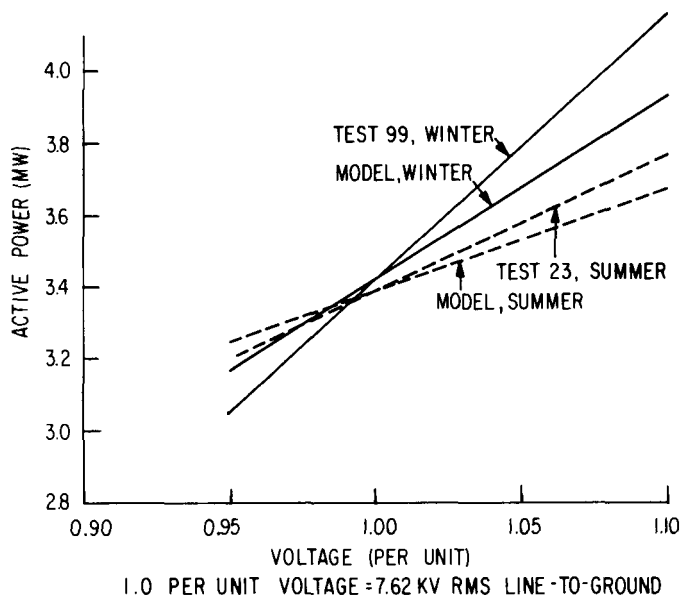


Figure 4-25. Model and curve fitted test results of active power for summer and winter tests at LILCO, Southhold substation.

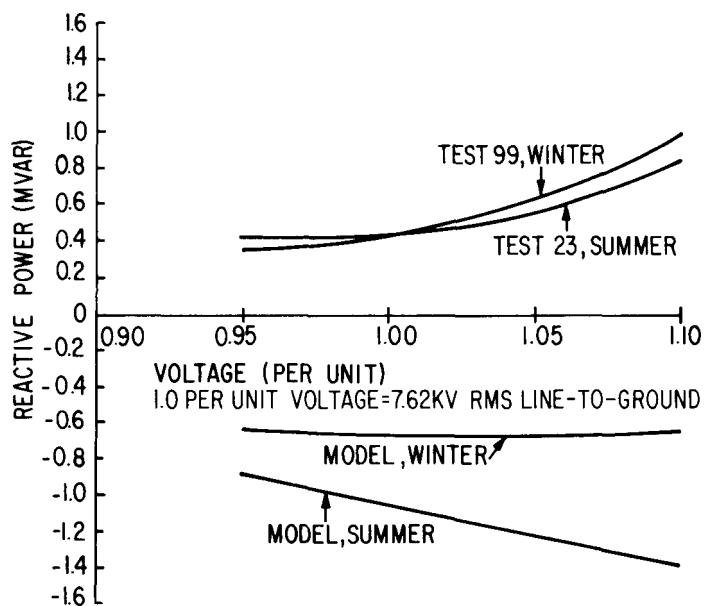


Figure 4-26. Model and curve fitted test results of reactive power for summer and winter tests at LILCO, Southhold substation.

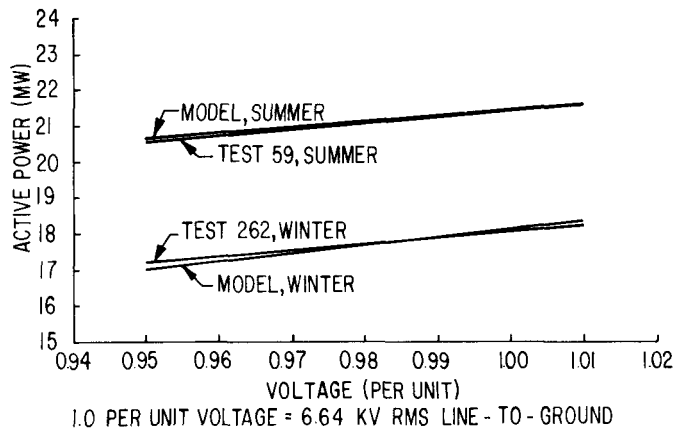


Figure 4-27. Model and curve fitted test results of active power for summer and winter tests at RG&E, Station 38 substation.

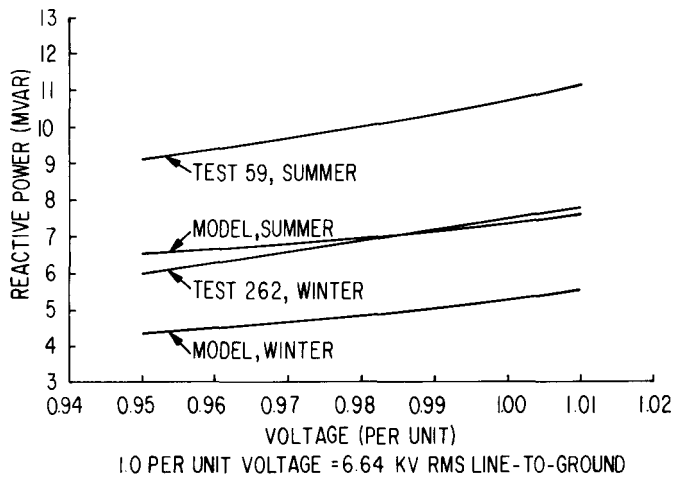


Figure 4-28. Model and curve fitted test results of reactive power for summer and winter tests at RG&E, Station 38 substation.

$$P = 3.42 (1 + 1.50 \Delta V - 0.09 (\Delta V)^2 + .44 \Delta F) \text{ MW}$$

$$Q = -.663 (1 + .555 \Delta V - 7.28 (\Delta V)^2 - 5.57 \Delta F + 28.81 \Delta V \Delta F) \text{ MVAR.}$$

The model predicted that active power is quite insensitive to frequency, a 1% change in frequency causing an approximate 0.44% change in active power. Since there is a greater concentration of resistive type loads in the winter, the predicted sensitivity is less than that for the summer. The predicted response of reactive power is of opposite sign to that of the summer case, increases in frequency causing decreases in the magnitude of the negative reactive power.

Figure 4-29 shows the results of a frequency test run at approximately peak time (with two capacitor banks on). The results shown in Figure 4-29 would support a general insensitivity of active power to frequency. As already discussed, the test results in a lagging instead of a leading power factor; detailed comparisons with the model are not worthwhile. It can be noted that the test results indicate changes in reactive power of opposite direction to the model prediction, and a greater sensitivity of reactive power to frequency at the low frequencies.

Figure 4-30 presents the results of a voltage-frequency test run shortly after the frequency test shown in Figure 4-29. Once again, it can be noted that active power is quite insensitive to frequency changes. The directions of reactive power changes with frequency are as generally expected, and the greater sensitivity of reactive power to frequency at the higher voltage points can be observed. The UTA model structure is not able to produce such a characteristic.

Table 4-7 presents curve fit data for four of the voltage-frequency tests. These tests were chosen because they involved the greatest range of changes in both voltage and frequency. (Equipment difficulties prevented the running of LTC tests immediately before or after the isolated tests.) The values of p_1 are consistent with previous results from the winter LTC tests. The average of the four values of p_1 , 0.27, although significantly different from the model value of 0.44, is quite small as predicted. The values shown for frequency sensitivity of reactive power are of the right order of magnitude as the model, but as noted earlier, differ in sign.

