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A Power Quality Study of Carnegie Mellon University

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Abstract
Carnegie Mellon University is a highly digitized university that has advanced research laboratories and sophisticated research and development operations. It is therefore useful to determine the nature and magnitude of power outages that a premier research institution like Carnegie Mellon faces, and the causes of these outages to mitigate future losses. Another objective of this study is to calibrate survey-based studies. The study advances the literature on existing survey-based studies and find that the perceptions of administrators pertaining to power quality losses are overstated. Based on power quality measurements, we affirm the hypothesis that Carnegie Mellon has a relatively stable power system with no serious disability. However, we find that costs of power outages pertaining to staff, students and faculty in certain departments to be significantly high and propose a set of remedial recommendations. The study also provide a range estimate of $5 million to $15 million for the total annual losses accruing to Carnegie Mellon.

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I. Introduction

Power outages and other power quality disturbances are costing the U.S. economy more than $119 billion annually, according to a recently released study sponsored by EPRI's Consortium for Electric Infrastructure to Support a Digital Society (CEIDS). The study shows that digital businesses were hit the worst, including firms that rely on data storage and retrieval, data processing, and research and development operations (e.g. Internet hotels, telecommunications, biotechnology, electronics manufacturing, and the financial industry). The study is largely based on a survey-based approach with survey forms mailed or emailed nation-wide to key personnel in each company.

Carnegie Mellon University is a large commercial consumer of electricity, using about 92.3 million kilowatt-hours (kWh) annually. It is also a highly digitized university that has advanced research laboratories and sophisticated research and development operations. It is therefore useful to determine the nature and magnitude of power outages that a premier research institution like Carnegie Mellon faces, and the causes of these outages to mitigate future losses.

In this paper, I will investigate the cost of power quality perceived by administrators and compare this to results based on an empirical model. This analysis is of direct relevance to the current debate on the accuracy of computing the costs of power quality disturbance. The other purpose of this paper is also to compare the costs of power quality between departments in Carnegie Mellon University with different academic activities and extrapolate these costs to determine the costs of power quality problems for Carnegie Mellon University in general. This study will also calibrate survey-based studies such as the CEIDS analysis of the cost of power quality on the U.S. economy. Finally, an appraisal of Carnegie Mellon power quality will be conducted. This is achieved by taking power quality measurements within Carnegie Mellon and comparing them to standards and benchmarks of previous research.

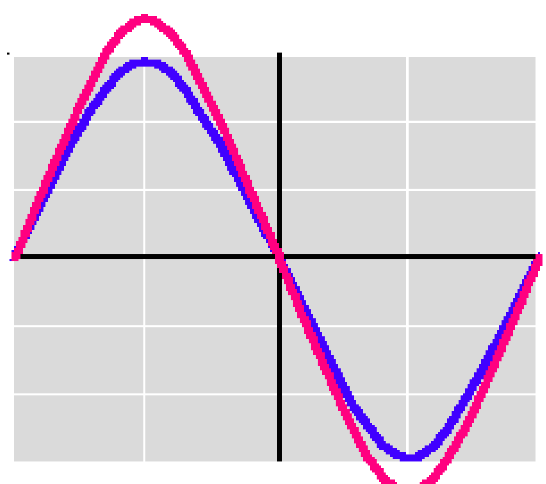
To set the stage for what follows, it is worth summarizing the main concerns that has been expressed about the costs of power quality problems in Carnegie Mellon University. On a micro level, power quality problems can cause both direct and indirect damages. Loss of work, inconvenience and damages to assets are its direct result while other damages such as crimes including vandalism and theft, attrition of laboratory equipment (eg. frequent overvoltages will wear out electrical devices over time) as well as the cancellation of projects as a result of late deadlines can be indirectly caused. Impacts and outage cost should be estimated in monetary value, which however is quite difficult in practice. Estimating the impacts on work during an outage is possible whereas estimating the impacts on life is somehow not easy, for example. This is so because the perspective of each consumer on the impacts of outage differs accordingly to his or her objective of power usage. University personnel categories, power quantity, interrupted activities, duration and period of outages should thus be the criteria of cost estimation.

2. Theoretical Background

Problems in power Quality

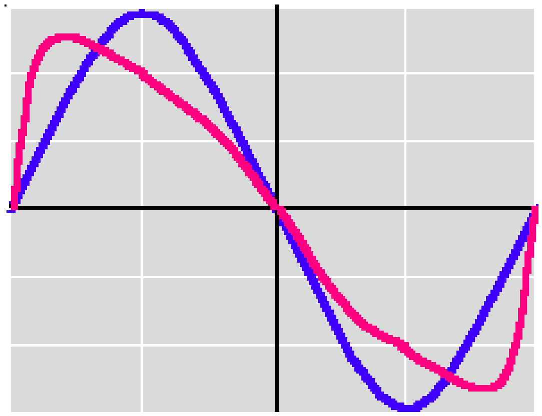
To evaluate the problems of power quality that is present in Carnegie Mellon University, it is necessary to characterize the common types of power quality problems and their features.

Overvoltage occurs when voltage magnitude is substantially **higher** than its nominal value for a sustained period of a few cycles. It is usually caused by sudden decreases in large system loads. Apart from direct damage by overvoltage in electrical devices (voltage magnitude exceeding the specified voltage level), the effect of persistent overvoltage is hardware failure in equipment due to current surges leading to overheating.



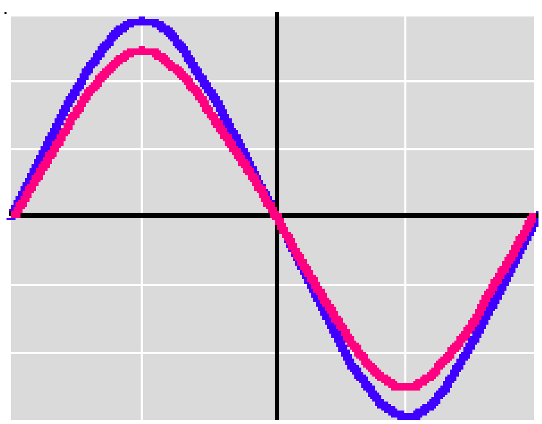
Overvoltage

Harmonics is characterized by a **distorted** voltage waveform which contains higher order harmonic voltage components (usually 3rd, 5th and 7th) which occurs for a sustained period of time on a regular basis. Harmonics can, for instance, originate from a SMPS (Switch Mode Power Supply) in computers, magnetic saturation of power transformer etc. The effect of harmonics include corruption & loss of data, system & server freeze, damage to eletric motors and increased line losses etc.



