ORNL/TM-2005/174

Reactive Power Laboratory

Synchronous Condenser
Testing & Modeling Results

Interim Report

August 22, 2005

Prepared by
Shawn D. Henry*
D. Tom Rizy
Pierre A. Boheme
John D. Kueck

Oak Ridge National Laboratory

* Visiting MSEE Student and PhD Candidate from the Florida State University, Tallassee, FL

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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
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[†] Visiting MSEE Student and PhD Candidate from the Florida State University, Tallassee, FL

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Glossary

CB	Circuit Breaker
CT	Current Senor or Transformer
DE	Distributed Energy Resource or Distributed Generation
FY	Fiscal Year which is from October 1 of one year to September 30 of the next year
HP	Horsepower which is equal to 745.7 Watts
KV	kilovolts or one-thousand volts
KVA	kilovolt-ampere, measure of capacity
KVAR	kilovolt-ampere reactive which is a measure of reactive power production
KW	kilowatts or one-thousand watts
ORNL	Oak Ridge National Laboratory
PF	Power factor
PG	Drantez/BMI PowerGuide 4400 Meter
SC	Synchronous Condenser (unloaded, overexcited synchronous motor)
SKM	SKM Power Systems Analysis Package
t_{sync}	synchronization period for the synchronous condenser

1. Objective

The subject report documents the work carried out by Oak Ridge National Laboratory (ORNL) during months 5-7 (May-July 2005) of a multi-year research project. The project has the overall goal of developing methods of incorporating distributed energy (DE) that can produce reactive power locally and for injecting into the distribution system. The objective for this new type of DE is to be able to provide voltage regulation and dynamic reactive power reserves without the use of extensive communication and control systems. The work performed over this three-month period focused on four aspects of the overall objective: 1) characterization of a 250HP (about 300KVAr) synchronous condenser (SC) via test runs at the ORNL Reactive Power Laboratory; 2) development of a data acquisition scheme for collecting the necessary voltage, current and power readings at the synchronous condenser and on the distribution system; 3) development of algorithms for analyzing raw test data from the various test runs; and 4) validation of a steady-state model for the synchronous condenser via the use of a commercial software package to study its effects on the ORNL 13.8/2.4kV distribution network.

1.1. Description of Equipment

ORNL is developing a “Reactive Power” Laboratory at building 3114 for studying reactive power supplied from both rotating and static-based DE. The purpose of this initial document is to report on the synchronous condenser portion of the testing at the Reactive Power Laboratory. The inverter-portion of the Laboratory will be operational in early FY06. The electrical design and layout of the Reactive Power Laboratory includes the following equipment:

- 250hp synchronous motor for use as a synchronous condenser
- 75A, 150A, and 300A programmable inverters
- Two 750kVA 2.4kV/480V pad-mount transformers for interfacing to circuits #4 and circuit #2 of the ORNL 13.8/2.4kV distribution network at the 3000 Substation
- 480V/900A three-phase electrical panel configuration for the 250HP synchronous condenser interface (via a 540A motor starter) to the ORNL 2.4kV distribution circuit #4
- 480V/600A three-phase electrical panel configuration for the inverter interface to ORNL 2.4kV distribution circuit #2
- 2 Dranetz/BMI PowerGuide 4400 Meters; one located at the motor/starter and the second at the electrical panel.
- Matlab/Simulink software
- dSpace real-time control hardware and software
- 150kW dc power supply for the programmable inverters
- 6.6kW dc power supply for excitation of the synchronous condenser
- 500kW resistive load with remote control
- 375kVAR inductive load with remote control
- 75HP Induction Motor for dynamic characterization of the synchronous motor

1.2. Data Acquisition and Data Analysis Algorithms

Data acquisition of SC is accomplished by configuring the Dranetz PowerGuide (PG) 4400 meters in a continuous data logging mode such that they record one second averages of the RMS voltages**,** currents, and power values. The sampled data is then saved to a compact flash data card and transferred to the desktop computer using a flash card reader. The data file is opened and accessed by using Dranview, a Windows compatible program developed by Drantez/BMI. Because of the data analysis limitations of Dranview, the retrieved files are then converted to text files and exported to Matlab for data-manipulation and further investigation. A series of Matlab M-files have been created to format, process and plot the data from the PowerGuide meters.

The use of Matlab eliminates the restrictions of Dranview by providing flexibility in the type of data analysis that can be performed. Further, it allows export of the data to Excel spreadsheets for data sharing with the project team. Algorithms employing minimal data processing were written to explore relationships that must be understood in order to properly characterize the SC. Furthermore, the same algorithms can be used to examine different tests, which reduce the time and effort required to investigate the data sets.

2. Synchronous Condenser Characterization

The objective of characterizing the SC is to understand its behavior and capabilities when providing reactive power to the distribution system for voltage regulation. There are several steps involved in this process. First, important characteristics of the SC, such as how much maximum reactive power can be provided, are identified for study. Second, several grid configurations are examined with the purpose of establishing testing scenarios. Third, SC operating guidelines, such as starting up the synchronous condenser at an excitation level that achieves unity power factor to ensure that the SC is at a neutral operating mode initially, were developed to provide a sequenced set of rules to follow each time a test is performed. Finally, tests runs were made that generate data to be analyzed.

2.1. Characteristics Explored

Characterization tests were performed to find the dynamic and steady state characteristics and to answer the following questions regarding the performance of the SC: 1) at what excitation level does the SC operate at unity power factor?, 2) how does the amount of reactive power output change as excitation changes?, 3) how much does reactive power output vary at a given excitation setting?, 4) how much real power does the machine consume as its reactive power output is increased?, 5) how much current does it inject into the network for a given configuration?, and 6) what impact does it have on the local and feeder voltages?

Transient characteristics have been identified for study and the following questions will be examined during the next phase of testing: 1) what is the transient and sub-transient reactance of the SC?, 2) what is the response behavior of the SC as it adjusts from supplying one level of reactive power output to another?, 3) what is the response time of the SC as it transitions from idle to a state in which it delivers a specified amount of reactive power?, and 4) how long can the SC inject current in excess of the full-load current (amps) without over-heating?

2.2. Description of Present Testing Configuration

Testing scenarios are examined to determine how to configure the distribution system in a way that provides optimum opportunities for testing of reactive power injection effects. Presently, the Reactive Power Laboratory is configured with the ORNL distribution system as shown in Figure 1. This figure shows the details for the primary side (2.4kV) of the service connections and what circuits and transformers connect the Reactive Power Laboratory to the ORNL network. The detailed secondary (480V) configuration of the laboratory in regards to circuit and transformer connections with the ORNL distribution system, power distribution panels, and specific laboratory components and how they are connected to the distribution panels are shown in Figure 2. The reactive power laboratory is currently fed by one 750kVA 13.8/2.4 kV transformer connected to circuit #4 and soon to be a second 750kVA transformer connected to circuit #2. These circuits are fed by ORNL substation 3000 which is located a short distance northwest of the Reactive Power Laboratory at building 3114. Substation 3000 has two incoming 13.8kV feeders coming directly from ORNL's main 901 Substation. The main 901 substation has two incoming 161kV lines from TVA.

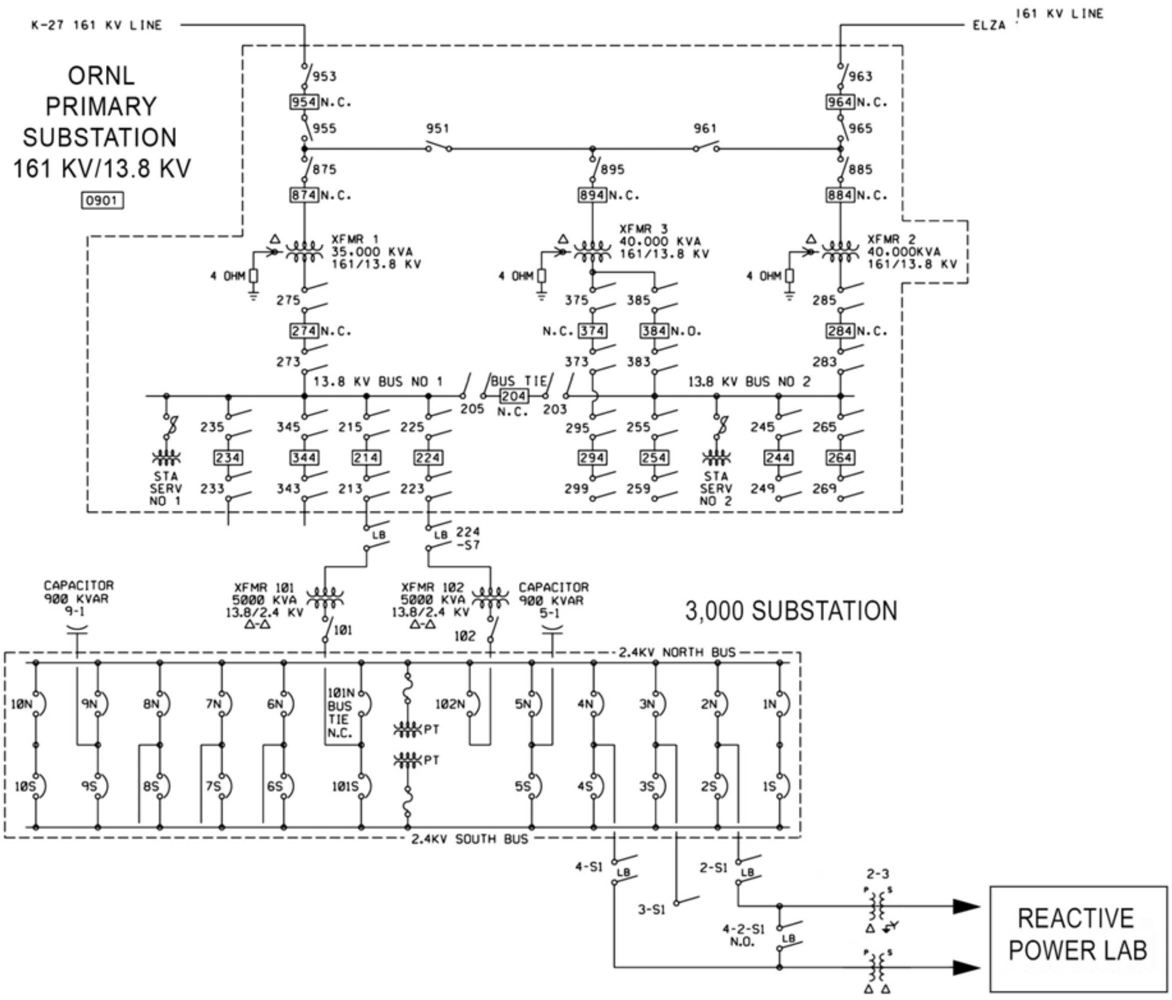

Figure 1. One-line diagram of Reactive Power Laboratory connection with the ORNL distribution system on the primary-side (2.4kV).