Figure 4-31 is yet another example of the increased sensitivity of reactive power to frequency at a higher voltage level. In this case the two voltage levels are

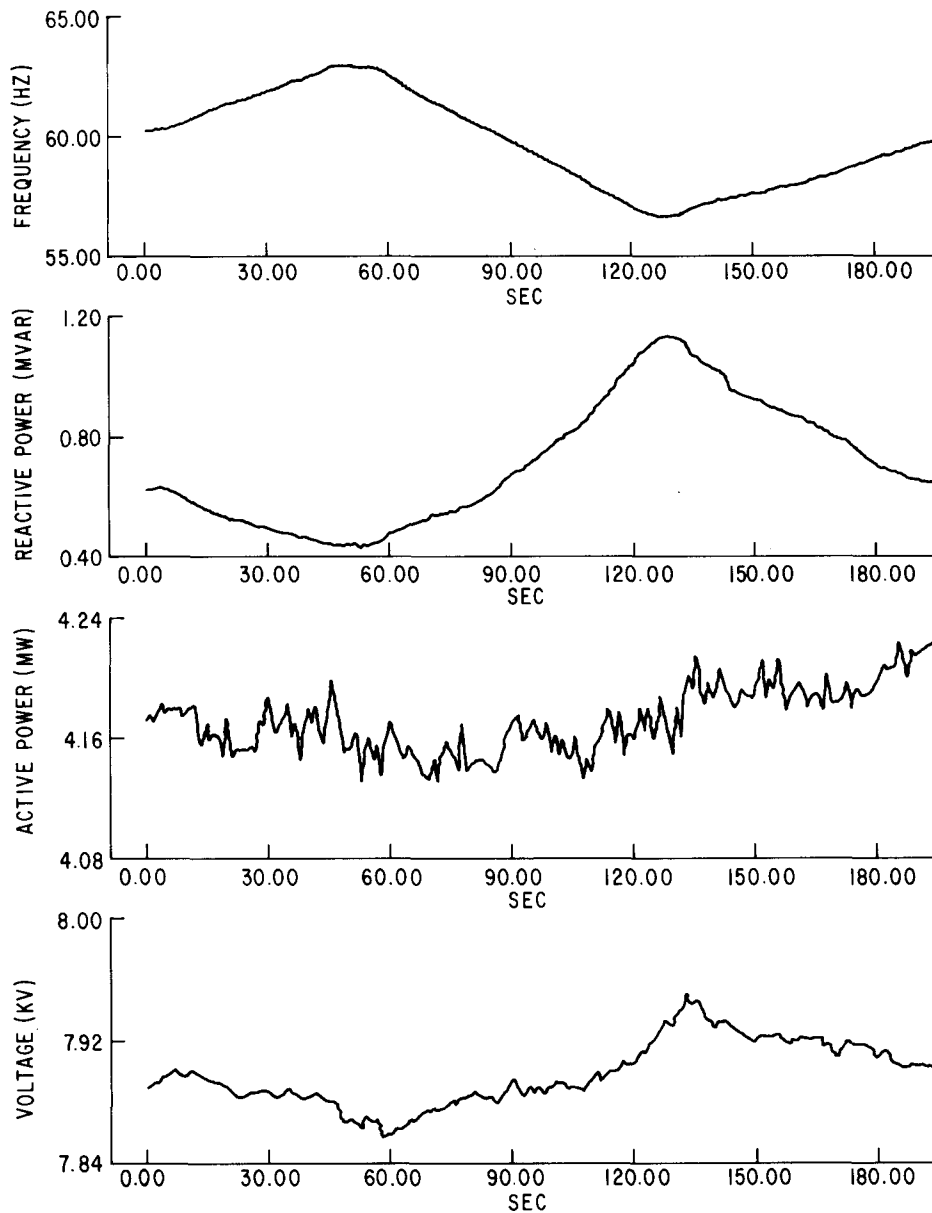


Figure 4-29. Frequency test results, LILCO, Southold substation, winter of 1978-79, Test 92, 1/18/79, 19:27, 2 Cap on.

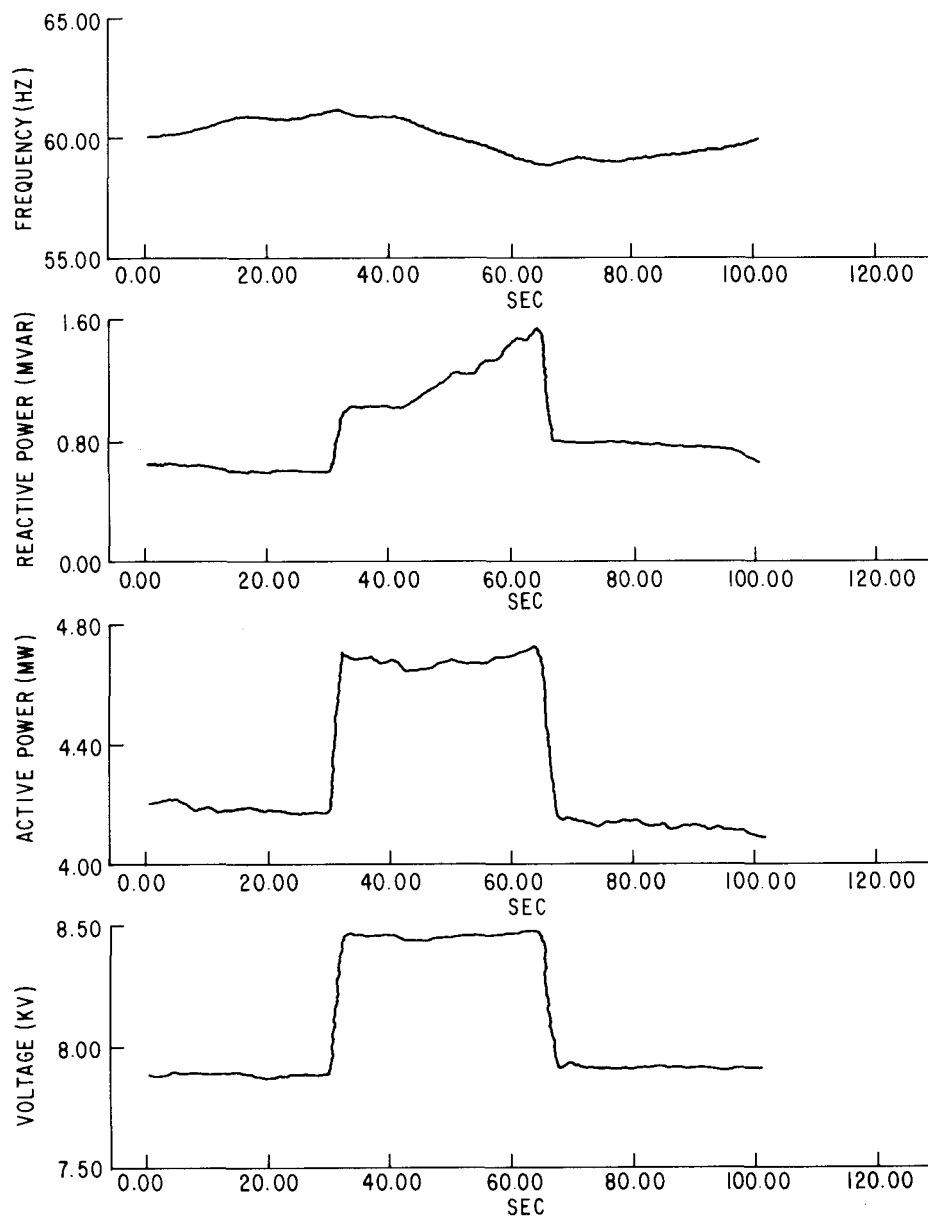


Figure 4-30. Voltage-frequency test results, LILCO, Southold substation, winter of 1978-79, Test 93, 1/18/79, 19:33, 2 cap. on.