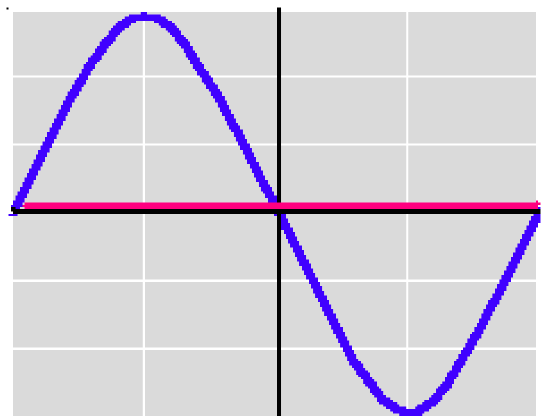
Harmonics

Undervoltage occurs when voltage magnitude is substantially **lower** than its nominal value for a sustained period of a few cycles. Undervoltage is usually caused by overload in electrical network or intentional utility voltage reduction to conserve power during peak demand periods in summer. The effect of undervoltage is system shutdown. An undervoltage for several cycles is known as a **voltage sag**.



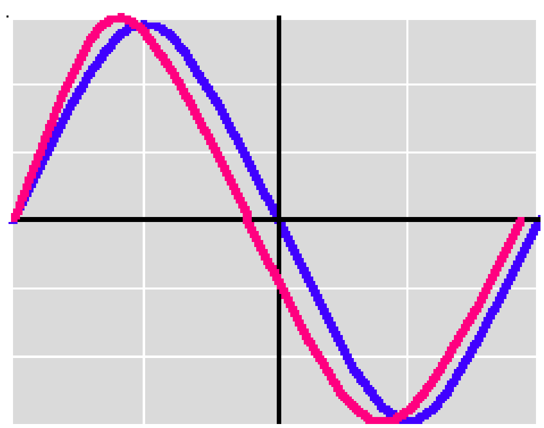
Undervoltage

Outage (Blackout) occurs when utility system voltage collapses for a few cycles or more (typically < 2 mins). It is usually caused by tripping of upstream circuit breaker due to overload, short-circuit, undervoltage, earth fault or earth leakage, utility failure like loss of transmission line etc. The effect is loss of data, system crashes and stoppage of continuous processes eg. aluminium smelting (this aspect has been the traditional concern of electric power companies).



Outage

Frequency Variation is characterized by change is frequency stability. It is usually caused by generator or small cogeneration sites being switched in or switched out. The effect of frequency variation is data loss, system crashes and equipment damage.



Frequency Variation

Switching Transients occurs when there are voltage disturbances which are shorter than sags and swells. They are due to severe load changes in adjacent systems, short circuit, propagation of surges through transformers. The effect of switching transients is power supply failure, hardware failure etc.

It is evident that power quality problems result in higher costs, more downtime, and reduced reliability and efficiency. Hence it is necessary to examine power quality problems in Carnegie Mellon University in a greater detail to understand the full costs that power quality problems engender.

Benchmarks for measuring Power Quality

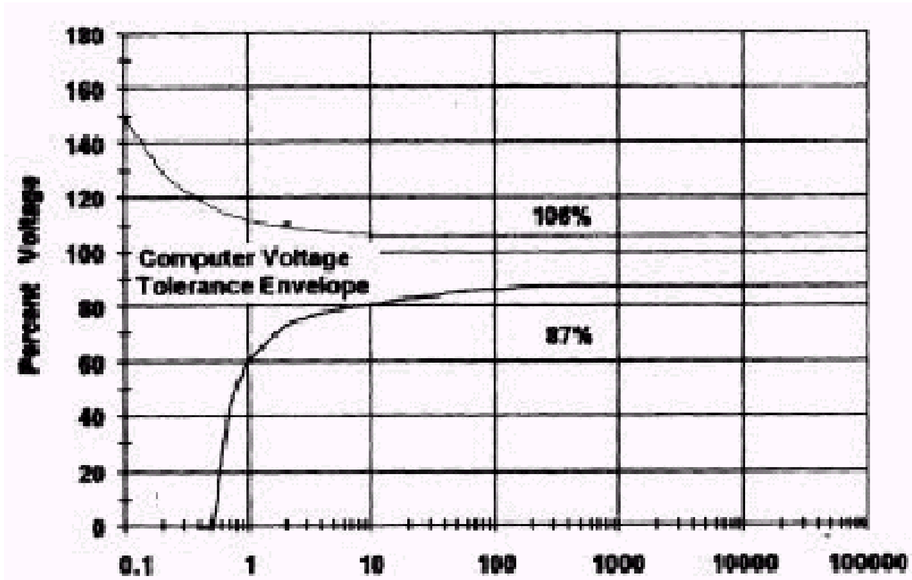
After looking at the common types of power quality problems, we need to look at the benchmarks of power quality and the indexes that encapsulate the power quality of a system. The benchmarks and indices will provide a theoretical framework on the methodology of measuring power quality in Carnegie Mellon University.

The CBEMA/ITIC Curve

The Computer Business Equipment Manufacturers Association (CBEMA) was formed as the trade association for the information technology industry which dealt with the host of issues stemming from technological changes and international competition.

CBEMA produced a susceptibility profile curve of this type in 1977 (Figure 2.1) which aided manufacturers in the design of power supply protection circuits. This curve has since become a standard reference within the industry.