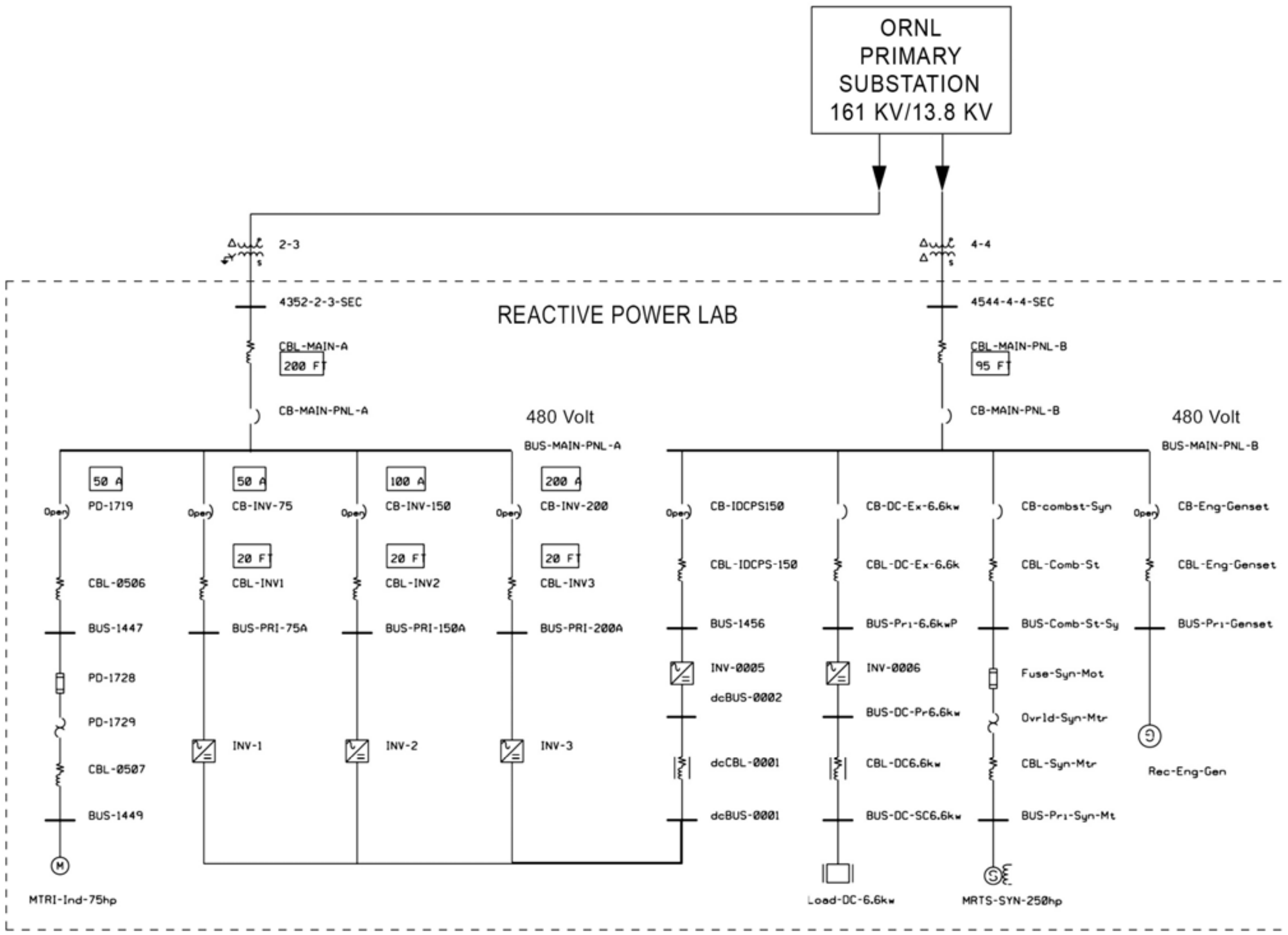

Figure 2. One-line diagram of the Reactive Power Laboratory electrical configuration on the secondary-side (480V) and its connection with the ORNL distribution system.

2.3. Synchronous Condenser Operating Guidelines

Operating guidelines were developed for manual operation of the synchronous condenser and the power supply for its excitation to ensure safety and to minimize the potential damage due to any mis-operation. In order to conduct a test, the SC is carefully transitioned from startup to operation. During the SC's startup, a 10-ohm resistor is initially placed via contactor operation in the excitation circuit to provide a soft start. During this time, the excitation voltage initially surges when the motor is first started and then drops to zero as the SC approaches synchronous speed at which time the resistor is switched out and the power supply switched into the excitation circuit. This soft starts the SC and minimizes the ac line voltage sag impact to the distribution system. Once the power supply is switched into the circuit, excitation can be manually or remotely operated and the SC characterization tests can begin. The power supply allows for both dial and keyboard entry of dc voltage/current settings. A user interface for the desktop computer can be used to remotely control the dial or keyboard settings of the power supply or to confirm a control sequence or to program a control sequence in memory. During the tests, the power supply was set up in the voltage control mode so that only the voltage needed to be set for its excitation change.

2.4. Test Results

Several tests have been performed to characterize the SC with respect to the base case circuit #4 configuration. The base case doesn't involve any significant loading or load dynamics on circuit #4. Later configurations will explore the startup of a 500HP motor downstream of the SC at the reactive power laboratory and greater loading and operation of chiller pump motors downstream of the SC. Also, the later configurations will explore reconfiguration of the circuit to add additional conductor and load impedance for the SC testing. This report examines tests conducted on May 24th and July 1st 2005. The test performed on May 24th, had three objectives: 1) determination of the peak current and minimum line voltage during SC startup; 2) investigation of the synchronization behavior of the SC; and 3) examination of the impact of the SC on line voltage and line current as its excitation is increased from lagging power factor (motor operation) to leading power factor (SC operation with overexcitation).

Figure 3 shows the ac line voltage and injected ac current at the 480V 900A panel for the test conducted on May 24th. The values reflect the average voltage and current for each second based on the real-time samples (up to 256 samples per cycle) taken by the two Drantez/BMI Powerguide 4400 meters. Note that during this particular test run, the SC was run to a high enough current to trip the motor starter breaker (CB trips) which was set to trip at 125% of 325A or 406A. Also, initially the excitation of the SC was set extremely low (0.1 Adc) and the SC didn't synchronize until the excitation current reached about 4 Adc.

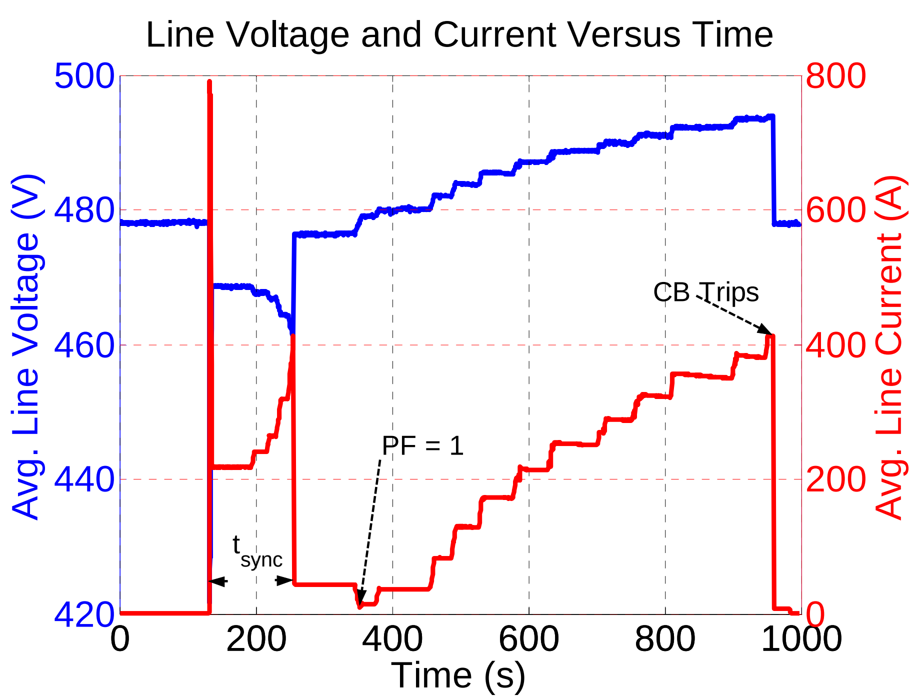

Figure 3. Line Voltage and Current versus Time (Test on May 24, 2005).

During startup, the line current reaches a peak of 775A causing the ac line voltage to drop from 477 V to 420V. Then, the current reduces to 220A with the SC motoring at virtually no excitation (about 0.1 Adc). During this particular test, the SC's current increases to 420A during the synchronization period, t_{sync}. After synchronization, the current immediately drops to 50A as the SC approaches unity power factor. The SC was found to not synchronize right away about 1 out of every 5 attempts. When the SC didn't synchronize initially, it required 3.5 to 4.5 Adc of excitation to synchronize. Next, as the SC is overexcited, it begins to supply reactive power (leading power factor, leading current) to the distribution system. The current increases to a maximum of 420A causing the voltage to rise to from 477 V (prior to SC operation) to 491V. Finally, after drawing 420A for a short period of time, the SC is tripped out of the circuit by the motor starter protection and the line voltage returns to 477V.

The objective of the test conducted on July 1st, 2005 was to obtain the line voltages, line currents, power consumed and SC power output values at different excitation levels. For this test, after the SC startup, the excitation voltage is immediately adjusted to about 90V in order to operate the SC at close to unity power factor to both minimize synchronization time and power/current draw on the distribution system. Putting the SC in a unity power factor mode places it in a neutral mode where it can serve as a spinning reserve ready to supply reactive power. During the test, the excitation voltage is increased in increments of 10Vdc to a maximum 290Vdc. The measurements taken at the SC terminals and it 480 distribution panel were used to generate the average values given in Appendix A.

Figure 4 and Figure 5 show the line voltage, line current, and SC power output versus the excitation voltage setting used for each step of the test.

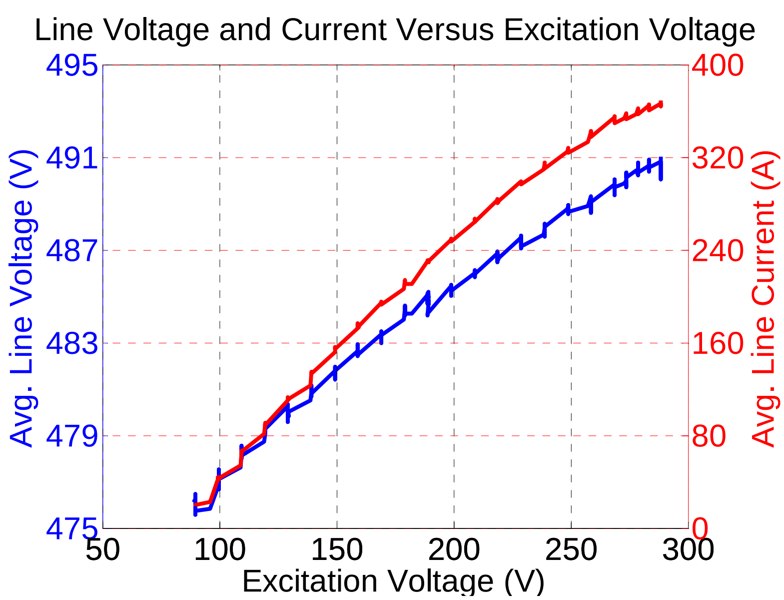

Figure 4. Line Voltage and Current versus Excitation Voltage (Test on July 1, 2005).

At the initial excitation setting of 90Vdc, the terminal ac voltage is 477V and the SC is drawing 19A of ac current. The reactive power output is 27kVAR and the power absorbed is 4kW during this initial state. As the excitation voltage is increased, the line current reaches a value of 370A, raising the voltage to 491V. The SC absorbs 15kW while delivering a maximum reactive power of 311kVAR.

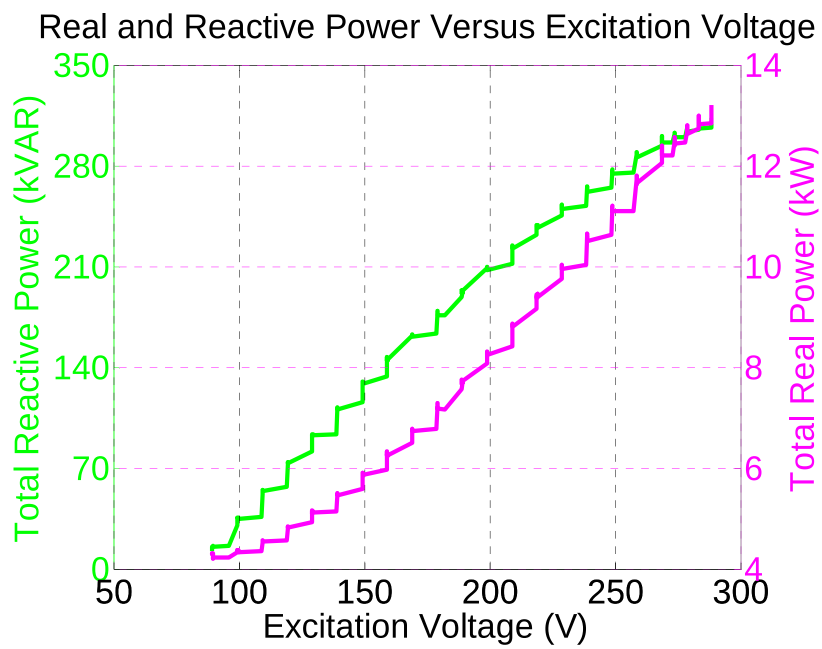

Figure 5. Real‡ and Reactive Power versus Excitation Voltage (Test on July 1, 2005).