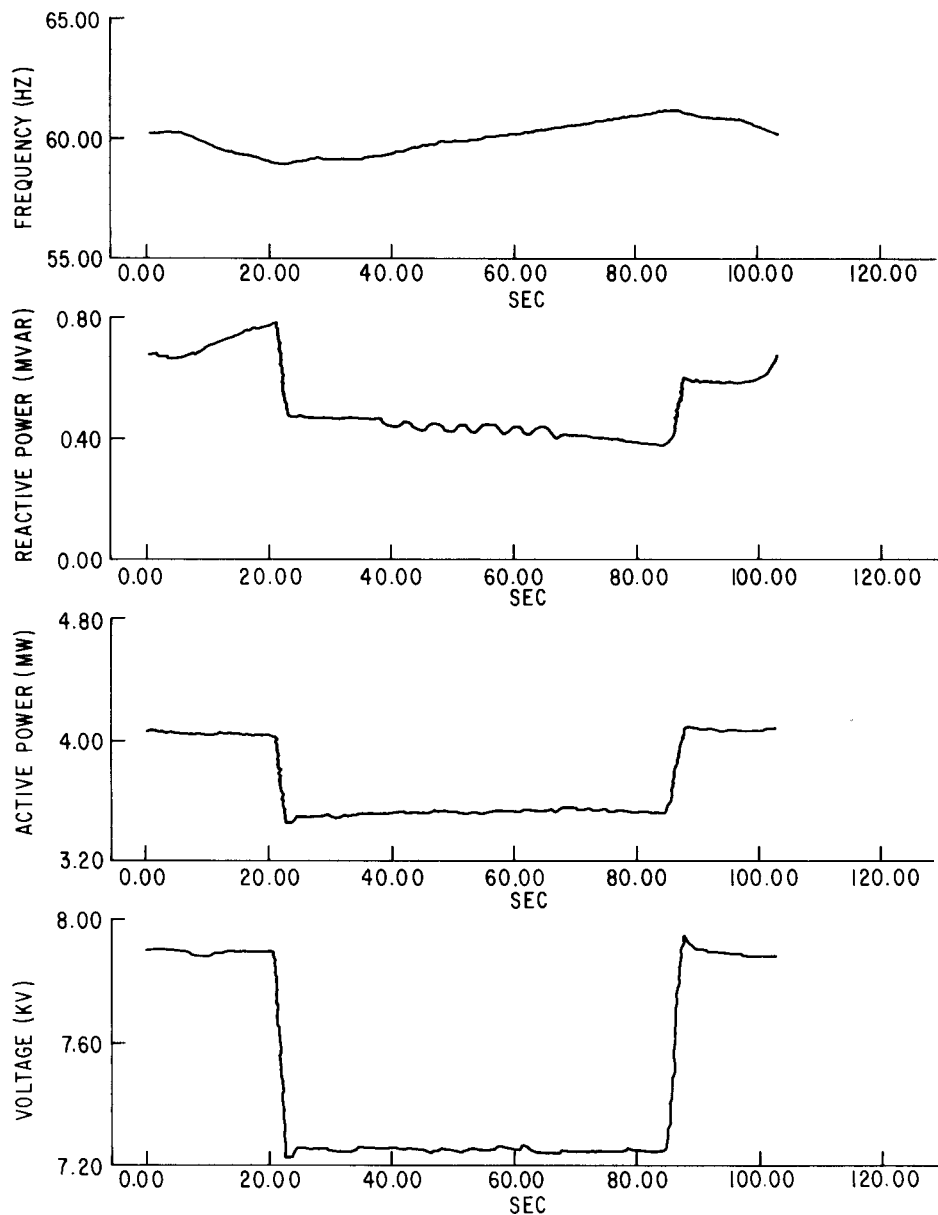


Figure 4-31. Voltage-frequency test results, LILCO, Southold substation, of 1978-79, Test 95, 1/18/79, 19:44, 2 Cap. on.

approximately nominal voltage and approximately 10% below nominal voltage. The sensitivity of reactive power to frequency at nominal voltage, 0.083 Mvar/hz, is approximately twice that at the lower voltage level, 0.042 Mvar/hz.

Table 4-7

COEFFICIENTS* OF CURVE FITTED TEST RESULTS FOR
VOLTAGE-FREQUENCY TESTS, LILCO, SOUTHDOLD SUBSTATION,
WINTER OF 1978-79 (2 CAP ON)

TEST NO.	DATE, TIME	P _o (MW)	Q _o (MVAR)	p ₁	p ₃	q ₁	q ₃
93	1/18 19:32	3.90	.413	1.80	.413	17.5	-19.7
94	1/18 19:36	3.76	.362	1.91	.066	2.07	-22.9
95	1/18 19:43	3.82	.559	1.65	.367	5.08	-6.62
96	1/18 19:46	3.87	.580	1.66	.245	4.43	-3.45

$$* \quad P = P_o (1 + p_1 \Delta V + p_3 \Delta F) \quad Q = Q_o (1 + q_1 \Delta V + q_3 \Delta F)$$

Dynamic Response

The GT trip tests at the Southold substation once again provided the best opportunity to evaluate the ability of the model to predict the dynamic characteristics of loads.

The results of the GT trip tests were studied in detail, and the conclusions reached were as follows:

- (1) The active and reactive powers respond with different time constants, the time constant for active power being approximately 70 milliseconds and the time constant for reactive power being approximately 25 milliseconds. These are very close to those observed during the summer tests.
- (2) Neither time constant is close to the one predicted by the model (0.0185 seconds). Thus, the winter tests gave further evidence that the UTA load modeling procedure does not properly model the dynamic response of loads.

SUMMER, 1979 TESTS

Tests were conducted during the summer of 1979 at the LILCO, Southold test site for two reasons: (1) to attempt to remove the inconsistencies in the reactive power voltage characteristics in the summer of 1978 tests; (2) to provide test data over a greater voltage-frequency range in order to facilitate curve fitting of the test results.

Prior to the summer tests, the 900 KVAR capacitor bank was removed from feeder #685 (Figure 3-1), and a 600 KVAR capacitor bank was added to feeder #684.