Figure 2.1



Source: CBEMA documents

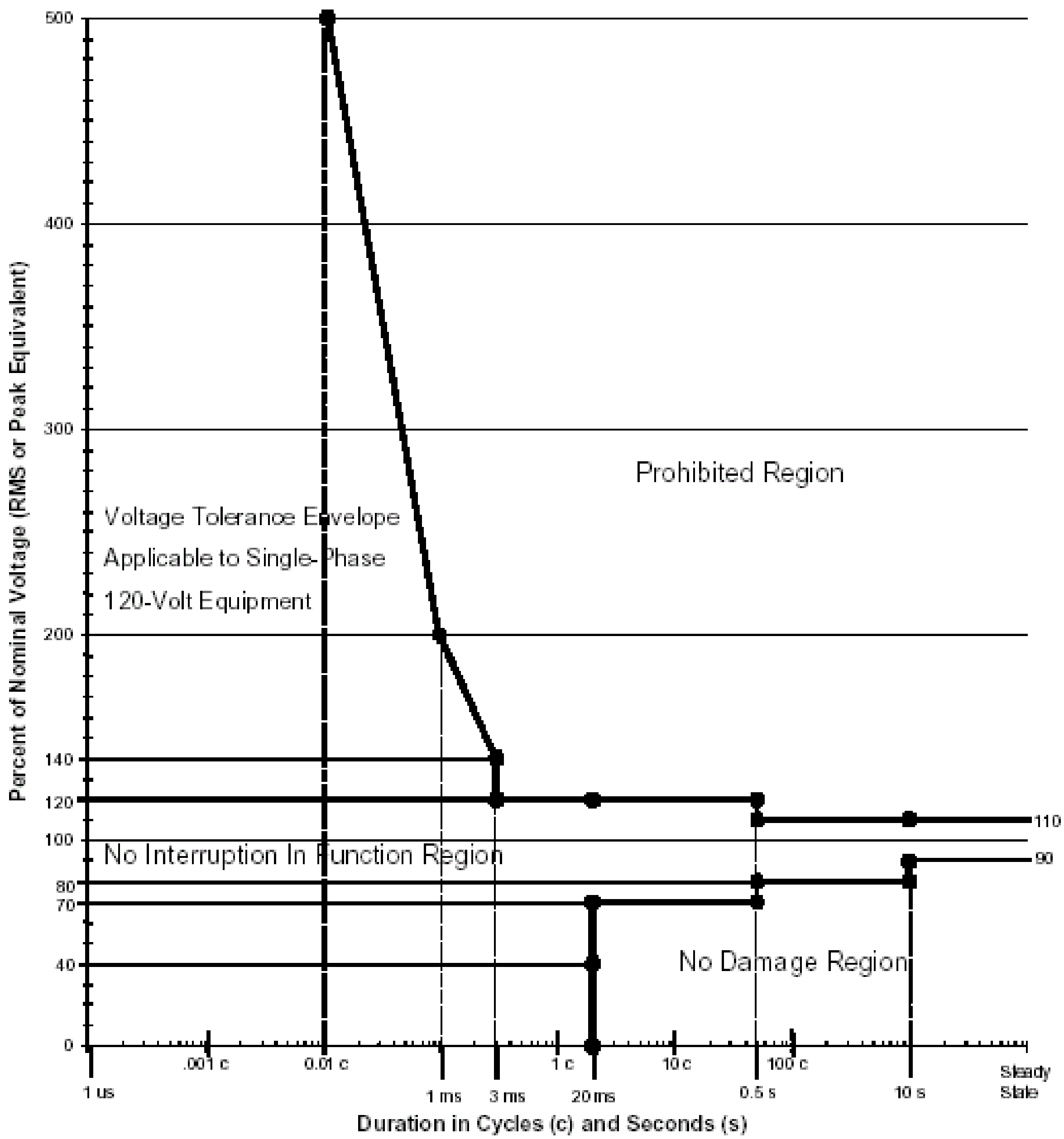
This organisation has been renamed ITIC (Information Technology Industry Council) who have updated the graph (Figure 2.2) in 1998 to represent modern practices for single phase information technology equipment (eg pc, copier, fax) as shown in Figure 2.2 for 120 V systems.

The Information Technology Industry (ITI) Curve describes an AC input voltage envelope which typically can be tolerated (no interruption in function) by most Information Technology Equipment (ITE). The Curve is applicable to 120V nominal voltages obtained from 120V, 208Y/120V, and 120/240V 60Hz systems.

These curves plot the percent of rated voltage (y-axis) against duration (x-axis). Equipment designed to ITIC specifications will operate satisfactorily in the region between the two curves. In the region above the curve, the equipment has a risk of being damaged. In the region below the curve, IT equipment would not function but it would probably not be damaged. These curves define power quality specifications for voltage. The same principles apply to both curves except that the ITIC curve is more refined for IT equipment and has more conservative boundaries. (ITIC decided to modify the CBEMA curve slightly as their belief was equipment was still prone to being damaged under the CBEMA curve limits).

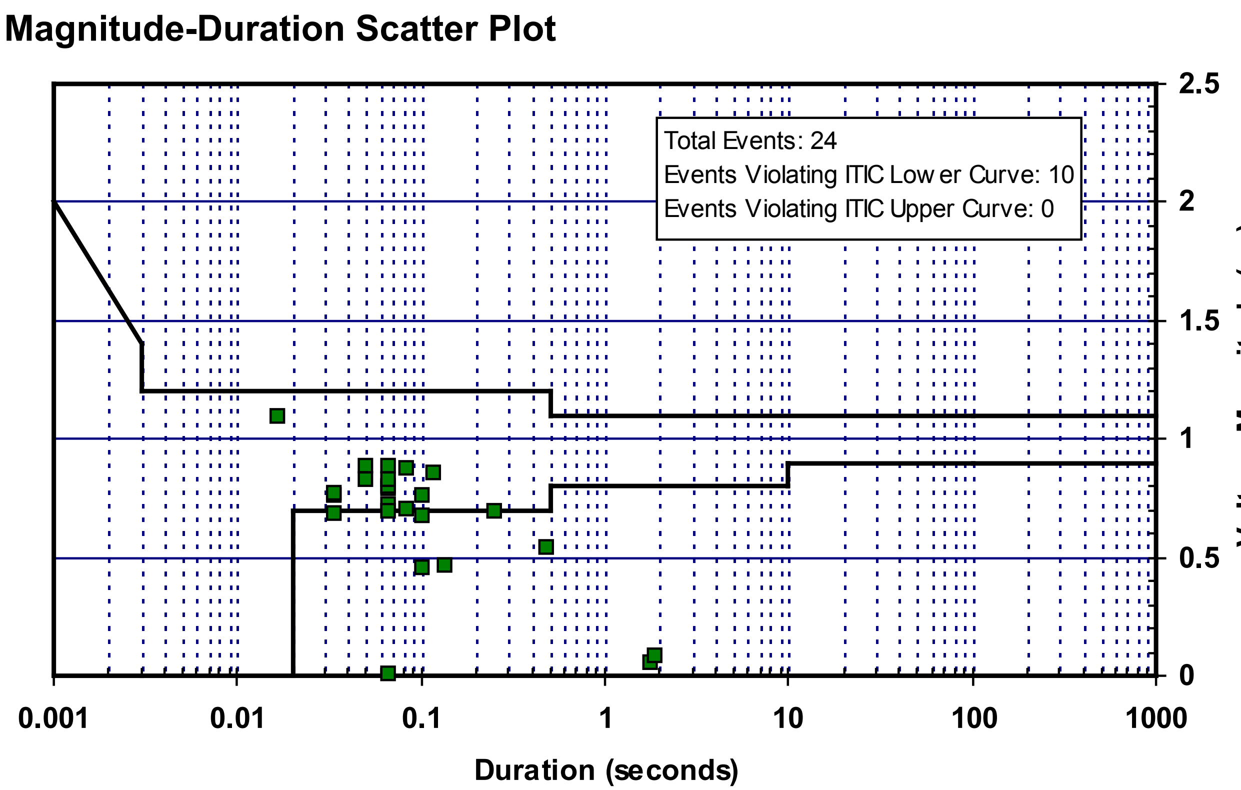
It is noteworthy that currently a similar curve for frequency of power outages / malfunction do not exist although it would be helpful to have one.

Figure 2.2



Source: Power Quality Centre (ITIC) documents

Figure 2.3
Compliance with the ITIC curve for a sample substation conducted in 1997



Source: IEEE Power Engineering Review, October 2001

To illustrate what actual power systems look like, Figure 2.3 is a scatter chart that shows the voltage sag events plotted against the ITIC curve of equipment sensitivity. It tabulates the voltage-sag performances of 1 substation at 24 time intervals monitored by the Pqview, which is a database software application developed by Electrotek Concepts, Inc (EPRI) that is designed to store and analyze large quantities of power quality-related disturbance and steady-state measurement data. In the figure, there are six distinct points that fall below the lower boundary of the curve. They show that there are 6 instances (of duration specified by the x-axis) which the device are not functioning, but the stoppage would not warrant damage to the device.