Figure 6 and Figure 7 show the line voltage, line current, and SC power output as functions of the excitation current supplied by the dc power supply. The dc power supply providing excitation for the SC used a voltage control mode so that voltage was the control variable driving the excitation power and subsequently the excitation current.

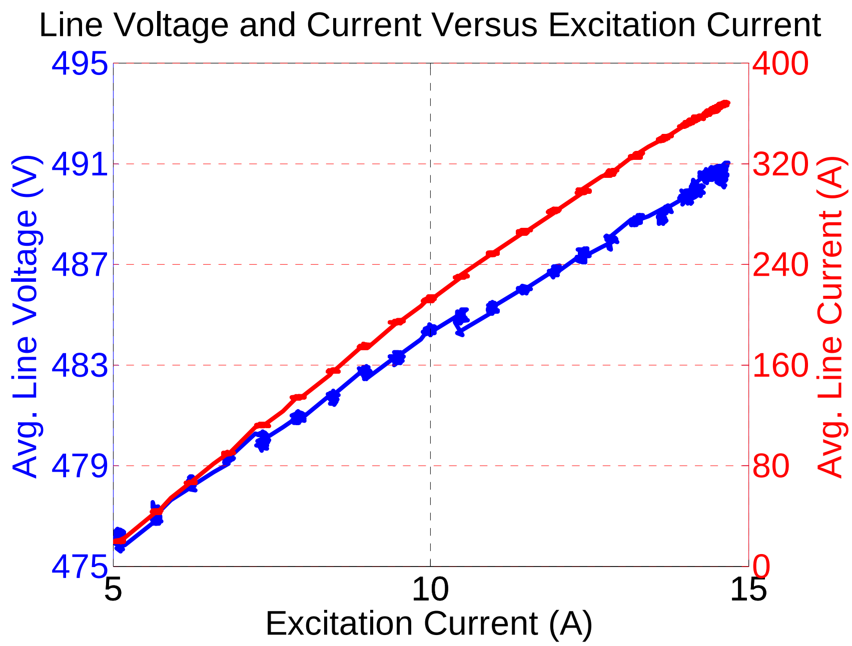

Figure 6. Line Voltage and Current versus Excitation Current (Test on July 1, 2005).

‡ The real power is that absorbed, not including field.

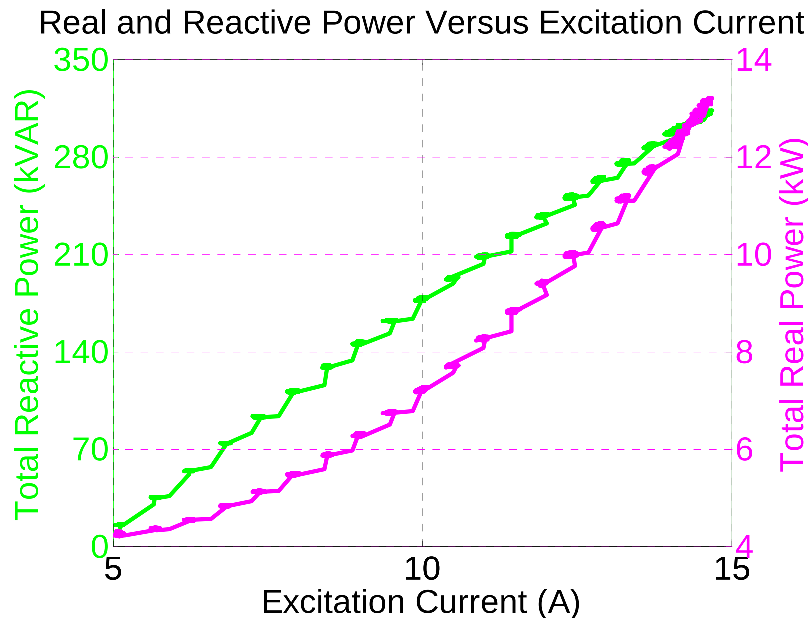

Figure 7. Real and Reactive Power versus Excitation Current (Test on July 1, 2005).

The excitation current starts at 5 Adc and increases by about ½ Adc after each 10 Vdc increase in excitation voltage. The line voltage, line current, and SC power output attain their maximum values at about 14.5 Adc over an excitation range of about 10 Adc. Additionally, the line current, line voltage, and SC reactive power output exhibit a linear relationship with the excitation current over the entire range.

Figure 8 and Figure 9 show the line voltage, line current, and SC power output as functions of the excitation power from the dc power supply.

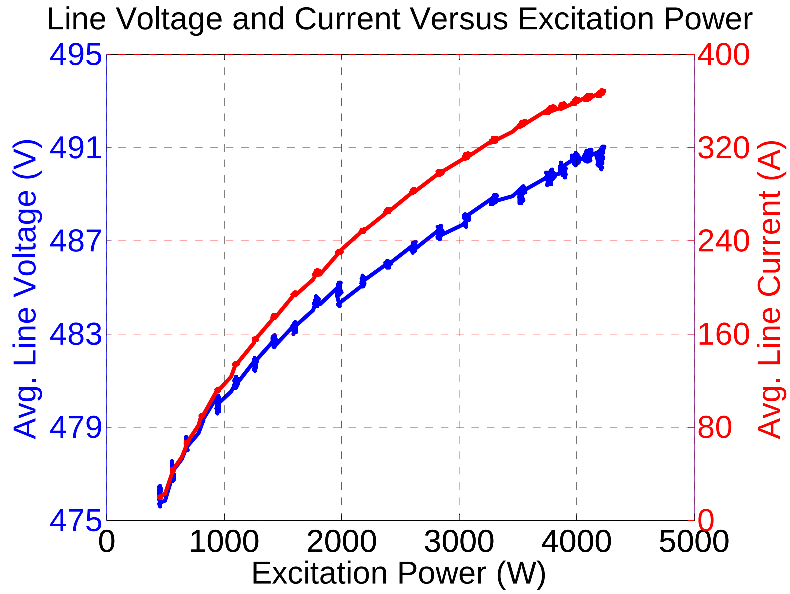

Figure 8. Line Voltage and Current versus Excitation Power (Test on July 1, 2005).

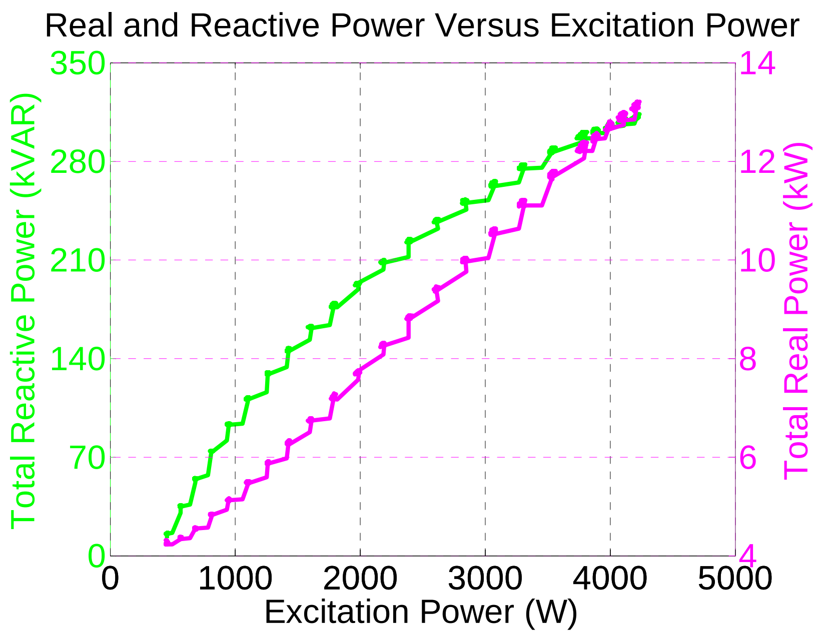

Figure 9. Real[§] and Reactive Power versus Excitation Power (Test on July 1, 2005).

The SC requires 4.2kW of excitation from the dc power supply in order to deliver its maximum reactive power output of 311kVAR. The line voltage and line current have a highly nonlinear relationship with the excitation power. Consequently, as excitation power is increased, its impact on the line voltage and line current is significantly reduced.

Figure 10 shows the relationship between the percentage of SC losses (total kW to kVA consumed) versus the SC reactive power output. During the initial reactive power output of about 16kVar, the SC operates at its highest loss percentage of about 26%. As the SC reactive power output is increased, the loss percentage decreases to about 4% corresponding to a more efficient operation of the SC. Additionally, the derivative of the percent losses with respect to the SC reactive power output is negative and approaches zero as the SC reactive power output is increased. At about 250kVar, the SC has its lowest percent losses or highest efficiency. After this point, an increase in SC kVar output appears to cause the percent losses to increase slightly. Additional tests in which the SC is stressed to its limit must be conducted to determine whether the percent losses will continue to increase.

The preliminary results from the May 24th and July 1st, 2005 tests provide insight into the capabilities and limitations of using an SC for voltage regulation. Additional tests are required to obtain a comprehensive set of results for complete characterization and to implement a local feedback control scheme.

3. SKM Analysis Results

A steady-state model of ORNL's X-10 power distribution grid was developed using the SKM power system analysis program; a commercial power flow analysis tool. The model represents the 1600-bus ORNL distribution system that was constructed based on information obtained

[§] The real power is that absorbed, not including field.

while recording data from the X-10 system over a twelve-month period. Utilizing data from this period, a balanced and averaged load model was created with a power factor of .85 lagging for each of the loads. The net power factor at the substation is 0.99 lagging because of the capacitors. The model includes non-linear loads that represent buildings by treating them as constant kVA loads. However, because these loads constantly change with the time of day and year while the SKM model assumes an unchanging load, real-time load data must be obtained prior to performing any additional simulation for improved modeling accuracy.

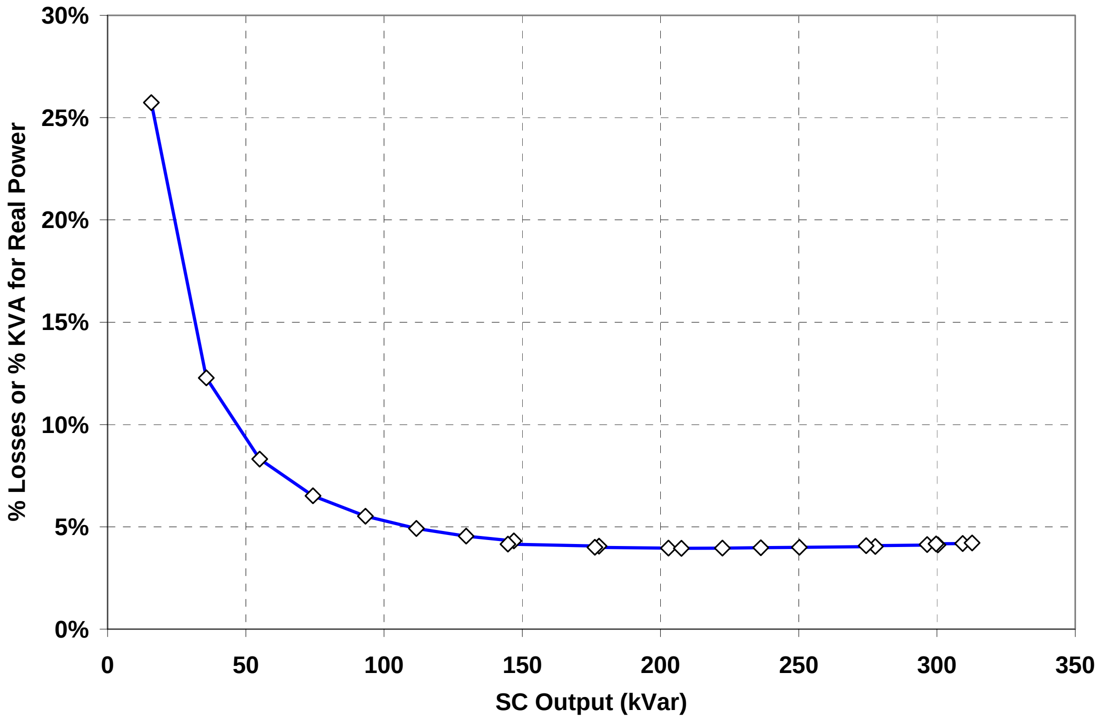

Figure 10. Percentage Loss versus SC Reactive Power Output (Test on July 1, 2005).