Steady-State Voltage Response

The complete steady-state load model for the Southold substation at summer peak, with one 600 kvar bank on, was as follows (distribution transformer saturation was modeled):

$$P = 3.72 (1 + 1.083 \Delta V + 0.046(\Delta V)^2 + .62 \Delta F) \text{ MW}$$

$$Q = 0.729 (1 + 4.863 \Delta V + 17.71(\Delta V)^2 - 8.86 \Delta F - 52.83 \Delta V \Delta F) \text{ MVAR.}$$

Cool weather was experienced during the tests; during test 16, the temperature was 73°F and the humidity was 89%. This made preparation of an accurate load model more difficult since most of the available load composition data was for peak (high temperature) conditions. It was assumed that at this temperature the air conditioning load would be 75% of that used for the summer of 1978 model. The other load components were increased in proportion to the percentages of the load they represented in order to realize an active power level of 3.72 megawatts at nominal voltage (7.62 kV).

Again, the LTC tests were used to determine the steady-state voltage response characteristics of the loads for comparison with the models. Figures 4-32 and 4-33 compare the model and curve fitted test results of steady-state voltage responses of active and reactive power for the LILCO, Southold substation. The test data chosen for comparison with the predicted results was that for the highest power level recorded during the tests within the general peak time.

As can be seen, the steady-state voltage response of active power agrees very well with the model (2.7% difference at 1.1 per unit voltage). As in all previous tests, there are significant differences between the model and test voltage responses of reactive power during peak time. As before, the variation in reactive power with voltage is greater than predicted, and the model predicts a lower overall value of reactive power than occurs during tests. The levels of reactive power observed with different numbers of capacitor banks 'on' did provide further confidence on the numbers of banks 'on' in the summer of 1978 tests.

Steady-State Frequency Response

As in the previous tests, the model predicted that active power is quite insensitive to frequency, and this was confirmed during the tests. Both the model and test results for the response of reactive power to frequency changes were in the same direction; that is, increases in frequency caused net decreases in reactive power. These were the first tests where this was consistently true. Also, as before, the tests indicated greater sensitivity of reactive power to frequency at the high voltage and low frequency points.

Time did not allow an extensive analysis of the voltage-frequency tests to determine whether the additional ranges (voltage-frequency tests were run in which frequency was changed by 4 Hz and voltage by 10%) provided more consistency in the determination of the polynomial coefficients.

Dynamic Response

Analysis of the results of the GT trip tests confirmed the conclusions reached in the previous tests. Figure 4-34 shows the results of GT trip test 43, and calculation of the time constants for active and reactive power response from this figure, results in time constants of approximately 75 milliseconds and 30 milliseconds for active and reactive power, respectively. These values are very close to those observed during all previous GT trip tests. The time constant predicted by the model was 15.8 milliseconds. Thus, as in all previous tests, the model does not accurately model the dynamic response.

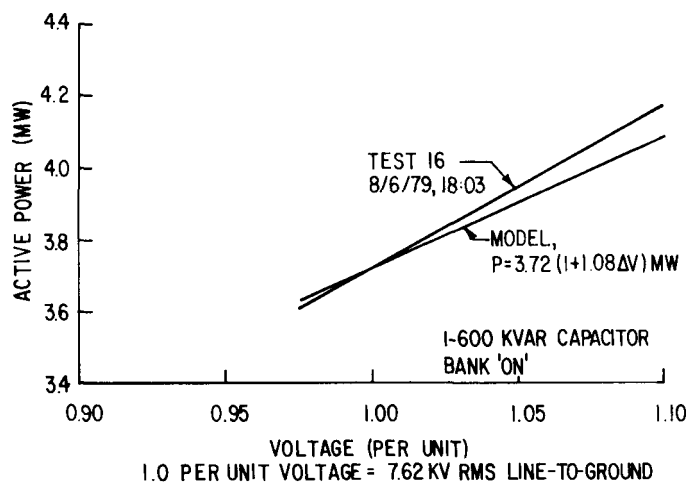


Figure 4-32. Model and curve fitted test results of active power for Test 16 at LILCO, Southold substation, summer of 1979, 8/6/79, 18:03.

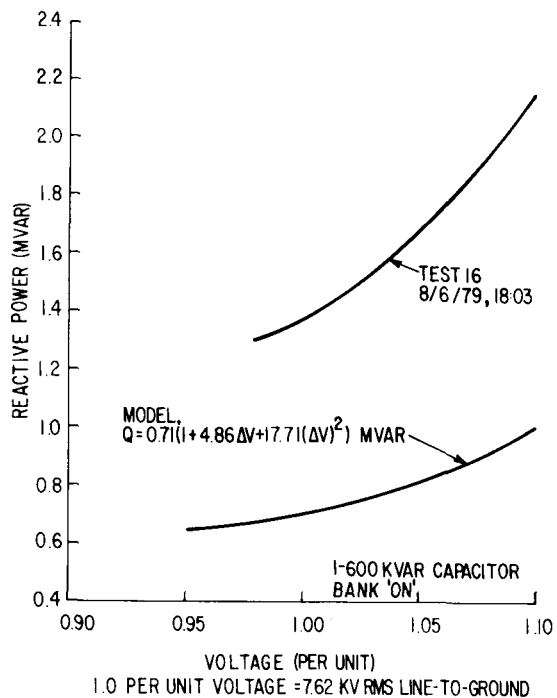


Figure 4-33. Model and curve fitted test results of reactive power for Test 16 at LILCO, Southold substation, summer of 1979, 8/6/79, 18:03.