Traditional Metrics for Voltage Quality

It is important to note that utility companies use a different set of metrics to examine power quality ie. the Industrial Index of Voltage Quality and Reliability. We need to look at the Industrial Index of Voltage Quality and Reliability to establish the common indexes that encapsulate power quality.

There are two indices of voltage quality ie. **Momentary Average Interruption Frequency Index** (MAIFI) which calculates the average frequency of momentary interruptions (i.e., those lasting under 5 min) and the **System Average RMS Variation Frequency Index** (SARFI) which provides a count of voltage sags, swells, and momentary interruptions for a system.

There are three indexes which capture the voltage reliability of a system, namely the **System Average Interruption Duration Index** (SAIDI) which is determined by dividing the sum of all customer interruption durations in a year by the number of customers served, the **System Average Interruption Frequency Index** (SAIFI) which is determined by dividing the accumulated number of customer interruptions in a year by the number of customers served and the **Customer Average Interruption Duration Index** (CAIDI) which is determined by dividing the sum of all customer interruption durations in a year by the number of customer interruptions

The drawback in using the metrics approach is that features like the exact voltage magnitude of an interruption/outage and the frequency of interruption/outage of a particular voltage magnitude cannot be captured. Hence it is important to note that power quality problems defined by ITIC would not be reported by these traditional metrics.

Who uses these indices

To understand whether these indices are applicable in our analysis, it is necessary to look at the users of these indices and their purposes of using them. Firstly, distributors of power utilize these indices to gauge the power reliability on their network to provide customer information so they can specify critical equipment specifications with more confidence in new installations, determine cost-effective sag mitigation techniques in old installations which are giving problems and for proactive planning and maintenance. For example, Detroit Edison's uses a "sag score" to administer its voltage sag contracts with its automotive customers in addition to the traditional indices.

For utility regulators, power quality monitoring is integral to maintain acceptable level of power quality disturbances and to assure that at individual customer level, there is a consistent high level of compatibility between customer processes and the electrical environment.

Other uses of the monitoring system can include information services for customers (such as Austin Energy), enhanced PQ services (such as Duke Energy), and contracts related to the quality of power being delivered (such as Detroit Edison).

After evaluating these indexes and their applications, we have modeled our experiments and tailored our measurements to capture an approximation of these indexes. It has to be noted that our measurements are constrained by the limitations of the measurement device due to cost and time. Using a more sophisticated measurement device is definitely a consideration for future study and suggests further lines of enquiry in the future.

III. Methodology

The project is divided into two major subtasks. The first subtask is the survey component. The second subtask involves measurement of voltage, current and power values over a one week period in Cyert hall, using a data-logger with the help of professional electricians. Cyert Hall is the principal facility for housing and maintaining Carnegie Mellon's dedicated servers and develops, maintain and supports the computing resources for the students, faculty and staff of Carnegie Mellon University. Carnegie Mellon's dedicated server, also known as the Andrew Server, is a pool of multi-user UNIX workstations that provide Andrew and UNIX resources for Macintosh, PC, and terminal users. They provide a general purpose multi-user computing environment, with access to the Andrew System, the complete set of standard UNIX applications, and to various Andrew and third party applications including email and file-transfer protocols etc.

Subtask I - Survey Component

This subtask has three major components, **verification** of the power reliability perception of surveys by surveying the administrators of Cyert Hall and **comparison** of the costs incurred due to power quality problems by a select group of staff, faculty and students in two departments of the university, **extrapolation** of the results to determine the annual costs of power quality problems in the entire university and comparing the results to the EPRI CEIDS study.

The principle of the survey method involved taking the direct approach of asking administrators, staff, faculty and students about their reliability experiences and perceptions. They were asked to identify their costs during an actual event or to estimate their costs for a series of hypothetical events. The survey took two approaches: direct costing (also referred to as enumeration or cost decomposition) or contingent valuation. In direct costing, staff, faculty and students were asked to estimate expenditures for a series of components, such as lost product, spoilage, damage to equipment, etc. Contingent valuation methods ask staff, faculty and students how much they would be willing to pay to avoid an event (willingness to pay) or how much they would be willing to accept in compensation for an event that has occurred (willingness to accept). Although in theory, these two should be equal, reported willingness to pay is usually less than willingness to accept. We therefore ask for both measures, and since actual reliability costs are assumed to lie somewhere between the two, we take the mean of the two values.

Part I - Survey Of Administrators To Verify Power Reliability Perception

For the first component, the survey method was targeted for the administrators of the Andrew server in Cyert Hall about their power reliability experiences and perception, the estimated cost they perceive and the contingent valuation. The goals of the survey was to establish the difference between the perceived loss due to power quality problems by administrators and the actual loss. The survey is derived from the survey used in the CEIDS study. The target population was the administrators of the Cyert Hall Andrew Server and CMU computing Services. The survey was designed to address quantitative and qualitative issues like the nature of the power quality problem, the frequency of occurrence, the estimated cost of the disturbance, which includes salary or work payment, cost to run/rent backup equipment, overtime payment, cost of loss of raw material, cost of re-starting the process, cost of damaged equipment, savings from unused materials, savings from energy bill, savings on wages that were not paid, facilities that had been installed at the facility and facility's total load coverage.

A comprehensive interview and discussion was also conducted post-survey with the concerned personnel in order to identify the 'significant ' problem areas. The direct survey began in May 21th. A copy of the Survey for the administrators of the Andrew server in Cyert Hall is included in **Annex A**.

Following that, actual data based on the historical log files of Cyert hall was computed and compared to those in the survey. For example, A question on what percentage of the outages typically falls into the following categories was asked, with choices ranging from less than 1 second to 4 hrs and longer. The response was then compared to data in the log files summarized by **Annex B.** The methodology for the calculations are detailed in **Annex C**.

The survey was handed out to Marty Altschul, FMS (Facilities Management Services) University Engineer and Kenneth Burner, Assistant Director for Hardware, Carnegie Mellon Computing Services.

Part II - Survey Of Staff, Faculty And Students To Compare Power Quality Costs

The goal of the 2nd component was to compare and contrast the different effects that power quality problems had on two different departments in Carnegie Mellon University, namely a more technical-oriented department and a department in the humanities. We are also interested in finding the difference in impact between a power outage originating from Cyert Hall (resulting in disruption of Andrew Server) and originating from the building that the department is situated. We also wish to determine how different durations of outage might affect the lost work done. Apart from power outages, we have also looked at power-related problems. (poor frequency control or harmonics).

The two departments chosen for the survey were the Social and Decision Sciences Department and the Electrical and Computer Engineering Department.