Simulations are performed by the following steps: 1) the model is configured to represent the actual system, 2) the load data is modified to reflect current system loading conditions and the SC power output is set appropriately, and 3) the SC is connected to the network and additional simulations are conducted that utilize the same load parameters or starting point. In step 2, the model is "calibrated" by disconnecting the SC from the network, appropriately adjusting the load parameters, and performing simulations until the real-time data matches the simulation data at specific network locations.

It is impossible to completely eliminate modeling inaccuracies because load dynamics will occur. Our goal is to minimize them by making appropriate load modifications before each test. This will be done in future tests by observing a snapshot of the real-time kW, kVAR, and kVA data at breaker 101S of substation 3000 immediately before a test is performed. Using this data, various loads will be adjusted in the SKM model by appropriately shedding or adding real and reactive power until the simulation produces a load demand that is equivalent to the real-time data snapshot observed at breaker 101S of substation 3000.

Several studies were performed to confirm the accuracy of the SKM model when compared to the SC test conducted on July 1st 2005. In order to obtain voltage and current measurements at distribution system locations outside of the Reactive Power Laboratory, PowerNet, a web-based program that records snapshots of real time data was used (see Appendix B).

Several tables (see Appendix B and C) were created by comparing the actual data obtained from the PG meters located at the Reactive Power Laboratory and the PowerNet displays with the SKM simulation results. Comparisons of voltage, current, real power and reactive power were created for various scenarios that correspond to increases in the SC output. The measurements are those obtained from the SC terminal and 480V panel by the PG meters and at breaker 101S of substation 3000 by the PowerNet/IQ Analyzer system.

With each adjustment in excitation setting, the SC was allowed to settle for about 2 minutes. Because the PG meters record data every second, each excitation setting has a window or series of data points that corresponds to it. In order to develop the tables, each data point in the table represents an averaged value that is computed by averaging all the data points within a given window or series.

The figure comparisons below show that the SKM results are very close to the actual test data of July 1, 2005 for each scenario. The first figure, Figure 11, shows the relationship between SKM model results for line voltage and current and measured values at the 480V panel of the SC versus reactive power output of the SC. The second figure, Figure 12, shows the relationship between the SKM model results for both substation and the SC panel voltages versus the SC reactive power output. The third figure, Figure 13, shows the relationship between the SKM model results for both substation and the SC panel currents versus the SC reactive power output.

The noticeable differences in model versus test results for some data points in these figures is due to the fact that the Substation (Powernet/IQ Analyzer) and Synchronous Condenser (PowerGuide meters) data upon which the input for each SKM run was based was not perfectly synchronized. As a result, some of the model results match quite well with the test data and some does not. In future efforts, we will be more diligent in synchronizing the data which should improve the modeling results and reduce the error. Also, these results indicate how important it is to synchronize datasets in order to get the best accuracy from your modeling efforts.

Figure 11 compares the SKM model results and test data for the SC panel versus reactive power output. It shows the response of the line voltage and current as a function of SC kVar output. The SKM model results closely follow the measured values of the July 1 test over the SC output range of 16kVar to about 150kVar. At about 150kVar, the SKM model results deviate slightly from the test data at various SC output settings. At these settings, the SKM model predicts a behavior that departs from the linear characteristic of the actual data. This behavior is more pronounced in the line current than the line voltage. However, after the SC output reaches about 275kVar, the accuracy of the SKM model improves.

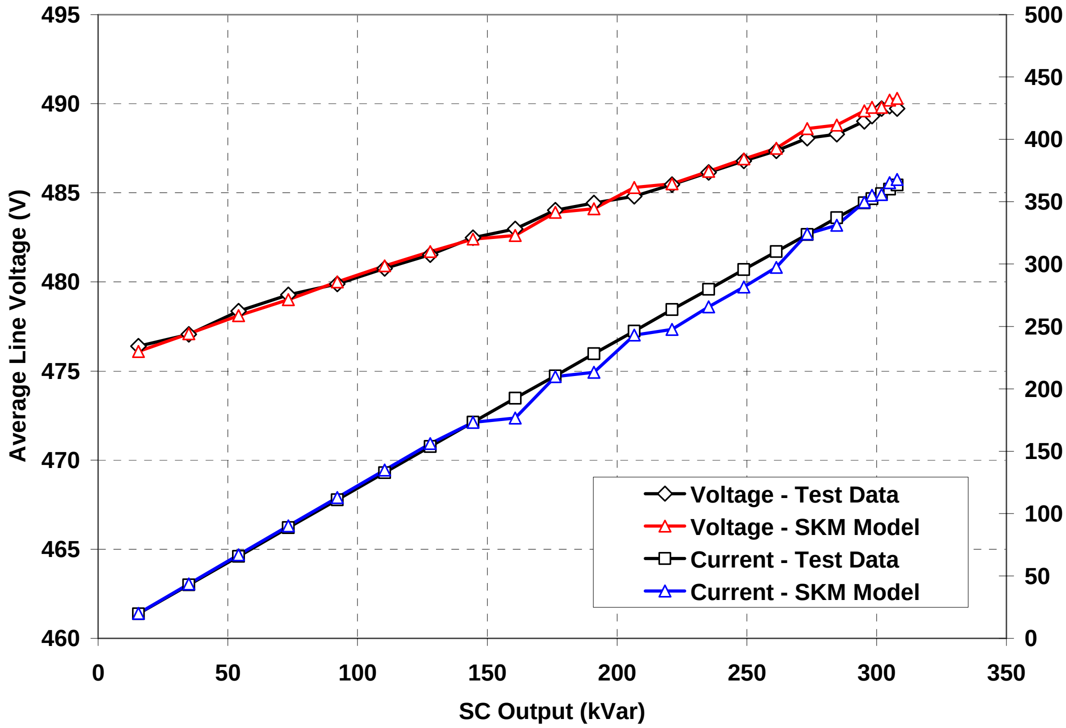

Figure 11. Modeled and Test Line Voltage and Current at the SC Panel versus SC kVar Output (July 1, 2005 Test).

Figure 12 shows a comparison between the SKM model results and test data for the SC panel and substation 3000. For this comparison, the substation and SC panel voltages are functions of the SC reactive power output. The objective of this plot is to confirm modeling accuracy and to show the relationship between the SC panel voltage and the substation voltage. In this plot, the SKM model predicts the SC panel voltage to be very close to the test data. However, errors exist between the model's expected substation voltage and the actual data. Part of this is due, again, to the accuracy of the PowerNet/IQ Analyzers taking the substation readings. The actual voltage is drifting in a range of plus or minus two volts when measuring at 2385V (2.4kV). This is a drift of less than 0.1% which could be attributed entirely to the IQ Analyzer and its CTs. In comparison, the model predicts a substation voltage that increases linearly with the SC output.

Figure 13 shows that the actual current at breaker 101S of substation 3000 has periods where an increase in current injection of the SC is associated with an increase in current at the substation. This behavior can be attributed to load dynamics occurring during the test run. Because SKM assumes a static load for each scenario, its model results shows a monotonic reduction of current at the substation as the SC reactive power output increases.

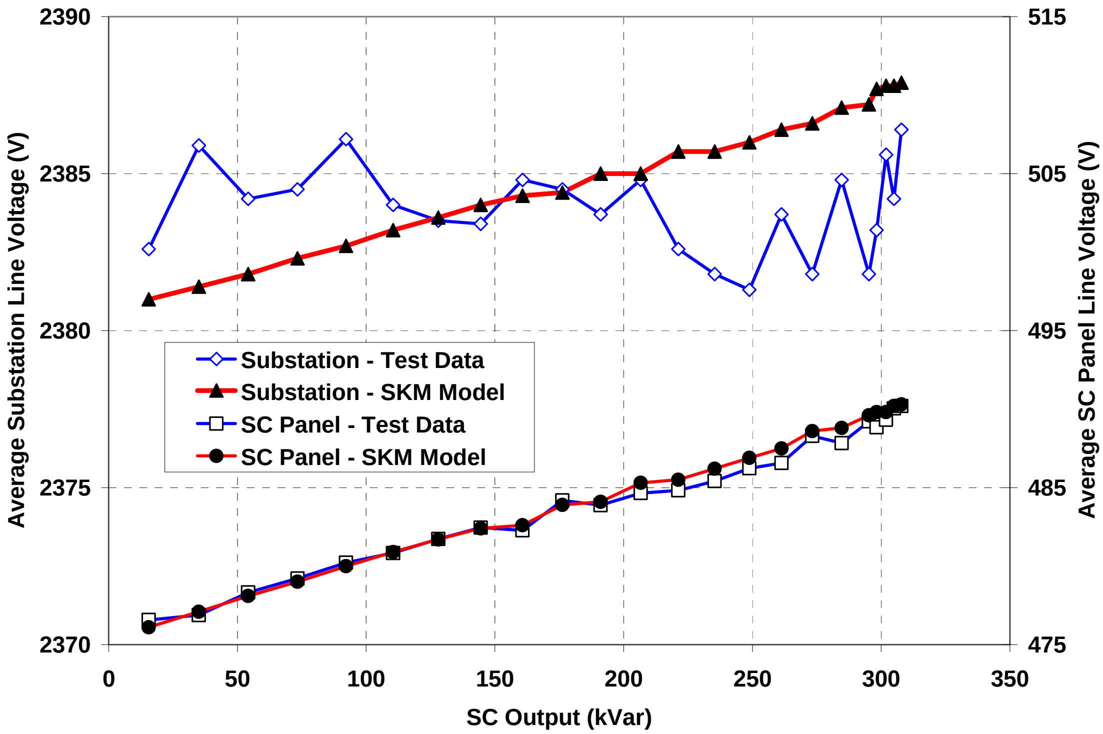

Figure 12. Modeled and Test Substation and SC Panel Voltage versus SC kVar Output (July 1, 2005 Test).