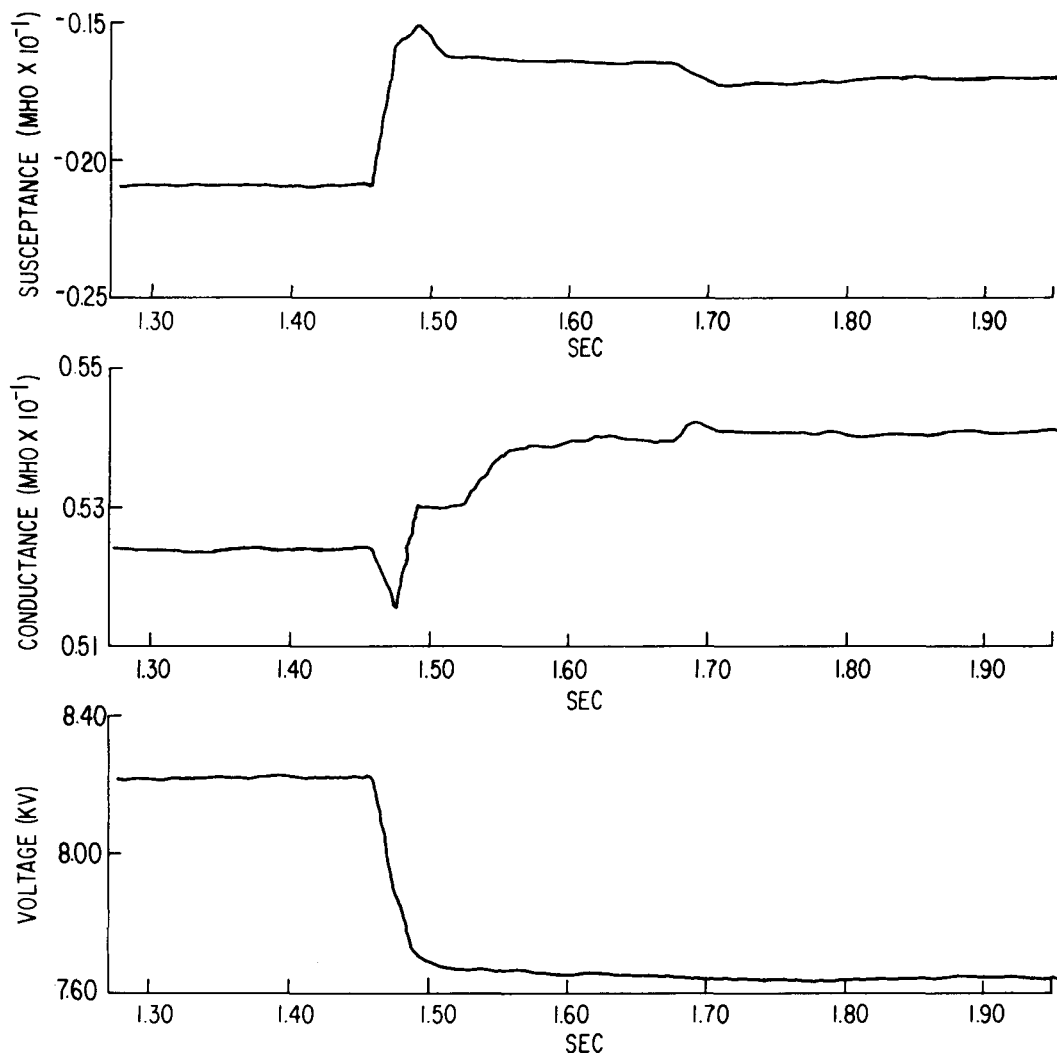


Figure 4-34. Measured response of admittance for GT trip test 43, LILCO, Southold substation, summer of 1979, 8/14/79, 18:50.

BISMARCK TESTS

As a part of efforts by Minnesota Power and Light Company and Montana-Dakota Utilities Company to improve their transient-stability simulation capability, a staged fault test was conducted in the Bismarck, North Dakota area. (The fault test was planned independently of the RP849 project.) The RTDDAS was used to record the response of a portion (approximately 50%) of the Bismarck load to this fault. Data was recorded at a sample rate of 150 samples per cycle; such complete load data during a fault is unique.

A load model was prepared using data supplied by Montana-Dakota Utilities Company after the tests. They supplied the following composition for the load in place before the fault test (some load was dropped during the fault): mercury vapor street lights - 1 megawatt, electric heat - 1 megawatt, incandescent lights - 1 megawatt, induction motors - 7.5 megawatts. The induction motor load consisted primarily of furnace, freezer, and refrigerator motors, and the DSAP model for small induction motors was used for this load. The model for fluorescent lights was used for the mercury vapor lights. The data was not based on any extensive load research inputs, but rather their best estimate of the composition. Thus, the Bismarck test case provided the opportunity to evaluate the whole load modeling methodology with a less detailed study of load composition. The resulting models of active and reactive power for the Bismarck substation were as follows:

$$P = 10.50 (1 + .514 \Delta V + .00365 (\Delta V)^2 + .773 \Delta f) \text{ MW}$$

$$Q = 5.33 (1 + 1.688 \Delta V + 2.234 (\Delta V)^2 - .871 \Delta f - 4.786 \Delta V \Delta f) \text{ MVAR.}$$

The LTC unit was used to change voltage before and after the fault test in order to determine the steady-state voltage response of the load. Figure 4-35 compares the model and test results for the test (TEST 2) run immediately before the fault test. As can be seen, significant errors exist in the models for both active and reactive power. In this case, it is the authors' opinion that the likely source of error is in the load composition data. The assumed percentage of induction motors is quite high, causing a flatter active power characteristic (induction motor active power is insensitive to voltage changes) and significantly higher values of reactive power. In all other test cases at all substations, the model predicts lower values of reactive power than observed during tests. (The model for Bismarck was prepared to match the power level that existed just prior to the fault which was run close to midnight.)

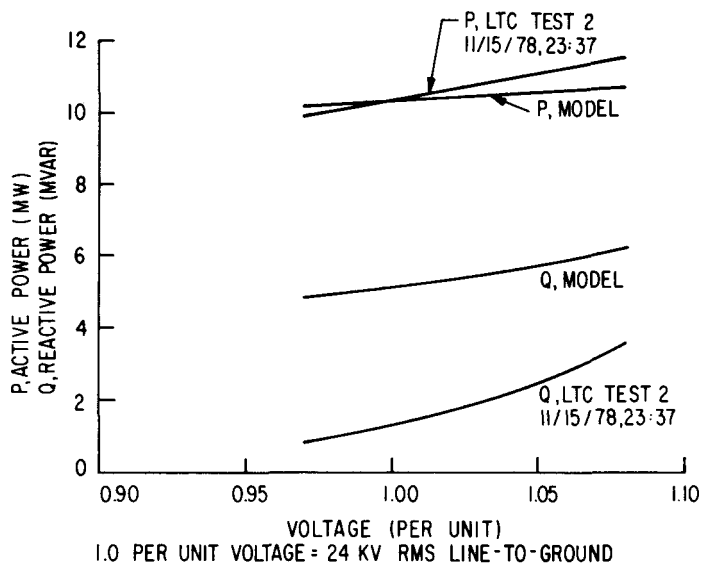


Figure 4-35. Model and curve fitted test results of active and reactive power for LTC test 2 at Bismarck substation, 11/15/78, 23:37.

Figures 4-36 and 4-37 show the results of the staged fault test in terms of power and admittance, respectively. The fault can be seen to last approximately 15 cycles; the initial voltage was 24.40 kV, and it decreased to a low of 9.78 kV. Marked on Figure 4-36 are values of reactive power calculated by a method which includes the effect of harmonics; note that there is very little difference in the results at this substation.

The model predicted a time constant of 13.88 milliseconds for both active and reactive power. From Figure 4-37 the time constants during the test can be calculated to be approximately 240 and 160 milliseconds for active and reactive power, respectively (the time constant was measured from the point following the clearance of the fault). Comparing Figures 4-36 and 4-37, another advantage of the admittance characteristics can be seen. Whereas the active and reactive power characteristics of Figure 4-36 are compounded by the effect of the system voltage swing, the admittance characteristics are not. This makes the evaluation of the load dynamic performance more straightforward.