The Department of **Electrical and Computer Engineering** is a technical department that is research intensive particularly in the advancement and development of methodologies and technologies to build devices for sensing, computing, communication, and storage of information, systems of computers and systems with computers for computing, sensing, communication, control, storage, and intelligent processing of information. Electrical and Computer Engineering is primarily based in Hammersclag Hall and has 133 staff and 56 faculty members. The number of graduate students the department employs is currently 251.

The Department of **Social and Decision Sciences** is an interdisciplinary undergraduate and graduate department that cuts across the social sciences, including decision theory, organization theory, and political economy. Although the department conducts some computational modeling of adaptive social systems, the department's chief focus is on the development of theories of social phenomena that do not always fit neatly into traditional disciplinary boundaries. There is a complementary emphasis on empirical testing of theory, leading to a common concern with methodology. The department has a staff of 15 and 18 faculty members. The number of graduate students the department employs is currently 18.

A subset of faculty, staff and students in both of Social and Decision Sciences Department and the Electrical and Computer Engineering Department was selected and 2 members of the faculty, 2 members of the staff and 2 students were consulted for each department. The time period covered by these results were from June 10th to June 24th 2002. It has to be kept in mind that this survey was conducted in summer semester and may not be representative of the actual cost of work loss in the normal academic semester (Spring and Fall).

A pilot survey was performed and the initial survey proved that workers did not response well to arbitrary work done when specific times were not mentioned. Hence the survey was modified slightly. In the new survey, the participants were asked (without prior warning) what they were doing at that particular instance of time when the surveyor entered the room. This ensued in better responses to answers. The method employed was a face-to-face interview. The survey is included in **Annex D**.

Part III - Calculating The Cost Of Outages To The Entire Campus

After the comparison study was established, all the departments in Carnegie Mellon are then classified to whether they have characteristics more similar to ECE or SDS. This is adjudged on the basis of academic activity, computing facilities, location of department and nature of research. The number of staff and faculty in each department are then enumerated. By indexing the number of staff and faculty as a proportion to the department it is most similar to (i.e. ECE or SDS), the weight of each department is derived.

Hence from the weight, the estimated cost of work loss for each department is derived by multiplying the cost of work loss experienced by either ECE or SDS by its respective weight. By aggregating the cost of work loss for all the departments, the actual cost of work loss is extrapolated for Carnegie Mellon University for a 1-second outage, 1-minute outage and 1-hr outage. Using the malfunction log files of Cyert hall as a guide, the number of 1-second outages, 1-minute outages, 1 hr outages is enumerated for Cyert Hall. Although this malfunction log file is not representative of the frequency and duration of power outages university-wide, we can use it as a source of reference in the absence of other log files.

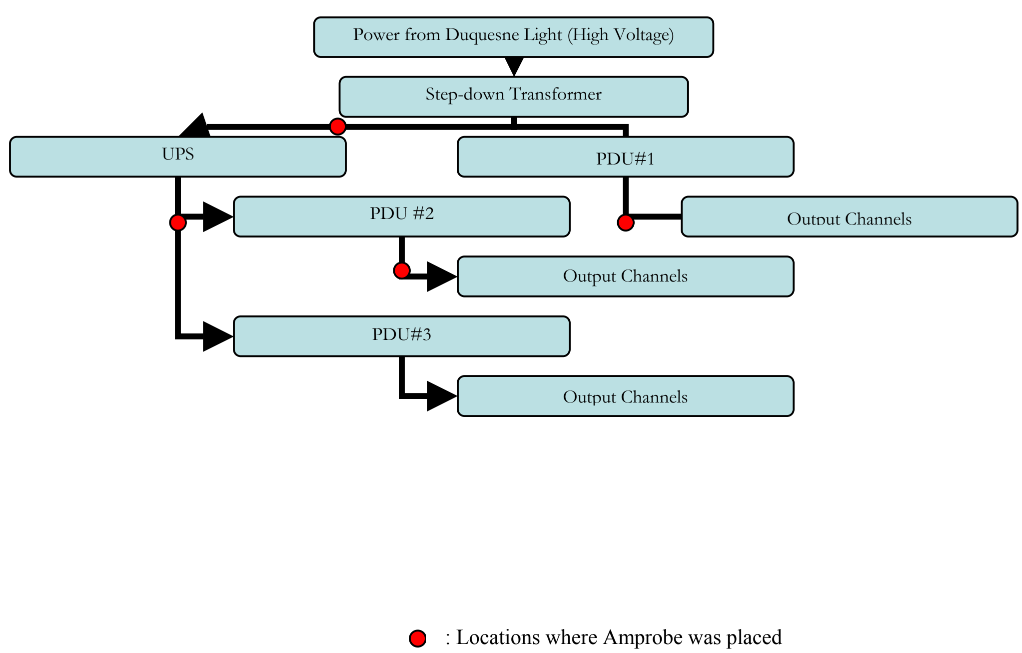
<u>Subtask II - Measurement of power quality statistics</u>

Power quality measurements were conducted in Cyert hall (basement) commencing from the week of June 17th June using an Amprobe DM-II data-logger. The experiment was supervised by two certified electricians and one certified air-conditioning mechanic. Voltage (root-mean-square), current (root-mean-square), real power, apparent power, reactive power and the power factor at selected locations were measured with a rate of 1 second over a 18 hr interval, from 6am to 12pm per day. The data-logger can hold approximately four hours of data before filling its memory, hence the data was downloaded to a computer every four hours.

Data was collected at four locations. The 4 locations are the 480V input side of the **Uninterruptible Power Supply (UPS)**, downstream of the UPS 480V (outlet side), output of Power Distribution Unit (PDU) #2 (208V) and output PDU #1 (208 V). An UPS is a device that sits between a power supply (e.g. a wall outlet) and a device (e.g. a computer) to prevent undesired features of the power source (outages, sags, surges, bad harmonics, etc.) from the supply from adversely affecting the performance of the device. The **Power Distribution Unit (PDU)** supplies and distributes power to the output channels and control and monitor the loads. Power is distributed by Duquesne Light at a high voltage (approximately 12000 V) and converted by a step-down transformer to 480V three-phase power and passed through a UPS. After the UPS regulates the voltage, the power is then routed through three PDUs which distributes the 208V three-phase power to the output channel. Figure 3.1 shows the flowchart of the power supply in Cyert Hall and where measurements were taken with the Amprobe.

For each location, certified electricians assisted in attaching the probes to the mains while Yinglan operated the data-logger and associated software, including the data downloads every four hours. At each location an HVAC load was cycled for 12 minutes (OFF for 2 minute-interval and ON for 2 minute interval - the whole process repeated 2 more times) The cycling of the HVAC was conducted by Mr John Duvall, a certified air-conditioning mechanic at the specified time of 1.05 pm per day. The data logger and the computer was placed on a cart and did not interfere with day-to-day operations in Cyert. Figure 3.1 illustrate the flow diagram of power in Cyert hall.