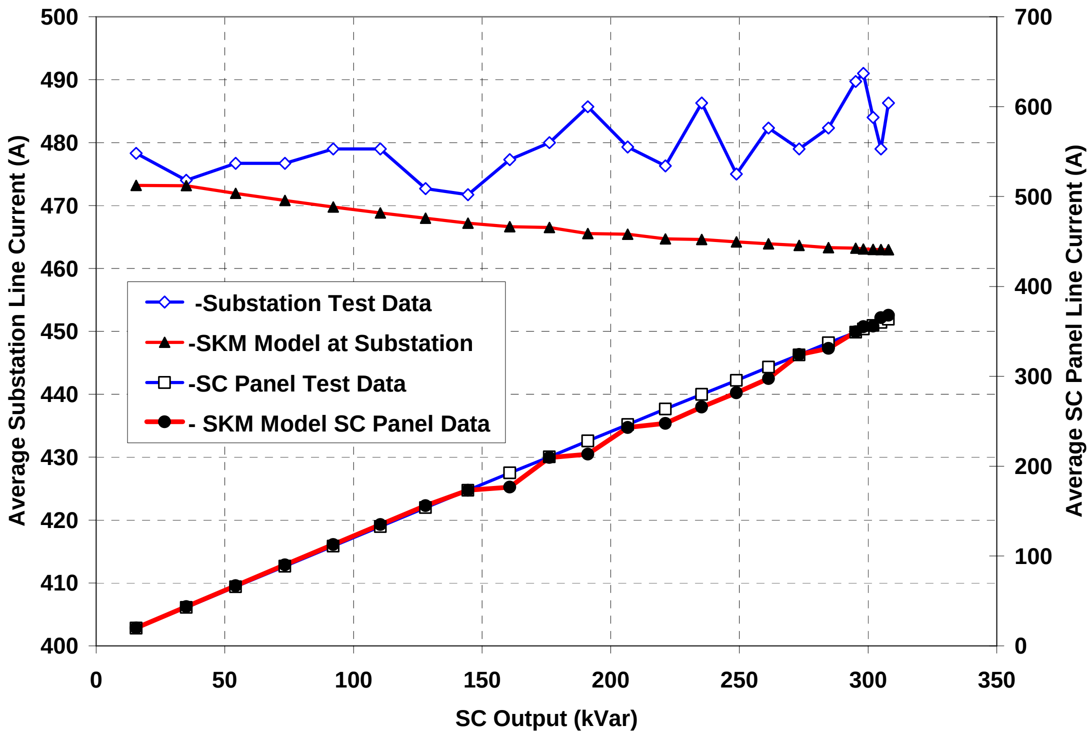

Figure 13. Modeled and Test Substation and SC Panel Line Currents versus SC kVar Output (July 1, 2005 Test).

These are preliminary comparisons performed to validate the SKM model of the ORNL distribution network with the SC operating at the Reactive Power Laboratory in a very basic electrical configuration. Additional comparisons of SKM results versus test data are given in Appendix D. Future testing will explore reconfiguration of the circuit to which the SC is connected to add dynamic motor loads and greater load as well as longer circuit length for greater circuit impedance. In the base case configuration, the SC is located quite close to the 3000 Substation and doesn't have as great an impact on line voltage due to the circuit stiffness as it would further downstream on the circuit. Also for future SC tests, the real-time conditions during each test run will be considered in the modeling to minimize the impact of load variations on the results. Furthermore, additional effort will be devoted to identifying and reducing any modeling versus test discrepancies.

4. Preliminary Conclusions

Several preliminary conclusions have been made as a result of the work conducted over this 3-month period.

- The SC injected 311 kVar of reactive power at 370A of line current during the test conducted on July 1st, 2005 and shows great potential for use as a source of reactive power for voltage support. However, our initial testing configuration has the reactive power injection at the beginning of the circuit close to the substation, which limits the SC impact on voltage close to the substation. Additional tests with new circuit configurations (more load, large dynamic motors and higher path impedance with an increased circuit length to the substation) and adjustments in SC location relative to other loads on the circuit are needed to better demonstrate its positive effects on the voltage support of a distribution system with higher path impedances and additional loads.
- The synchronization time of the SC can be minimized by immediately setting the field voltage and current such that the SC is operating at unity power factor immediately after the SC is started and the power supply is supplying power to its excitation circuit. Failure to do so may cause the SC to unnecessarily produce high currents and draw large amounts of reactive power before it begins to supply reactive power to the network. This situation becomes extremely important in cases where there is an immediate demand for reactive power such as the prevention of voltage collapse and the SC is not synchronized. Normally, the line current of the SC decreases as excitation is applied after startup and excitation current is between 3.5 to 4.5A. We found that one out of every five times when the SC is started and not immediately set to unity power factor (by applying 85 to 90V of excitation) that the SC doesn't synchronize until the minimal excitation level (about 4A) is reached. As a result the current instead of being around 200A after it is started can be closer to 400A.
- The excitation and losses of the SC (percentage of real power needed to spin the SC divided by the KVA capacity of the device) especially at lower than a 15% output level are significant making a strong case for an inverter-based reactive power producing DE. We found the losses to settle to about 4% once the SC is operated at 50% and higher output.
- When considering the use of multiple SC units, the potential for circulating currents must be examined. It will be necessary to develop a voltage droop characteristic to ensure appropriate distribution of reactive power from each unit.

- Initial comparisons have shown that the simulation model based on SKM is fairly accurate except for the modeling of substation voltages and currents which can be affected by overall changes on the distribution system. For real-time power analysis, a proper estimation of the load distribution must be made. Furthermore, with a proper estimation, future scenarios may be simulated before the actual tests are done to have an overall understanding of the system's behavior.

Appendix A. Synchronous Condenser Test Data (July 1, 2005)

As indicated in the report, real-time data was measured and collected every 1 sec at the synchronous condenser terminals using one Drantez/BMI PowerGuide (PG) 4400 meter. A second PG meter measured voltage, current and power data the 480V power distribution panel for the SC. The following tables show the average data for each excitation setting of the synchronous condenser. These values were calculated by averaging the 1 sec data samples for the length of time (2 to 3 minutes) that the synchronous condenser was held at a particular excitation setting.

A.1. Averaged Measurements at SC Terminals

Table 1 shows the averages of the data recorded by the PG meter located at the SC terminal.

Table 1. Averages of PG data measured at the SC terminal.[**]

Excitation Setting			SC Terminal Output			
Voltage (Vdc)	Current (Adc)	Power (W)	Total (kVar)	Voltage (V)	Current (A)	Total (kW)
90	5.10	457.47	15.99	476.3	19.8	4.3
100	5.68	566.21	35.20	476.8	43.5	4.4
110	6.24	683.30	54.54	478.2	66.6	4.6
120	6.81	813.64	73.81	479.2	89.8	4.8
130	7.36	952.59	92.83	480.3	112.3	5.1
140	7.92	1104.75	111.32	481.0	134.1	5.5
150	8.47	1264.65	129.00	481.9	155.4	5.9
160	8.98	1429.34	145.71	482.7	175.9	6.3
170	9.49	1606.75	162.10	482.5	173.3	6.3
180	10.00	1791.40	177.73	484.5	213.8	7.2
190	10.47	1979.92	192.76	484.2	210.6	7.2
200	10.98	2185.17	208.43	485.1	249.3	8.1
210	11.47	2396.55	223.17	485.2	247.3	8.2
220	11.95	2614.96	237.44	485.9	264.7	8.8
230	12.40	2839.13	251.11	486.7	280.6	9.4
240	12.84	3065.78	263.78	487.2	296.9	10.0
250	13.25	3297.30	275.84	489.0	328.3	11.2
260	13.67	3535.28	287.41	488.6	324.3	11.1
270	14.06	3776.38	298.14	489.6	354.8	12.4
275	14.18	3880.58	301.16	489.4	349.9	12.2
280	14.33	3993.03	304.90	490.1	353.3	12.4
285	14.46	4100.15	308.01	490.8	364.2	12.9
290	14.59	4209.02	310.92	491.0	368.4	13.2

[**] Each data point in the table represents an averaged value that is computed by averaging all the 1sec data points within a given window or series for the SC setting.

A.2. Averaged Measurements at the 480V Panel of the Synchronous Condenser

Table 2 shows averages of the data recorded by the PG meter located at the 480V panel.

Table 2. Averages of PG data measured at 480V panel.[††]

Excitation Setting			SC Panel Output			
Voltage (Vdc)	Current (Adc)	DC Power (W)	Total (kVar)	Voltage (V)	Current (A)	Total (kW)
90	5.10	457.47	15.57	476.40	19.66	4.76
100	5.68	566.21	35.00	477.06	42.87	4.81
110	6.24	683.30	54.18	478.36	65.77	4.96
120	6.81	813.64	73.33	479.27	88.71	5.22
130	7.36	952.59	92.16	479.88	111.13	5.53
140	7.92	1104.75	110.43	480.76	132.86	5.90
150	8.47	1264.65	127.98	481.53	153.84	6.32
160	8.98	1429.34	144.50	482.48	173.22	6.77
170	9.49	1606.75	160.74	482.97	192.54	7.28
180	10.00	1791.40	176.17	484.02	210.39	7.81
190	10.47	1979.92	191.09	484.43	228.12	8.37
200	10.98	2185.17	206.61	484.80	246.33	9.01
210	11.47	2396.55	221.20	485.46	263.52	9.66
220	11.95	2614.96	235.31	486.15	279.79	10.35
230	12.40	2839.13	248.82	486.79	295.55	11.07
240	12.84	3065.78	261.32	487.36	310.11	11.79
250	13.25	3297.30	273.23	488.06	323.78	12.53
260	13.67	3535.28	284.65	488.29	337.12	13.28
270	14.06	3776.38	295.23	489.01	349.08	14.03
275	14.18	3880.58	298.21	489.30	352.46	14.30
280	14.33	3993.03	301.91	489.72	356.37	14.63
285	14.46	4100.15	304.98	489.85	359.97	14.92
290	14.59	4209.02	307.90	489.72	363.44	15.21

[††] Each data point in the table represents an averaged value that is computed by averaging all the 1sec data points within a given window or series for the SC setting.

Appendix B. Distribution System Measurements (July 1, 2005)

ORNL's PowerNet system was used to gather real-time measurements on the ORNL distribution system during the tests of the SC at the Reactive Power Laboratory. PowerNet is a commercial data acquisition system provided by Cutler-Hammer and it gathers readings from Cutler-Hammer IQ Analyzers that are located at various locations on the ORNL distribution system. The IQ Analyzers measure current, voltage and provide power readings at these locations. During the SC tests conducted at the Reactive Power Laboratory, we were interested in the voltage, current and power readings at the 3000 Substation which feeds circuit #4 where the Reactive Power Laboratory is connected. Some example and readable displays (not from the July 1st test) are shown in the first section below. The three displays are the type of snapshots that were taken for each kVar output level of the synchronous condenser. In all, twenty-three different output levels were tested. A compilation of the PowerNet data from the display screens for each synchronous condenser output level is given in section B.2.

B.1. PowerNet Displays

Figure 14, Figure 15, and Figure 16 show examples of the output display of the recorded voltages, currents, and power data obtained from PowerNet. The voltage readings of Figure 14 reflect the secondary (2.4kV) side of substation 3000.

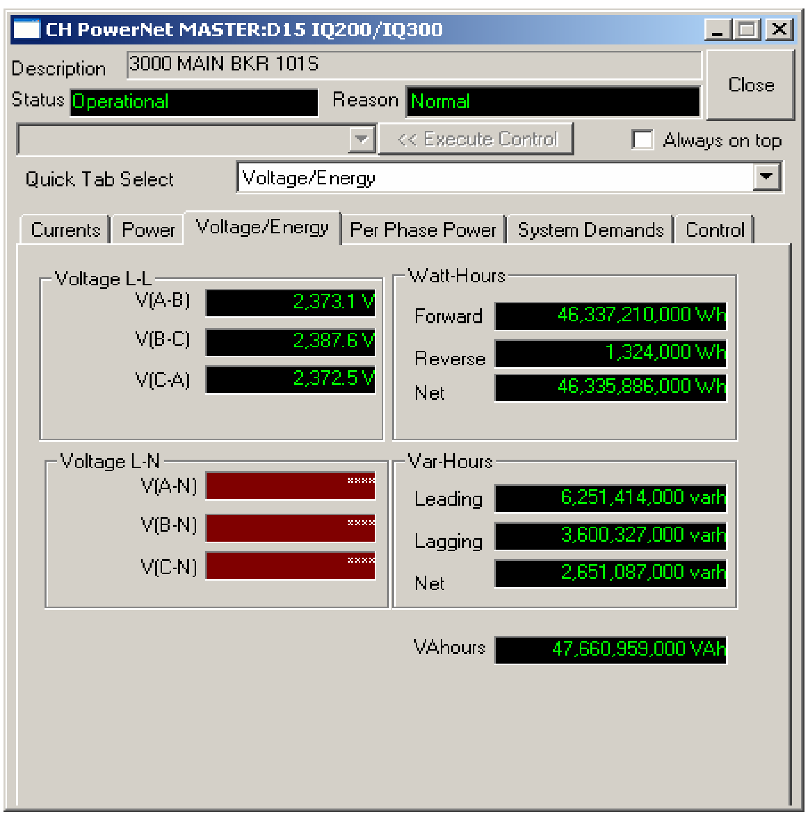

Figure 14. PowerNet Voltage Data Output Display (Example, Not from July 1, 2005 Test).