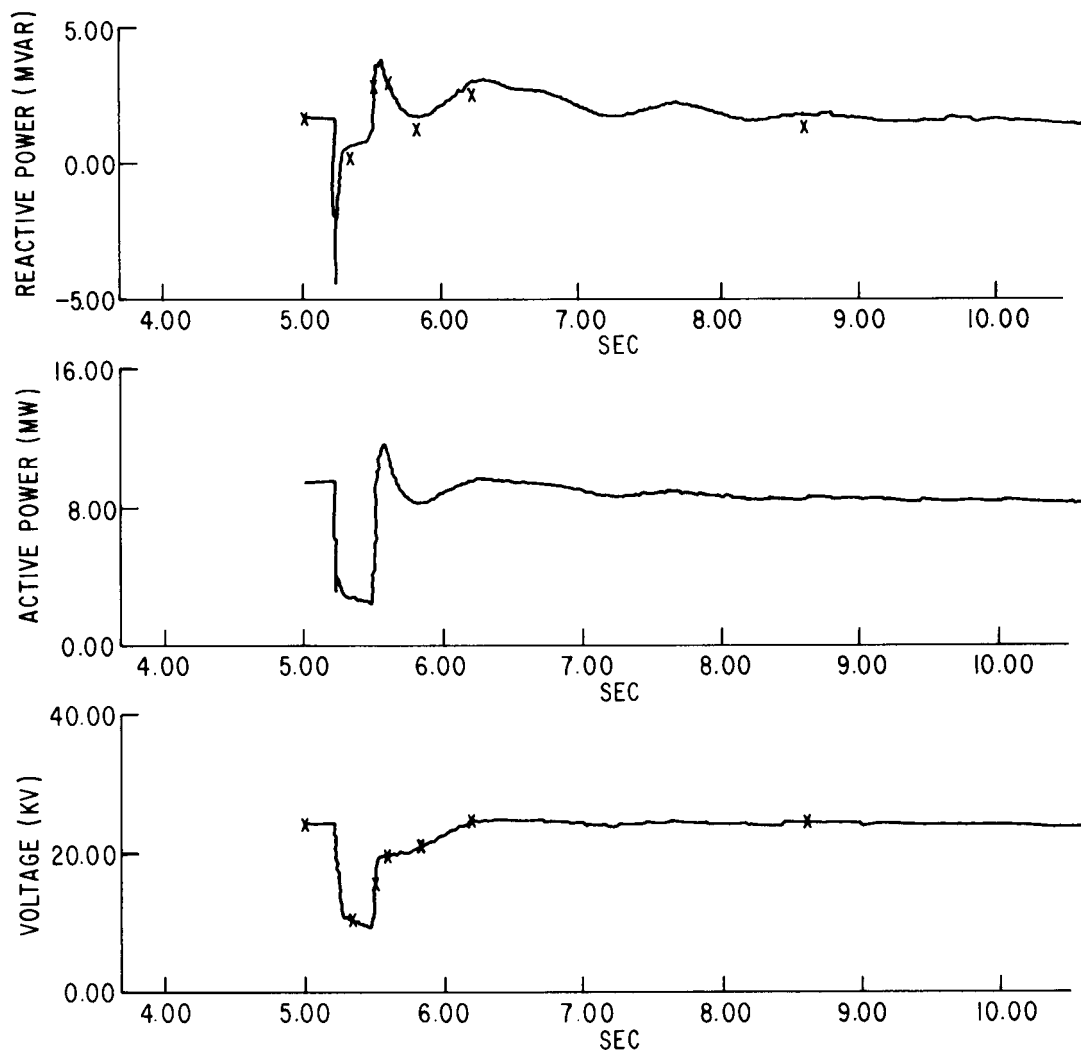


Figure 4-36. Load characteristics for staged fault test in terms of active and reactive power, Bismarck substation, 11/16/78, 00:20.

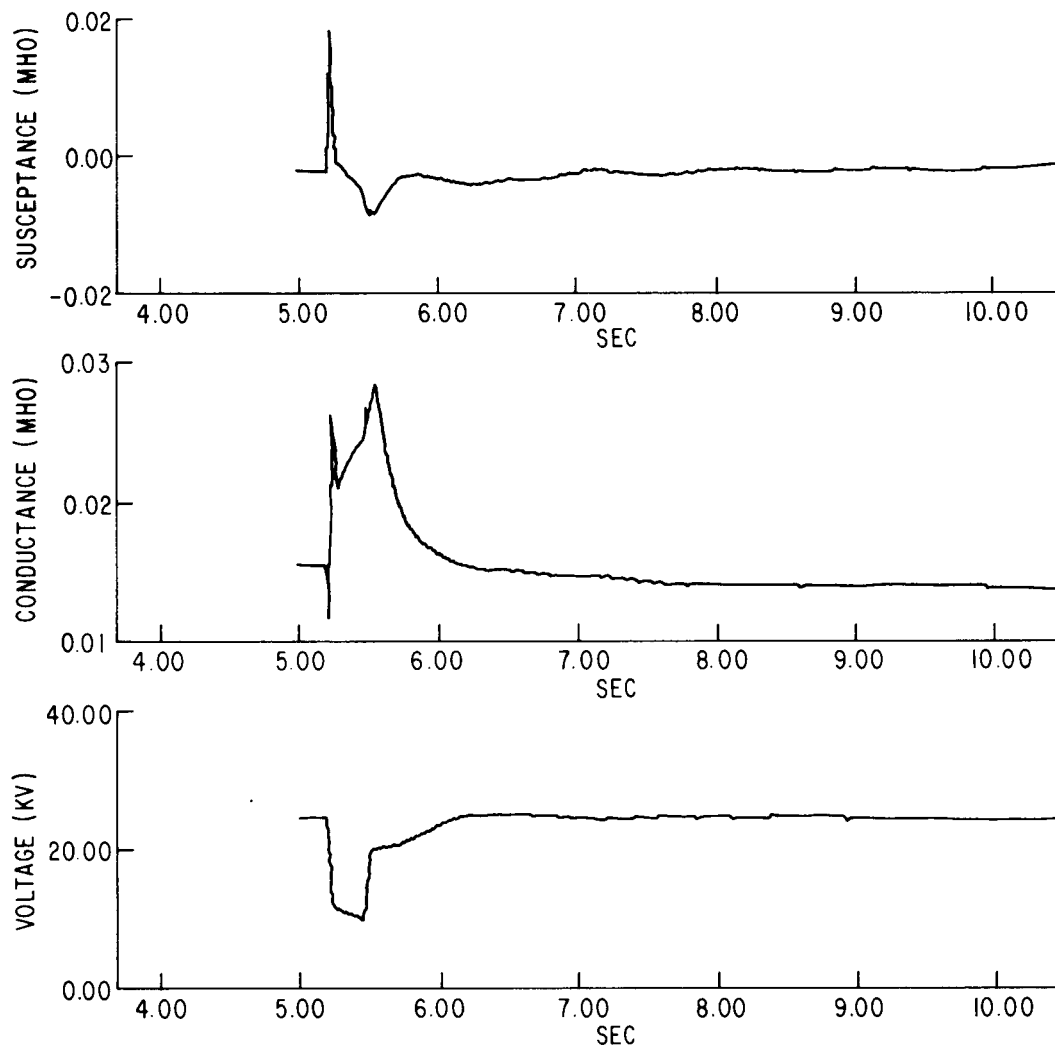


Figure 4-37. Load characteristics for staged fault test in terms of the real and imaginary parts of the load admittance, Bismarck substation, 11/16/78, 00:20.

The data collected during the Bismarck fault test is very important. The determination of load response to such faults is the objective of this project. The length and severity of the fault produced the most severe voltage conditions realized during the tests. Also, the dynamic response observed is of the order of concern for transient stability studies. All other tests produced time constants much lower than generally of interest.

The observed load dynamic performance is characteristic of a load with a significant amount of induction motor load. Reactive power decreases, in fact it reverses direction, and following the clearance of the fault, there is a significant increase in active power. These same characteristics can be seen in the system simulations made with motor loads in Volume 2, Load Model Guidelines, of this final report.