Figure 3.1
Flowchart of Power Supply in Cyert Hall



IV. Results and Discussion

Subtask I

Part I - Survey Of Administrators To Verify Power Reliability Perception

From Table 4.1, the estimate by administrators of Cyert of the total annual cost due to power quality problems to Cyert Hall is $67978 while the approximate based on the malfunction log files in Cyert Computing Services is $24179. The estimation by the administrators is an **overestimation** by a factor of approximately 3.5 times.

Table 4.1

Difference in Perception of Total Annual Cost Due to Power Problems

	Annual Costs in Thousand Dollars
Estimate by Administrators of Cyert Hall	**68**
Approximate calculations Based on Malfunction Log Files of Cyert Computing Services	**24**

Sources: Cyert Computing Services Malfunction Log Files(Environment and Miscellaneous)

The reasons for the magnitude of difference may be that the sample size is insufficient ie, sampling two administrators in Cyert is insufficient. However, the survey conducted by EPRI's Consortium for Electric Infrastructure to Support a Digital Society (CEIDS) based its results on survey results from one administrator in each company and the criteria for accepting a survey is that more than fifty percent of the questions are answered. Hence it is reasonable to believe that the sample size is sufficient because the questions asked were modeled after the questions used by the CEIDS panel.

Secondly, the "golden benchmark" was calculated using a average wage of $25 for each staff in Carnegie Mellon is merely an approximate and because detailed salary statistics cannot be obtained due to confidentiality reasons. Additionally, some power quality problems may not be recorded in the malfunction log files although this incidence is unlikely.

This result is significant to our analysis. Because we know that the result is an overestimation, it may suggest that we should treat the survey results in Part II conservatively. However, it is also important to consider that the survey administered to the facilities administrators in Part I requested them to consider costs to **others** while in Part II, the survey of faculty, staff and graduate students asked them to consider costs to **themselves**. The administrators may not be fully aware of the details of the lost cost incurred by individuals ex-ante, while the evaluation by individuals is likely to comprise of other incidents that the administrators have overlooked. Hence, the results from Part I can only be used as a source of reference in the absence of other more reliable methods. We believe the actual factor of overestimation in Part II to lie between 1 to 3.5 times. The detailed documentation of the formulae and equation used in computing the result is included in Annex C.

Part II - Survey Of Staff, Faculty And Students To Compare Power Quality Costs

<u>Overall</u>

From Table 4.2, It can be seen that the costs of power quality problems for ECE is higher than SDS for staff (**~2.7 times** for a 1-hour outage) , slightly higher for SDS graduate students **(~1.5 times**) while the costs of power quality problems is significantly higher for SDS than ECE for faculty level **(~4 times** for a 1-hour outage).

Table 4.2
<u>Costs of Power Quality Problems Per Outage by Department for a 1 hour Outage</u>

	Staff	**Graduate Students**	**Faculty**
Electrical and Computer Engineering	$181	$46	$435
Social and Decision Sciences	$66	$73	$1736

There are two principal reasons for this result. Firstly, it is noteworthy that faculty in ECE have daily backup of their work on a separate ECE server so any work that is lost can be recovered from the server; the maximum they can lose in a power outage is a day's worth of work. For SDS, the work of faculty is stored in their personal computers. In the case of power outages causing data corruption, the loss of data is significant, with up to two week's worth of work lost. Hence this is shown in the high costs of power quality problems for SDS faculty.

Secondly, the focus on computing is definitely higher in ECE than SDS and there are more computers per staff in ECE than SDS. Hence power quality problems for staff has more severe repercussions for ECE than SDS, especially when staff are not entitled to daily backups of their data on the server for the ECE department.

From Table 4.2, It can also be seen that the costs of power quality is **highest** for faculty for both departments, followed by staff and then graduate students for ECE respectively. In SDS, graduate students incur more costs in terms of power quality costs than staff. The reason is that a faculty has an average hourly wage of $70, which is 2.8 times for than the $25 at staff level and 8.8 times more than the $8 at graduate student level. Hence the cost per hour of work lost has a higher value than staff and graduate students, hence ceteris paribus, a power outage is likely to be more costly for faculty than staff or graduate students.

In ECE, the staff include researchers and administrators and the majority of the researchers conduct computationally-intensive experiments while the administrators are in charge of multiple computers or in certain cases, computer laboratories. Hence the cost of a power outage is higher for staff than for graduate students. It is also noteworthy that the magnitude of the costs of power quality of staff in ECE is much higher than that of SDS. This is because the number of computers in ECE is about 20 times more than SDS.

In SDS, both the graduate students surveyed were responsible for conducting computationally-intensive modeling of adaptive social systems while the staff were mainly responsible for doing administrative projects which involved more of paperwork, filing and organizing materials. Hence a power outage would be more detrimental for the graduate students than the staff in SDS.

Table 4.3
Cost of Andrew Server Disruption by Department for a 1 hour Disruption

	Staff	**Graduate Students**	**Faculty**
Electrical and Computer Engineering	$0	$0	$0
Social and Decision Sciences	$2	$1	$9

From Table 4.3, it can be seen that the costs of Andrew server being disrupted by a power outage is negligible for ECE. ECE has an independent ECE server backed up on UPS. Staff, faculty and students is primarily dependent on that server to check mail, save and load documents as well as run simulations.

In comparison, the cost of the Andrew server being disrupted is higher for SDS than ECE. The main issue is email access and access of information via the Andrew server. The underlying reason is because SDS faculty, staff and student are dependent on the Andrew server to access email and access information.

Computers/Printers/Laptops/Routers

From Table 4.4, we can see that the number of personal computers (excluding laptops) in ECE is approximately 20 times more than that of SDS. There are 78 printers in ECE compared to 12 (includes deskjets and laserjets) in SDS **(~ 6 times)**. There are about 4 times as many laptops in ECE than SDS. Because laptops have an independent battery source, they would not be affected if there was a power outage. This would help us understand the magnitude of the problem relative to all computer usage.

Table 4.4
Comparison of Inventory across Departments

	Electrical and Computer Engineering	Social and Decision Sciences
No. of Personal Computers	861	39
No. of Laptops	41	11
No. of AFS Servers	7	5
No. of Printers	78	12
No. of UPS	4	2

Servers/ UPS Backup Servers

ECE has slightly more Andrew File System (AFS) servers than SDS; 7 compared to 5 in SDS. An Andrew File System Server serves to backup files and document from the local drive into the server. Any servers going down in ECE may affect all the servers to go down or none at all, this depends on the timing and configuration of the server at the particular moment. Similarly, the servers in SDS do not support department-wide applications, they only support various projects that the different professors are working on. It is uncertain whether a power outage would totally derail operations in SDS.

The number of UPS in SDS and ECE were about the same (4 in ECE, 2 costing $700 and 2 costing $1400, 3 in SDS). This is disproportional because ECE has more computers than SDS. The UPS coverage of ECE computers is evidently insufficient. In the survey, it was found that only Professor James Hoe's computer and Professor John Miller's computer are on UPS, which would limit the damage that a power outage had on their computers. The rest of the computers are not on UPS. Mr Louis J Anschuetz (Network Manager of ECE) estimates that about 900 computers out of 1300 computers (including lab equipment) would be affected by a power quality problem. He estimated that the worst case in history is that 10 hard disk have been damaged due to a lightning storm causing a split-second power outage. He also approximated that there was an average of 1 incident hard-disk damage, 0.1 memory burn and 0.1 motherboard if there is a split second power outage. He quotes "Dr Phllips Koopman's $20000 super-computer had to be replaced because the power outage took out the fans and the CPU was fried from overheating."