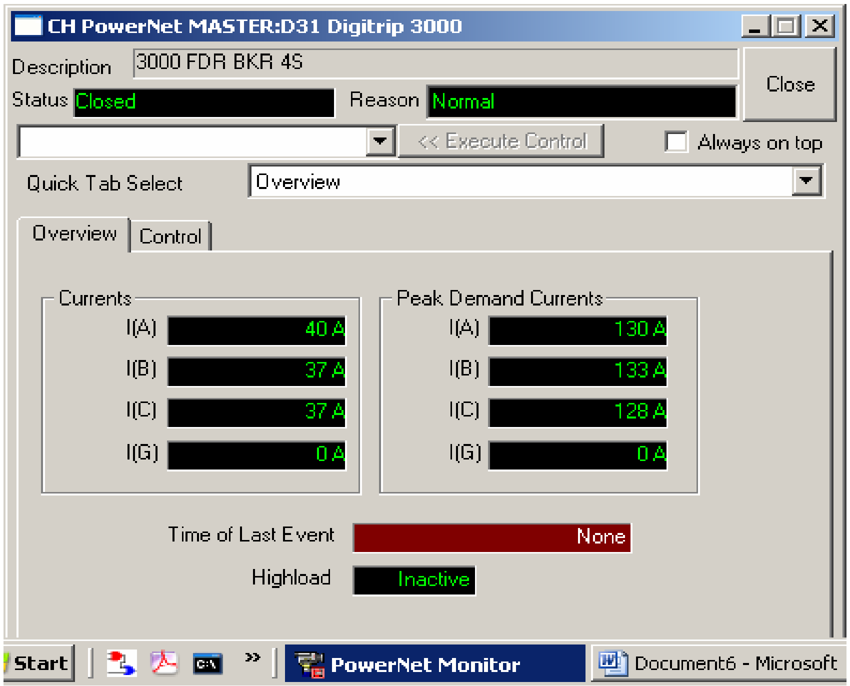

Figure 15. PowerNet Current Data Output Display (Example, Not from July 1, 2005 Test).

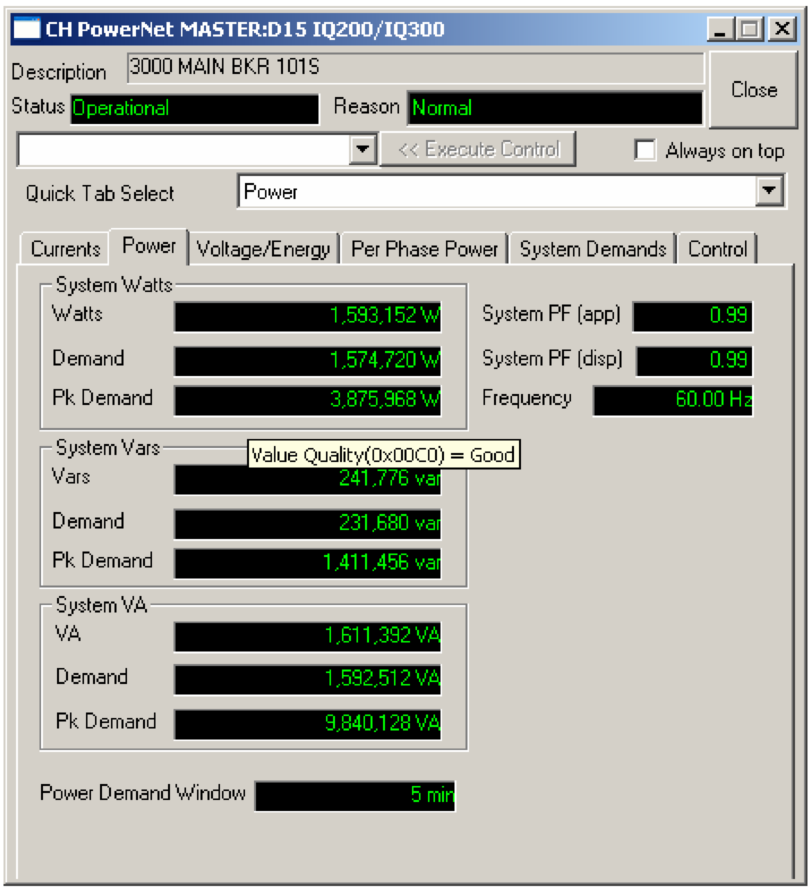

Figure 16 PowerNet Power Data Output Display (Example, Not from July 1, 2005 Test).

B.2. PowerNet Data

The table below shows all of the data gathered for the measurements at the 3000 Substation during the SC tests on July 1st at the Reactive Power Laboratory. It is a compilation of the voltage, current and power measurements taken by the IQ Analyzer meter at the 3000 Substation and was obtained from the type of displays given in the previous section.

Table 3 shows the PowerNet data recorded at 101S of 3000 Substation.

Table 3. PowerNet data recorded at breaker 101S of 3000 Substation.

SC Excitation Setting			PowerNet Data			
Voltage (Vdc)	Current (Adc)	Power (W)	Total (kVar)	Voltage (V)	Current (A)	Total (kW)
90	5.10	457.47	494.1	2382.6	478.3	1888.0
100	5.68	566.21	471.1	2385.9	474.0	1874.9
110	6.24	683.30	449.7	2384.2	476.7	1883.7
120	6.81	813.64	450.1	2384.5	476.7	1886.7
130	7.36	952.59	446.0	2386.1	479.0	1899.4
140	7.92	1104.75	447.0	2384.0	479.0	1909.4
150	8.47	1264.65	393.8	2383.5	472.7	1887.0
160	8.98	1429.34	366.8	2383.4	471.7	1885.2
170	9.49	1606.75	368.7	2384.8	477.3	1914.9
180	10.00	1791.40	358.1	2384.5	480.0	1926.5
190	10.47	1979.92	371.3	2383.7	485.7	1945.6
200	10.98	2185.17	355.5	2384.8	479.3	1922.9
210	11.47	2396.55	330.1	2382.6	476.3	1920.6
220	11.95	2614.96	312.8	2381.8	486.3	1955.1
230	12.40	2839.13	291.1	2381.3	475.0	1910.5
240	12.84	3065.78	287.2	2383.7	482.3	1949.1
250	13.25	3297.30	269.9	2381.8	479.0	1932.2
260	13.67	3535.28	267.7	2384.8	482.3	1946.6
270	14.06	3776.38	256.8	2381.8	489.7	1978.8
275	14.18	3880.58	256.6	2383.2	491.0	1982.3
280	14.33	3993.03	266.8	2385.6	484.0	1962.5
285	14.46	4100.15	240.7	2384.2	479.0	1954.1
290	14.59	4209.02	252.0	2386.4	486.3	1972.7

Appendix C. SKM Modeling Results

The kVar output of the synchronous condenser (SC) for each of the test run settings (twenty-three different excitation levels) was used as input to the SKM power flow analysis program. The voltage, current and power results generated by the program at the SC terminals, the 480V distribution panel supplying the SC and at the 3000 Substation feeding circuit #4 which the SC is connected to are given in the sections and tables below.

C.1. SKM Modeling Results at the Terminals of the Synchronous Condenser

Table 4 shows the SKM results for each scenario at the SC terminal.

Table 4. SKM Results For Scenarios At Synchronous Condenser Terminals.

Excitation Setting			SKM Results for SC Terminals			
Voltage (Vdc)	Current (Adc)	Power (W)	Total (kVar)	Voltage (V)	Current (A)	Total (kW)
90	5.10	457.47	15.9	476.1	20.0	4.3
100	5.68	566.21	35.9	477.2	43.7	4.4
110	6.24	683.30	55.2	478.2	66.9	4.6
120	6.81	813.64	74.7	479.2	90.2	4.9
130	7.36	952.59	93.7	480.1	112.8	5.2
140	7.92	1104.75	112.2	481.1	134.9	5.5
150	8.47	1264.65	130.2	482.0	156.1	5.9
160	8.98	1429.34	147.5	482.8	176.6	6.3
170	9.49	1606.75	144.6	482.7	173.1	6.3
180	10.00	1791.40	178.8	484.4	213.3	7.3
190	10.47	1979.92	175.8	484.2	209.7	7.2
200	10.98	2185.17	204.3	485.6	243.1	8.1
210	11.47	2396.55	208.3	485.8	247.7	8.3
220	11.95	2614.96	223.9	486.6	265.8	8.9
230	12.40	2839.13	237.5	487.2	281.6	9.4
240	12.84	3065.78	251.2	487.9	297.4	10
250	13.25	3297.30	280.3	489.3	331.1	11.3
260	13.67	3535.28	274.4	489.0	324.2	11.1
270	14.06	3776.38	301.9	490.3	355.8	12.4
275	14.18	3880.58	296.4	490.1	349.5	12.2
280	14.33	3993.03	301.3	490.3	355.1	12.5
285	14.46	4100.15	310.2	490.7	365.3	13.0
290	14.59	4209.02	312.4	490.8	367.8	13.2

C.2. SKM Modeling Results at the 480V Panel of Synchronous Condenser

Table 5 shows the SKM results of scenarios located at the 480V panel.

Table 5. SKM Results at 480V Panel.

Excitation Setting			SKM Results			
Voltage (Vdc)	Current (Adc)	Power (W)	Total (kVar)	Voltage (V)	Current (A)	Total (kW)
90	5.10	457.47	15.9	476.1	20.0	4.3
100	5.68	566.21	35.8	477.1	43.7	4.5
110	6.24	683.30	55.0	478.1	66.9	4.7
120	6.81	813.64	74.2	479.0	90.2	5.1
130	7.36	952.59	92.9	480.0	112.8	5.6
140	7.92	1104.75	111.1	480.9	134.9	6.1
150	8.47	1264.65	129.9	481.7	156.1	6.2
160	8.98	1429.34	147.1	482.6	176.6	6.7
170	9.49	1606.75	144.2	482.4	173.1	6.6
180	10.00	1791.40	178.2	484.1	213.3	7.7
190	10.47	1979.92	175.2	483.9	209.7	7.6
200	10.98	2185.17	203.5	485.3	243.1	8.8
210	11.47	2396.55	207.5	485.5	247.7	8.9
220	11.95	2614.96	222.9	486.2	265.8	9.6
230	12.40	2839.13	236.5	486.9	281.6	10.2
240	12.84	3065.78	250.0	487.5	297.4	11.0
250	13.25	3297.30	278.9	488.8	331.1	12.5
260	13.67	3535.28	273.0	488.6	324.2	12.2
270	14.06	3776.38	300.3	489.8	355.8	13.8
275	14.18	3880.58	294.8	489.6	349.5	13.5
280	14.33	3993.03	299.6	489.8	355.1	13.8
285	14.46	4100.15	308.5	490.2	365.3	14.4
290	14.59	4209.02	310.7	490.3	367.8	14.6

C.3. SKM Modeling Results for each scenario at location 101S of 3000 Substation.

Table 6 shows the SKM results for each scenario at location 101S of the 3000 Substation.

Table 6. SKM results for each scenario at location 101S of 3000 Substation.