The objective of the RP849-1 project was to evaluate the load modeling methodology developed by UTA. In the Bismarck case there is little agreement between model and test, and in the author's opinion more accuracy could have been obtained if more exact load composition data was available. Also, there is much more to be gained from an analysis of the Bismarck data beyond simply evaluating the load model. The admittance characteristics appear to be an excellent vehicle for this research. It appears from the admittance characteristics of Figure 4-37 that one can determine the response of the dynamic portion of the load, and separate the static and dynamic portions of the total load (as defined by UTA). As explained previously, the jumps in the admittance characteristics would be attributable to the static loads, and one of the jumps seen during the fault period is probably attributable to the loss of the mercury vapor street lights during the fault.

Appendix A
UTA MODEL DESCRIPTION
DEVELOPMENT OF THE POWER SYSTEM LOAD MODEL
(Extracted from UTA final report, EPRI EL-849, Volume 3)

The Equivalent Steady-State Load

The equivalent steady-state load is represented by nonlinear functions for the real power and the reactive power versus the voltage and frequency of the equivalent bus:

$$\begin{aligned} F_{SS,P} &= f(V_{EQ}, f_{EQ}) \\ F_{SS,Q} &= f(V_{EQ}, f_{EQ}) \end{aligned} \tag{A-1}$$

Where $F_{SS,P}$ and $F_{SS,Q}$ are functions formed by the sum of the real and reactive powers, respectively, of the steady-state loads. The steady-state P and Q can be represented by polynomials.

The Equivalent Dynamic Load

The equivalent dynamic load is composed of basically two components, a steady-state component and a dynamic response component. These components are combined in a unique way to form two first-order differential expressions, one for real power and one for reactive power. These expressions give the instantaneous real power and reactive power of the equivalent dynamic load for values of voltage and frequency as variable functions of time.

The steady-state component of the equivalent dynamic load is obtained and represented in the same manner as the steady-state load, by nonlinear functions for the real and reactive power versus the voltage and frequency of the equivalent bus:

$$\begin{aligned} F_{DS,P} &= f(V_{EQ}, f_{EQ}) \\ F_{DS,Q} &= f(V_{EQ}, f_{EQ}) \end{aligned} \tag{A-2}$$

Where $F_{DS,P}$ and $F_{DS,Q}$ are functions formed by the sum of the steady-state real and reactive power values, respectively, on the dynamic (induction motor) loads.

Since the dynamic load is composed of induction motors, the expressions for the dynamic response components of the real and reactive power can be written as:

$$F_{DI,P(i+1)} = P_{Di} \left(\frac{V_{i+1}}{V_i} \right)^2 + \frac{\partial P_{Di}}{\partial f_i} (f_{i+1} - f_i) \quad (A-3)$$

$$F_{DI,Q(i+1)} = Q_{Di} \left(\frac{V_{i+1}}{V_i} \right)^2 + \frac{\partial Q_{Di}}{\partial f_i} (f_{i+1} - f_i)$$

Where P_{Di} and Q_{Di} are the i th step total P and Q for the equivalent dynamic load, respectively. Initially, $P_i = P_o$ and $Q_i = Q_o$, the steady-state solution values of the equivalent dynamic load as solved with the "larger" system.

V_i, V_{i+1} are the voltage magnitudes at steps i and $i+1$, respectively. Assuming the speed of the induction machine remains constant during the small time interval, ΔT , the dynamic power responds according to $(V_{i+1}/V_i)^2$.

$\frac{\partial P_{Di}}{\partial f_i}, \frac{\partial Q_{Di}}{\partial f_i}$ are the frequency variation coefficients, and are designated as $K_{f,P}$ and $K_{f,Q}$. The coefficient $K_{f,P}$ is essentially constant and will normally need to be calculated only once, at the steady-state operating point. However, the variation of reactive power with frequency, $K_{f,Q}$, is voltage dependent and may need to be calculated at each operating point. Because the variations in frequency are usually very small, this term is insignificant.

Equation A-3 expresses analytically the physical fact that, for instantaneous changes in voltage, the motor speed will not change immediately and the induction motor will initially appear as a constant impedance load. As the motor speed changes, however, it will depart from a constant impedance characteristic. It will be necessary then to add the dynamic effect of motor speed changes.

Experimental data has indicated that the response of dynamic loads to sudden changes of voltage can, in general, be modeled as a first order differential equation.

$$P_D = F_{DI,P} + \frac{F_{DS,P} - F_{DI,P}}{1 + T_S \cdot p} \quad (A-4)$$

$$Q_D = F_{DI,Q} + \frac{F_{DS,Q} - F_{DI,Q}}{1 + T_S \cdot p}$$

Where P_D, Q_D are the total dynamic load real and reactive power, respectively;

$F_{DI,P}, F_{DI,Q}$ are the dynamic response components, equations (A-3);

$F_{DS,P}, F_{DS,Q}$ are the steady-state components of the induction motor loads, equations (A-2);

T_S is the system time constant;

p is the differential operator.

Note that for a steady-state condition the derivative terms are zero and $P_D = F_{DS,P}$, the steady-state characteristic of the dynamic load. For an instantaneous change the derivative terms dominate, and $P_D = F_{DI,P}$, the dynamic response. At any time after a change in voltage the total dynamic power will be a combination of the dynamic response and the difference between the steady-state and dynamic response modified by the time constant, T_S .

Equations (A-4) are altered for solution as follows:

$$P_D - F_{DI,P} = \frac{F_{DS,P} - F_{DI,P}}{1 + T_S \cdot p}, \quad Q_D - F_{DI,Q} = \frac{F_{DS,Q} - F_{DI,Q}}{1 + T_S \cdot p}$$

let $P' = P_D - F_{DI,P}$ and $Q' = Q_D - F_{DI,Q}$

$$F' = F_{DS,P} - F_{DI,P} \text{ and } G' = F_{DS,Q} - F_{DI,Q}$$

$$\text{Then } P' = \frac{F'}{1 + \frac{T}{S} \cdot p}, \quad Q' = \frac{G'}{1 + \frac{T}{S} \cdot p}$$

or, in typical differential equation form,

$$\frac{d}{dt} P' + \frac{1}{T_S} P' = \frac{1}{T_S} F', \quad \frac{d}{dt} Q' + \frac{1}{T_S} Q' = \frac{1}{T_S} G'$$

As an example, the solution of this equation to a step change in voltage would proceed as shown below.

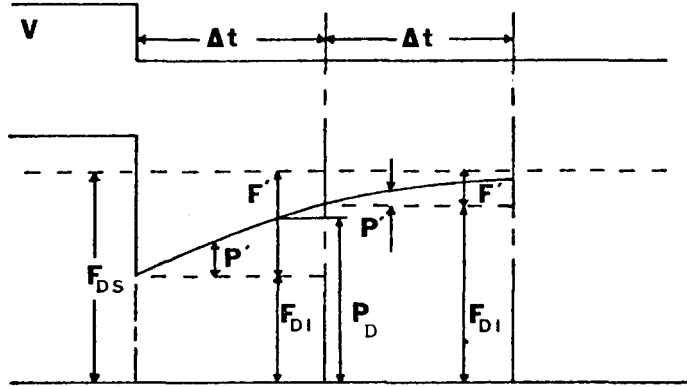


Figure A-1. Response of an Equivalent Dynamic Load

The Equivalent Line Loss Load

The line loss coefficients, $K_{L,P}$ and $K_{L,Q}$ are the ratios of P_{loss} and Q_{loss} to the total of the steady-state and dynamic load currents squared. P_{loss} , Q_{loss} , and the current are obtained from the steady-state solution of the system, and the simplifying assumption is that the system line losses will be proportional to I_{EQ}^2 , the total equivalent steady-state and dynamic load current squared.