Power Quality Problems Affecting Andrew Server In SDS

In SDS, a loss of the Andrew System [the staff would get kicked out of Mulberry email, the internet, the Student Information System via TerraTerm and the Research Participation Website. Most reported would only take them a few minutes to reboot and the lost time would be the time to check mail on mulberry and send mail. On the system level, little work would be lost since the staff uses those systems to access information, not to actually create work - so the only time involved would be to reboot. There would be no dollar amount of loss attached to a 1 second power. The answer is the same for a 1 minute power outage, However, the mean estimated monetary cost for SDS for a 1 hour outage is substantial. The average value of lost work for a 1 hr power outage is $60. They would not be able to get much work done for the day and they estimate the loss to be equivalent to a day's worth of work. This is because they would go home because the effect of power outage has a large effect on their clerical work.

At the student level, the only loss which they perceive is the loss of access of email. They estimate the loss to be negligible (5 minutes for most cases) because most check mail infrequently and email does not directly pertain to their work. There would not be any significant loss of work.

At the faculty level, there will be some lost work due to Andrew Server going down. The main issue is email access via an Andrew email account. The surveyed faculty members estimates 15 minutes to retype their emails. However. it was found that they would not be affected much if the lack of access of email was for a duration of 1 hour. This was because they had other projects which did not involve conferencing via email. However, at the time of survey Dr Julia Downs was working on a paper and was sending email back and forth frequently regarding revised editions of the paper. The lost time in having to relay the message is documented in Table 1.1.

Power Quality Problems Affecting Andrew Server In ECE

At the staff level, the loss of access of the Andrew server is milder than SDS. There will be no lost work due to Andrew Server going down. The majority of the staff uses an ECE email account and does not telnet to Andrew server. It was found that zero computers would be affected. The only loss of functionality would be disrupted World Wide Web access if Andrew goes down; but the staff surveyed does not need to use the World Wide Web for his job.

At the student level, the loss of access to Andrew results in them being unable to put up webpages/resources on the web. The lost cost is the extra time incurred in publishing the results on the web again. But it has to be noted that ECE students mostly use the World Wide Web for reference purposes only and losing access to it would not have a deterministic impact.

At the faculty level, the loss of access to Andrew Server includes online documentation hence there would be loss work done in the form of unsaved work being lost. A professor surveyed estimates that he would lose 1 hr worth of documentation for a 1 second outage. For a duration of outage longer than 5 minutes, he would work on another project which does not involve Andrew and so the lost work is insignificant from this point onwards. (See Table 1.1 for more details)

Power Outage In Hamerschlag Hall (ECE)

For power outage in Hamerschlag hall itself, printer servers would go down and the computers would go down for a split second and reboot. In worst case scenario, a split second power outage might lead to damage to the computer and lead to hardware damage, data loss.

At the staff level, the loss of functionalities includes losing access to print servers and the local afs servers. ECE technical staff would not be able to use software in the ECE server and check email in their ECE account. Access to the ECE server is integral to their job and a power outage would affect their work drastically. The network manager, Mr Louis J Anschuetz, estimates a lost time of 5 hrs to re-establish and re-verify network connections in ECE. The staff interviewed mentioned a mean of 0.5 hrs of lost work done for a 1 second outage.

For a 1hr outage, computers on UPS would have a 20 minute before they shut-down. Laptop would not be affected. However, only an approximate 400 computers out of 1300 are on UPS, so this implies that the probability that the computers going down and re-booting in the event of a power outage is very high. The probability for desktops going down in the event of a power outage is about 70%.

At the student level, there is a large degree of variation in lost time according to the type of work they are doing. A graduate student website designer would lose 1 hr's worth of work while a research programmer would lose the whole day's (7.5 hrs) worth of programs if there was a power outage (His facility is not backed up by UPS and the hard disk is not backed up nightly)

At the faculty level, there was a tenor of empirical evidence that a power quality problem would be severe. Even though their hard-disk is backed up nightly, the professors concurred they would lose an hour of work at least and some type of the work that they have done (programming) cannot be recovered. The mean value of the unrecoverable work is estimated to be $150.

Lab Equipment/Simulations in ECE

A staff researcher interviewed would lose 3 to 4 days worth of simulations but added that his simulations have checkpoints so they are periodically saved.

A faculty reported that he would lose 3 hrs of simulation (However, he added that the researcher does not have to be present when simulation is running. The value of simulation depends on the quality of the simulation. It cannot be quantified)

Hard Disk Damage in ECE

All staff, student, faculty agreed that hard disk damage due to a power quality problem is devastating. For the faculty, their hard disk is backed up nightly by an AFS server so information can be recovered up to the point when they started work on that day. However, a hard-disk damage to the research staff and students would take a variable duration of 1 work day to 2 weeks to recover. The mean period taken was a week.

Duration in ECE

For a 1 minute power outage, the results are the same as above. However, if the power outage is 1 hr, the most popular response would be to go home if the power does not come back on immediately. The majority of the ECE staff and faculty do not work at home, so the lost cost is equivalent to a day's worth of work.

Power Outage in Baker Hall (SDS)

For power outage in Baker hall itself, the effect is distinctly less severe for the staff and faculty.

For graduate students, Janice Golenbock and Uri Simonsohn, they would lose an average of 2 hours of programming time. For Janice, she values her lost work to be $50. For the simulation that she is running, she would need another 30 minutes to recover the lost work. Uri's hourly wage is $25.

The staff would lose access to Word and Excel programs, as well as get kicked out of Mulberry email, the internet, the Student Information System via TerraTerm and professor's meeting schedule. It would only take them a few minutes to recover the lost work, so the only time involved would be to reboot. There would be no dollar amount of loss attached to a 1 second power outage - only annoyance.

For faculty level, the faculty surveyed were Dr Miller and Dr Downs. Dr Miller was running a computational modeling process and is concurrently documenting his scientific work. It would take approximately 1 hr to recover these documentation data. The computational modeling process is on UPS and when asked if there wasn't an UPS, his response was that it would take approximately 4 hours to recover these lost data. Dr Downs would need approximately 20 minutes to retrieve the hard copy of the paper that she was working with her co-author because Mulberry did not work.

Lab Equipment/Simulations in SDS

The lost work due to lab equipment re-booting is negligible in SDS. For the simulation that is run in the SDS department, the duration is short (ranging from 30 minutes to 1 hr). Hence, it is evident that the lost work due to lab equipment in ECE is of a larger magnitude in ECE than in SDS.