SC Excitation Setting			SKM Results			
Voltage (Vdc)	Current (Adc)	Power (W)	Total (kVar)	Voltage (V)	Current (A)	Total (kW)
90	5.10	457.47	489.1	2381.0	473.20	1887.7
100	5.68	566.21	472.9	2381.4	473.16	1891.7
110	6.24	683.30	449.4	2381.8	471.93	1892.2
120	6.81	813.64	428.1	2382.3	470.81	1892.3
130	7.36	952.59	408.4	2382.7	469.77	1892.5
140	7.92	1104.75	385.3	2383.2	468.82	1893.0
150	8.47	1264.65	365.4	2383.6	467.97	1893.4
160	8.98	1429.34	345.5	2384.0	467.20	1893.9
170	9.49	1606.75	325.4	2384.4	466.52	1894.6
180	10.00	1791.40	332.6	2384.3	466.63	1894.3
190	10.47	1979.92	295.2	2385.0	465.44	1895.7
200	10.98	2185.17	297.7	2385.0	465.54	1895.6
210	11.47	2396.55	264.0	2385.7	464.70	1897.2
220	11.95	2614.96	262.9	2385.7	464.60	1897.5
230	12.40	2839.13	246.7	2386.0	464.22	1898.4
240	12.84	3065.78	235.2	2386.4	463.92	1899.1
250	13.25	3297.30	219.6	2386.6	463.67	1900.2
260	13.67	3535.28	189.7	2387.2	463.23	1902.5
270	14.06	3776.38	193.1	2387.1	463.32	1902.1
275	14.18	3880.58	158.5	2387.8	463.01	1904.4
280	14.33	3993.03	163.3	2387.7	463.08	1904.7
285	14.46	4100.15	159.8	2387.8	463.04	1905.0
290	14.59	4209.02	152.8	2387.9	462.98	1905.5

Appendix D. Model Results Versus Test Data of July 1, 2005

Additional comparison plots of the SKM model results versus the test data of July 1st are provided below. The test data that was used is the average of the data streams for each excitation power setting for the SC that was run during the test. The SKM model results and test data used to create these comparisons are provided above in the earlier appendices.

The noticeable differences in model versus test results for some data points in the following figures (especially Figure 17, Figure 19, and Figure 22) is due to the fact that the Substation (Powernet/IQ Analyzer) and Synchronous Condenser (PowerGuide meters) data upon which the input for each SKM run was based was not perfectly synchronized. As a result, some of the model result matches quite well with the test data and some does not. In future efforts, we will be more diligent in synchronizing the data which should improve the modeling results and reduce the error. Also, these results indicate how important it is to synchronize datasets in order to get the best accuracy from your modeling efforts.

Difficulties with varying load in the distribution system are representative of a “real, operating” distribution system. One of the goals of our reactive power program will be to develop a local controller that can regulate voltage independently when several DE sources are operating in parallel. This will be challenging on a “real” system where flows and voltages are constantly changing, but this environment will be ideal for proving engineering characteristics and design guidelines before field tests are performed at utilities.

D.1. Modeled versus Test Values at SC Terminals

The next four figures show the line voltage, line current and power response of the SC to the change in excitation power or reactive power output of the SC. The first figure shows line voltage and current versus excitation power. The second figure shows the line voltage and current versus reactive power output of the SC. The third and fourth figures show the real power consumption and the reactive power injection of the SC versus excitation power and reactive power, respectively.

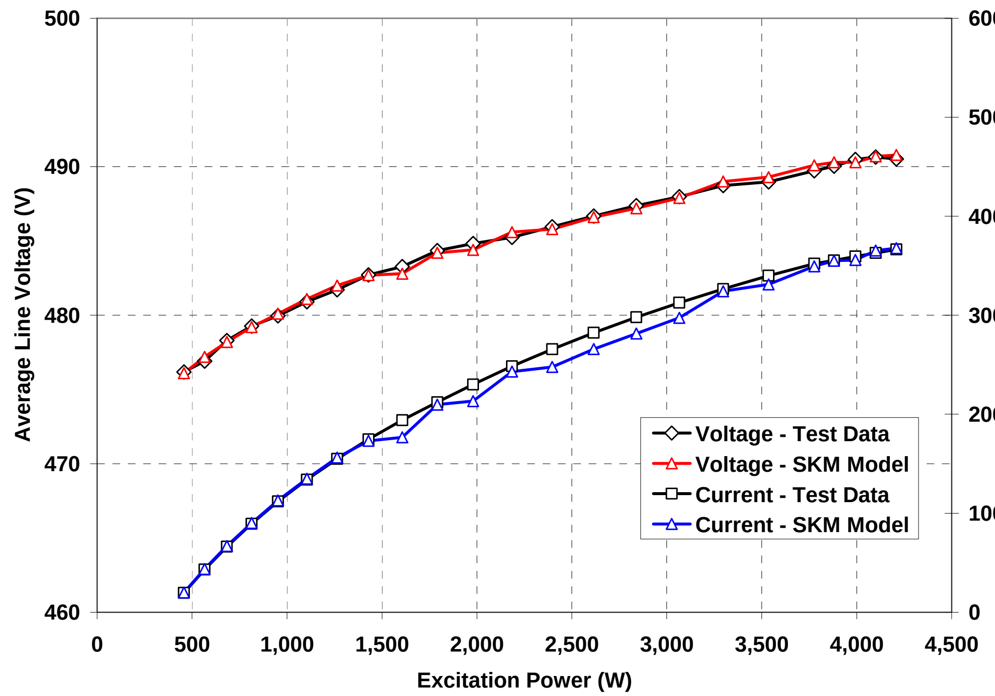

Figure 17. Modeled and Test Line Voltage and Current at the SC Terminals versus Excitation Power to the SC (July 1, 2005 Test).

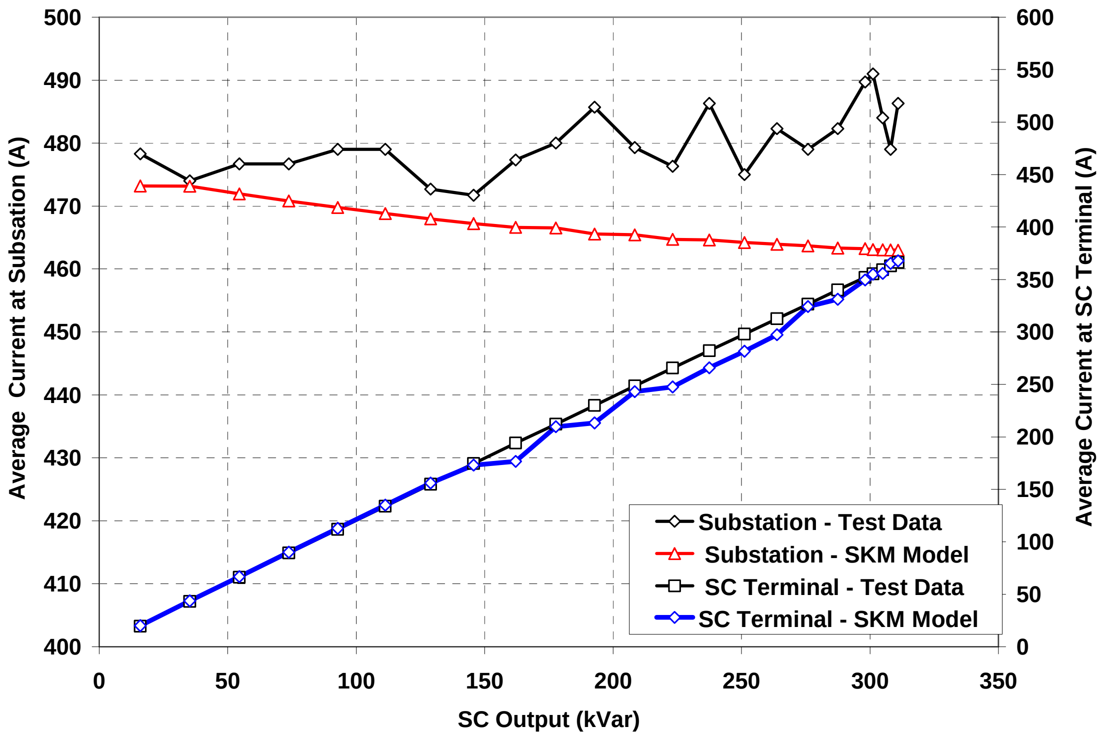

Figure 18. Modeled and Test Line Voltage and Current at the SC Terminals versus SC kVar Output (July 1, 2005 Test).

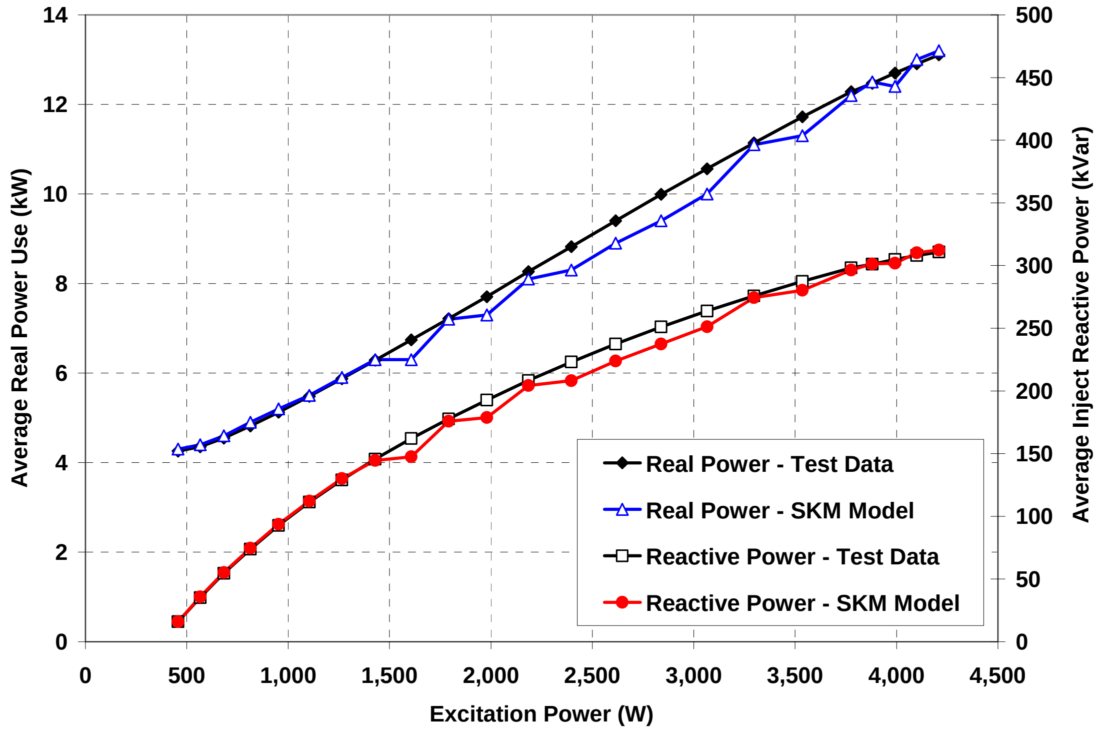

Figure 19. Modeled and Test Real and Reactive Power at the SC Terminals versus Excitation Power to the SC (July 1, 2005 Test).

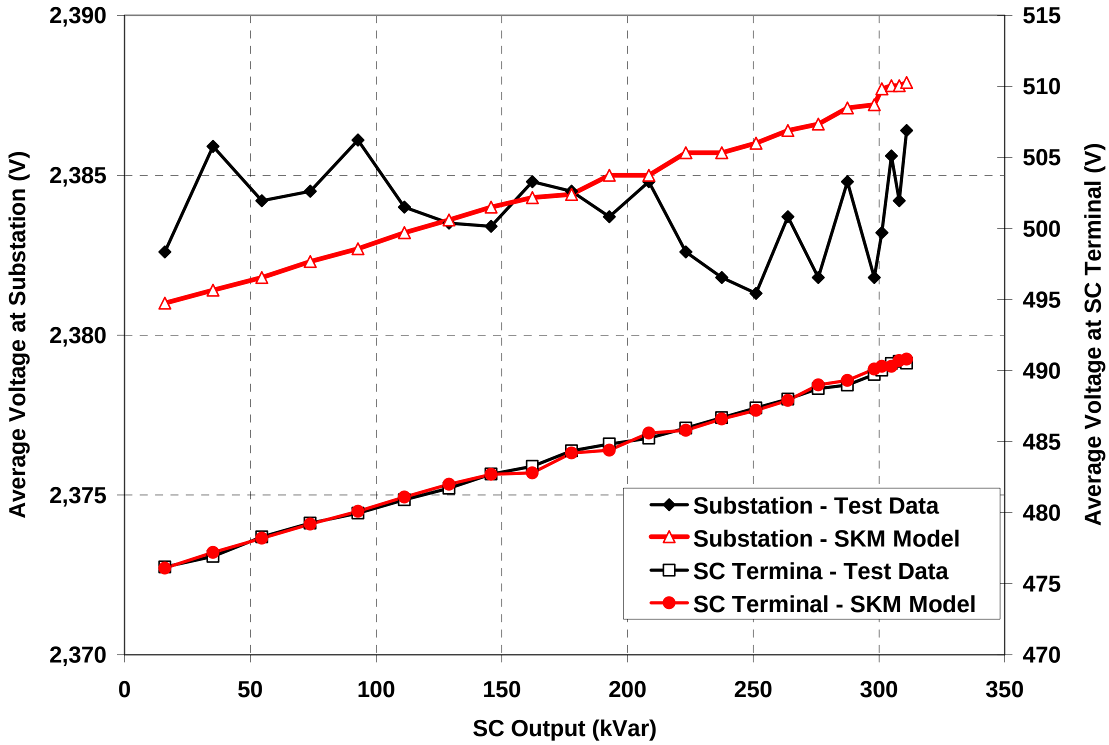

Figure 20. Modeled and Test Real and Reactive Power at the SC Terminals versus SC kVar Output (July 1, 2005 Test).