The complete, simplified load model as it appears at the equivalent bus is shown below.

EQUIVALENT BUS

Steady-State Load	Dynamic Load	Line Losses
$P_S = F_{SS,P}$ $Q_S = F_{SS,Q}$	$P_D = F_{DI,P} + \frac{F_{DS,P} - F_{DI,P}}{1 + T \cdot p}$ $Q_D = F_{DI,Q} + \frac{F_{DS,Q} - F_{DI,Q}}{1 + T \cdot p}$	$P_L = K_{L,P} \cdot I_{EQ}^2$ $Q_L = K_{L,Q} \cdot I_{EQ}^2$

Figure A-2. Simplified Load Model

Each of the elements in the above expressions is described as follows:

$F_{SS,P} = f(V_{EQ}, f_{EQ})$, $F_{SS,Q} = f(V_{EQ}, f_{EQ})$: functions formed by the sums of the real and reactive powers, respectively, of the steady-state loads. These will, in general, be polynomial expressions of the following form:

$$F_{SS,P} = a_1 + b_1 V_{EQ} + c_1 V_{EQ}^2 + d_1 f_{EQ} + e_1 V_{EQ} \cdot f_{EQ}$$

$$F_{SS,Q} = a_2 + b_2 V_{EQ} + c_2 V_{EQ}^2 + d_2 f_{EQ} + e_2 V_{EQ} \cdot f_{EQ}$$

$F_{DS,P} = f(V_{EQ}, f_{EQ})$, $F_{DS,Q} = f(V_{EQ}, f_{EQ})$: functions formed by the sums of the real and reactive powers, respectively, of the dynamic loads. These will, in general, be polynomial expressions (within the induction motor stable operating region) of the following form:

$$F_{DS,P} = a_3 + b_3 V_{EQ} + c_3 V_{EQ}^2 + d_3 f_{EQ} + e_3 V_{EQ} \cdot f_{EQ}$$

$$F_{DS,Q} = a_4 + b_4 V_{EQ} + c_4 V_{EQ}^2 + d_4 f_{EQ} + e_4 V_{EQ} \cdot f_{EQ}$$

$F_{DI,P}$, $F_{DI,Q}$: the dynamic response components determined from the previous time step of the equivalent dynamic load real and reactive power, respectively. The relationships are shown in equation (A-3).

T_S = the system time constant determined by

$$T_S = \frac{\sum T_i \cdot CAP_i}{\sum CAP_i}$$

where T_i is the time constant of the i th machine: and CAP_i is the capacity of the i th machine.

$K_{L,P}, K_{L,Q}$: the line loss coefficients, see bottom page.

$$K_{L,P} = \frac{P_{loss}}{I_{EQ}^2} ; K_{L,Q} = \frac{Q_{loss}}{I_{EQ}^2}$$

I_{EQ} : The total equivalent steady-state and dynamic load current.

$$I_{EQ} = \frac{(P_S + P_D) - j(Q_S + Q_D)}{V_{EQ}^*}$$

The total load at the equivalent load bus is

$$P_{EQ} = P_S + P_D + P_L$$

$$Q_{EQ} = Q_S + Q_D + Q_L$$

where each component is a function of voltage and frequency in the steady-state case and where in the dynamic case P_D and Q_D are functions of time and P_S , Q_S , P_L , Q_L become indirectly functions of time.

A block diagram of the simplified load model is shown in Figure A-3.

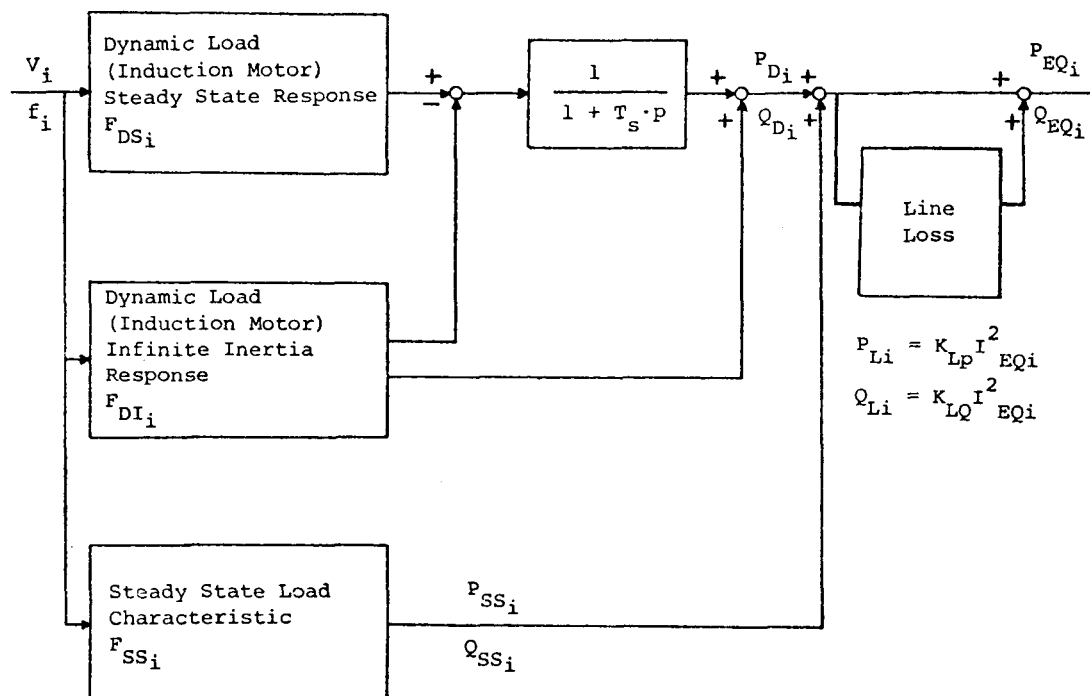


Figure A-3. Block Diagram of simplified load model.

Appendix B
LOAD COMPOSITIONS FOR TEST SITES

LOAD TYPE	LILCO, SOUTHOLD			RG&E, STATION 38	
	LOAD COMPOSITIONS, %			LOAD COMPOSITIONS, %	
	1978	1978-79	1979	1978	1978-79
	<u>SUMMER</u>	<u>WINTER</u>	<u>SUMMER</u>	<u>SUMMER</u>	<u>WINTER</u>
Resistive	24.2	42.5	28.9	5.9	6.7
Incandescent Lights	9.1	26.4	11.0	5.7	6.5
Fluorescent Lights	13.0	15.0	15.6	51.5	58.4
Induction Motor (default data*)	51.9	13.5	42.4	19.9	0
Induction Motor (user specified**)	1.8	2.6	2.1	17.0	28.4

* All loads with small induction motors used DSAP default data; in this case, the program uses stored data completely.

** For these motors some data was specified - an initial loading of 75% was used, it was assumed that shaft torque varied as the square of speed, and the inertia constant was taken as 1.0.