D.2. Modeled versus Test Values at SC Panel

Figure 21 shows the line voltage and current at the panel for the SC as a function of excitation power. The model's accuracy is highest for excitation powers less than about 1500W and greater than about 3250W. Additionally, the model shows higher accuracy in its line voltage behavior.

Figure 22 shows the real and reactive power at the panel for the SC as a function of excitation power. It compares modeled power values with the test data at the SC panel. It shows the modeled and actual response of the SC reactive power output and real power consumption as excitation power is varied. The SKM model results are very accurate up to the 1500W excitation setting. At this point, the model predicts a real and reactive power output that is slightly less than the actual test data. At about 3250W, the model's reactive power response regains its accuracy while the real power behavior maintains its same level of error. Additionally, the plot shows that as excitation power is increased, the injected reactive power begins to saturate while the losses begin to increase.

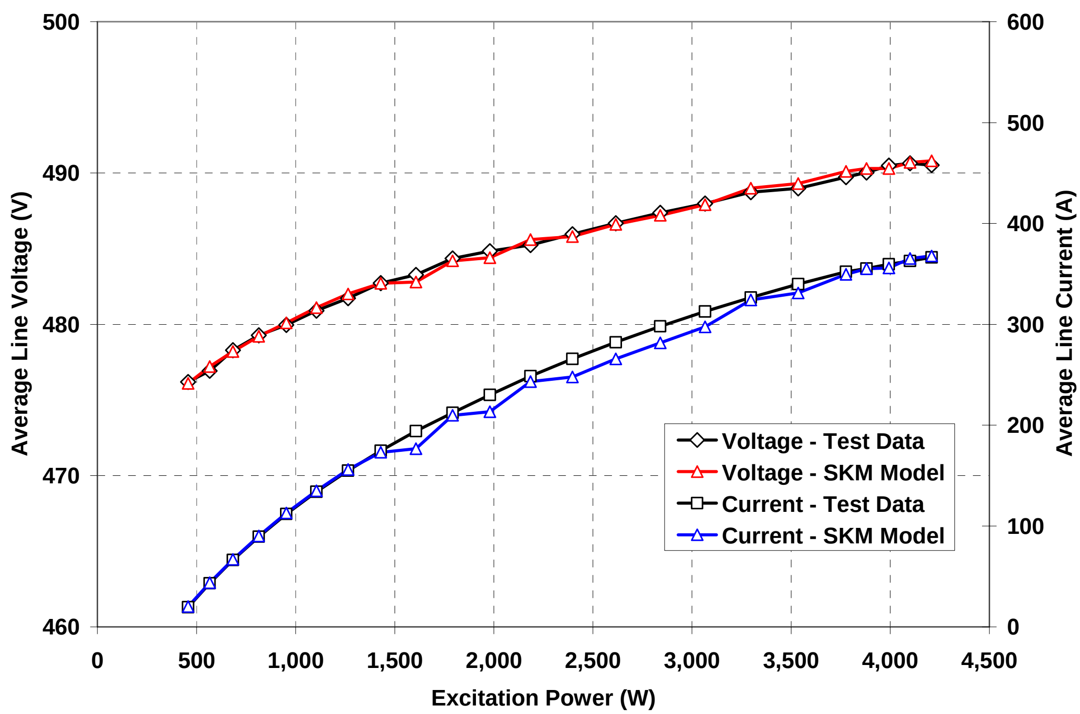

Figure 21. Modeled and Test Line Voltage and Current at the SC Panel versus SC Excitation Power (July 1, 2005 Test).

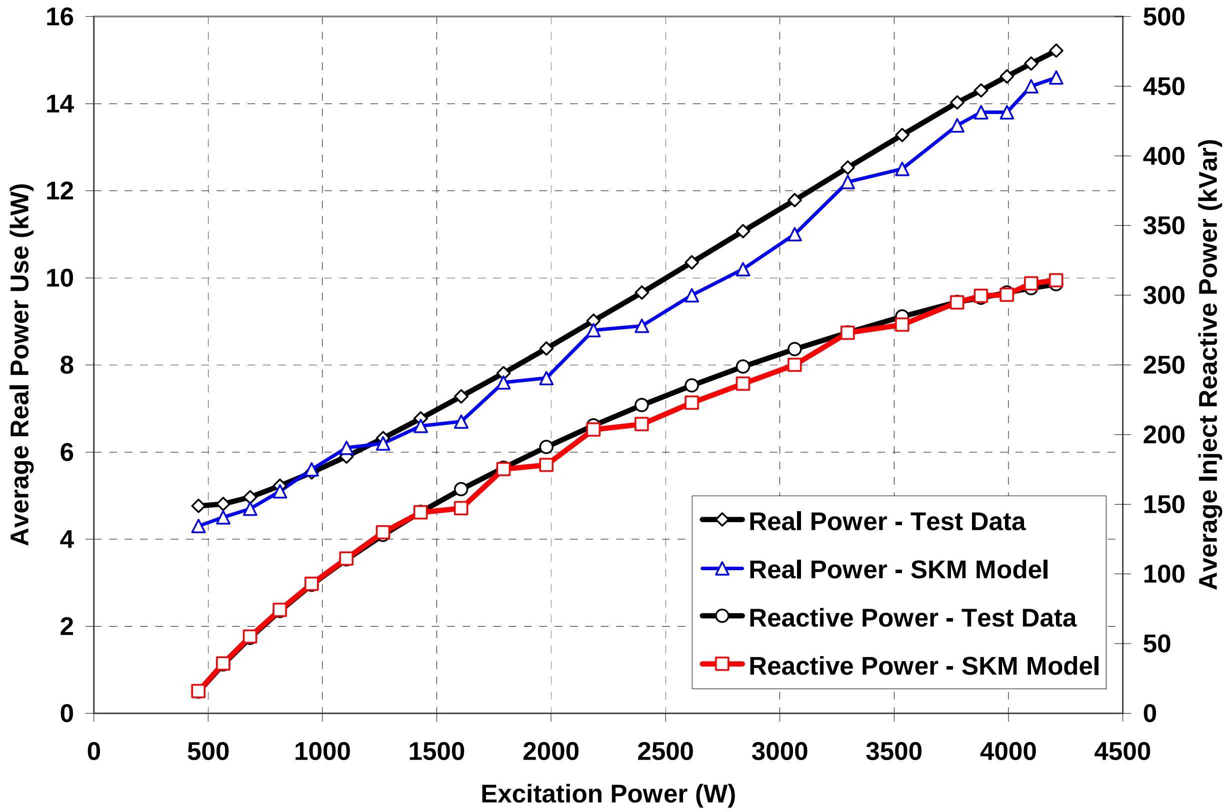

Figure 22. Modeled and Test Real and Reactive Power at the SC Panel versus SC Excitation Power (July 1, 2005 Test).

D.3. Modeled versus Test Currents at Substation and SC Panel

Figure 23 explores the substation and SC panel currents as functions of the SC reactive power output. In this plot, the SKM model predicts the SC panel current to be very close to the test data. However, large errors are observed between the model's expected current and the actual current at the substation. The model predicts a substation current that decreases linearly as the current at the SC panel increases. The actual current shows an unpredictable behavior having no relationship with the SC panel. Additionally, as the actual current at the SC panel is increased, the substation current continues to increase. This oscillating phenomenon is caused by load dynamics that occurred during the test run. Because the model assumes a static load, its predicted substation voltage does not show any fluctuating behavior. Thus, the model results are not practical in this case because load demand varies with time. For future SC tests, the real-time conditions during each test run will be considered in the modeling to minimize the impact of load variations on the results.

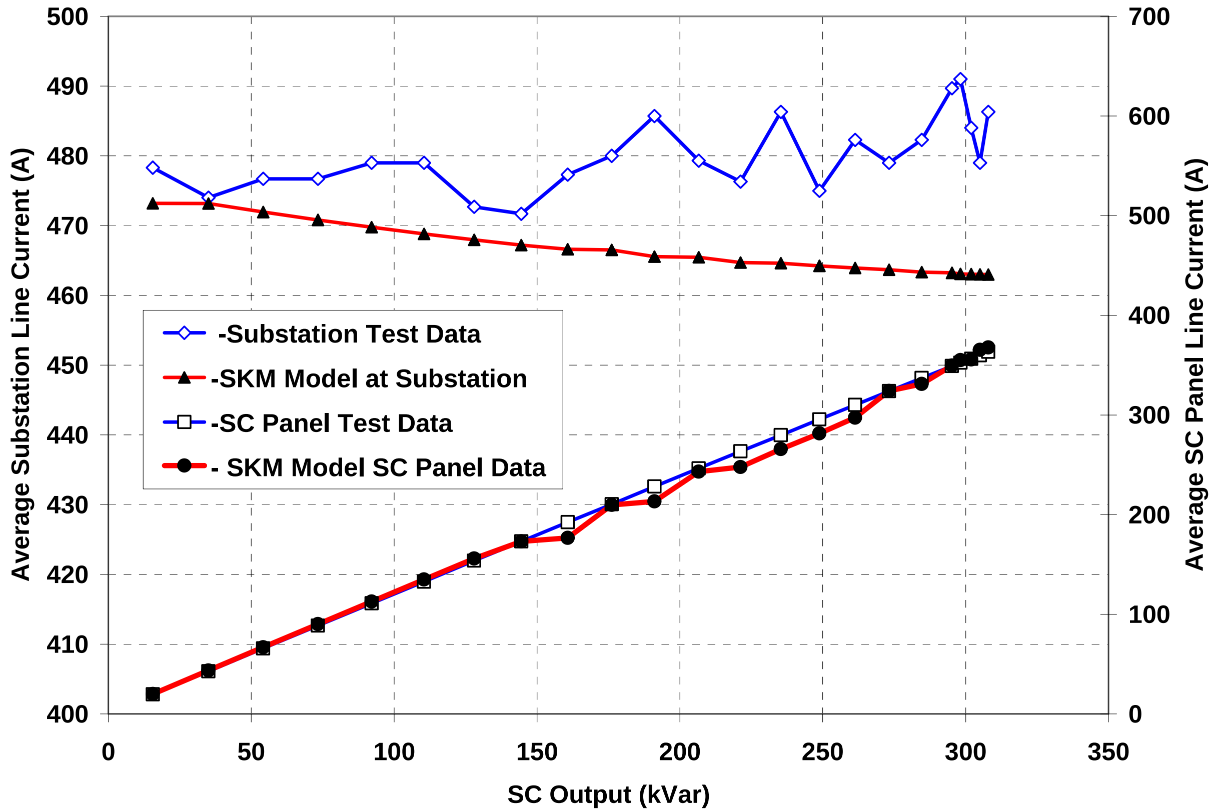

Figure 23. Modeled and Test Line Current at the Substation and at the SC Panel versus SC kVar Output (July 1, 2005 Test).