Hard Disk Damage in SDS

Like ECE, it would be a catastrophe in terms of lost work if data was corrupted by the power outage. The duration to recover the lost data ranges from 3.5 hrs to 2 weeks. The mean time taken is estimated to be 1 week. The noticeable difference is that the faculty do not have their hard-disks backed up nightly in SDS, compared to ECE and so they tend to spend more time recovering the lost data.

Duration

If the outage was 1 hour, the staff wouldn't be able to do much work at all - they attach a mean value of $40 - $50 to this outage. A staff interviewed says that she has a project that she can do outside of the office and there would be very little lost work time. However, when asked that there was uncertainty as to when the power would be back on, the reply was that they might spend a few hours waiting and then just leave and work on office project another day. A mean loss cost was estimated to be around $75. The faculty and staff response was to go home.

Miscellaneous

All the people surveyed felt that the lost work due to fax machines and telephone being affected is insignificant. (This question was asked because cordless phones will not work without electricity and fax machines are mostly connected to the power source). Quite a substantial number have cellular phones so a power outage would not affect them. The lost cost is just the time incurred in faxing the document or in making the call again.

The majority did not work at night in the office. For the remaining few who did work in the office, they would go home immediately if there was a power outage, so the lost cost is not significant.

Almost all said that poor frequency control or transients would not affect them if the duration is not protracted. Common reactions were annoyance and frustration if the transients ensue in flickering of the lights or monitors but there would be no tangible lost work. However, harmonics may lead to overheating of electrical devices(in particular the neutral and transformers) and this may cause data corruption in personal computers. Another suggested problem was low-frequency magnetic interference which might also interfere with the power supply and also result in overheating of the hard disk, causing damage to data. Data loss is an important consideration which will be addressed later in the report.

Part III - Calculating The Cost Of Outages To The Entire Campus

The total cost due to 1 second power outage university-wide is approximately **$1.1 million dollars.** The total cost due to a 1 minute power outage university-wide is also approximately **$1.1 million dollars.** The total cost due to a 1 hour power outage university-wide is approximately **$1.6 million dollars.** The key components of the cost are mostly immeasurable productivity losses plus small real equipment losses as a result of the power outage. It is noteworthy that the increase in cost is not linear in time.

A 1 minute power outage has a similar effect to a 1 second power outage in terms of work lost and reactions of individuals. Hence the total costs are similar when the figures are rounded. However, the impact of a 1 hour outage and the reactions of individuals to a 1 hour outage is different from a 1 second or 1 minute power outage. Although the instantaneous data lost is the same for a power outage lasting 1 second, 1 minute or for 1 hour, there is a substantial longer time for which the personnel is unable to do work in the case of 1-hour power outage. Moreover, most personnel will go home if the outage is protracted i.e. more than 30 minutes.

The total cost of an campus-wide outage to the Andrew server is about **3 thousand to 9 thousand dollars.**

Using the model we have devised above, the total annual cost of power quality problems lies between the range of **5 million dollars to 15 million dollars.**

This range has been adjusted after taking into account of results in Part I, which indicates that survey results tend to **overestimate** by a factor of 1 to 3.5 times because the surveys in Part I and Part III were based on the same survey methodology and principle. The questions asked in both surveys were modeled after questions used by the CEIDS panel, suggesting that the results of that study may also be an over-estimate, but probably less than one order of magnitude.

Additionally, in the absence of other accurate malfunction log files for campus-wide power outages, the malfunction log files for Cyert hall can only be used for a source of reference and the report should be updated once other reliable malfunction log files of the campus is available.

It is noteworthy that the range of 5 million dollars to 15 million dollars in annual losses due to power quality is comparable to the annual amount (approximately 5 million dollars) Carnegie Mellon University spent on electricity per annum. We observe that the range of \$5 million -\$15 million form approximately $\frac{1}{8000}$ to $\frac{1}{24000}$ of the \$119 billion of the total annual cost of power quality problems affecting the U.S. economy CEIDS report estimated by the CEIDS report. It may suggest that the estimate is too high, but it is more likely that Carnegie Mellon is a computationally intensive institution and a significant proportion of high-value research is conducted in the university.

The detailed calculations are available in **Annex E**.

Sub task II - Power Quality Measurements

Method of analysis

The analysis of the data is based on a dataset of more than 60,000 measurements and will be broken down into 3 subtasks. The first subtask will find the mean voltage of the

measurement point and find the standard deviation of the voltage. I have also stratified the voltage measurements by time. The second subtask will find the minimum voltage, current, power and power factor and the times at which they occur.
The third component will display graphically the distribution of the voltage (ranked).

From the first subtask[1], it was found that the standard deviation of the voltage was greatest in the input side of the UPS (480 V) as seen in Table 5.1. The was expected because this is the power supplied by Duquense Light before it passes through the UPS. The variation in voltage was significantly lower for the downstream of the UPS. This shows that the voltage variability is reduced by the UPS and power after passing through the UPS is "cleaner".

Table 5.1

Mean Voltage and Mean Difference of Voltage [2]

I. 480V input side of the UPS

Mean Voltage (A): 275.5312 V

Mean Difference(overall)	1.447525927 V
Mean Difference (Morning 6am-12pm)	1.205309569 V
Mean Difference (Afternoon –1pm-6pm)	1.714627404 V
Mean Difference (Night 7pm-12 midnight)	1.462903379 V

II. Downstream of the UPS 480V (outlet side)

Mean Voltage (A): 278.5813415

Mean Difference(overall)	0.084285V
Mean Difference (Morning 6am-12pm)	0.085451V
Mean Difference (Afternoon –1pm-6pm)	0.080253V
Mean Difference (Night 7pm-12 midnight)	0.087461V

III. Output PDU #1 (208 V)

Mean Voltage (A): 119.4974 V

Mean Difference(overall)	0.824285 V
Mean Difference (Morning 6am-12pm)	1.039861 V
Mean Difference (Afternoon –1pm-6pm)	0.849239 V
Mean Difference (Night 7pm-12 midnight)	0.505957 V

[1] Measurements were taken at the one terminal and one base of the Y-connection circuit hence for a 480V input, by potential divider principle, we should expect to see a mean of 280V for the upstream and downstream UPS.

[2] in three-phase power

IV. Output of PDU #2 (208V) (on UPS)
Mean Voltage (A): 121.21845465296

Mean Difference(overall)	0.047415 V
Mean Difference (Morning 6am-12pm)	0.044729 V
Mean Difference (Afternoon –1pm-6pm)	0.045041 V
Mean Difference (Night 7pm-12 midnight)	0.0523 V

The standard deviation of the voltage was lowest in Output PDU#2 and lower than in PDU #1. This is in accordance with theory because output PDU #2 is on the UPS and the voltage on PDU #2 appears to be more stable.

There were also evidence that the mean voltage A varies more in the afternoon for the input side of the UPS, and at night for the downstream of the 480V UPS, at night for output of PDU#2 and in the morning of Output of PDU#1. It is expected that we should see more variation in voltage if we could measure at a higher frequency.

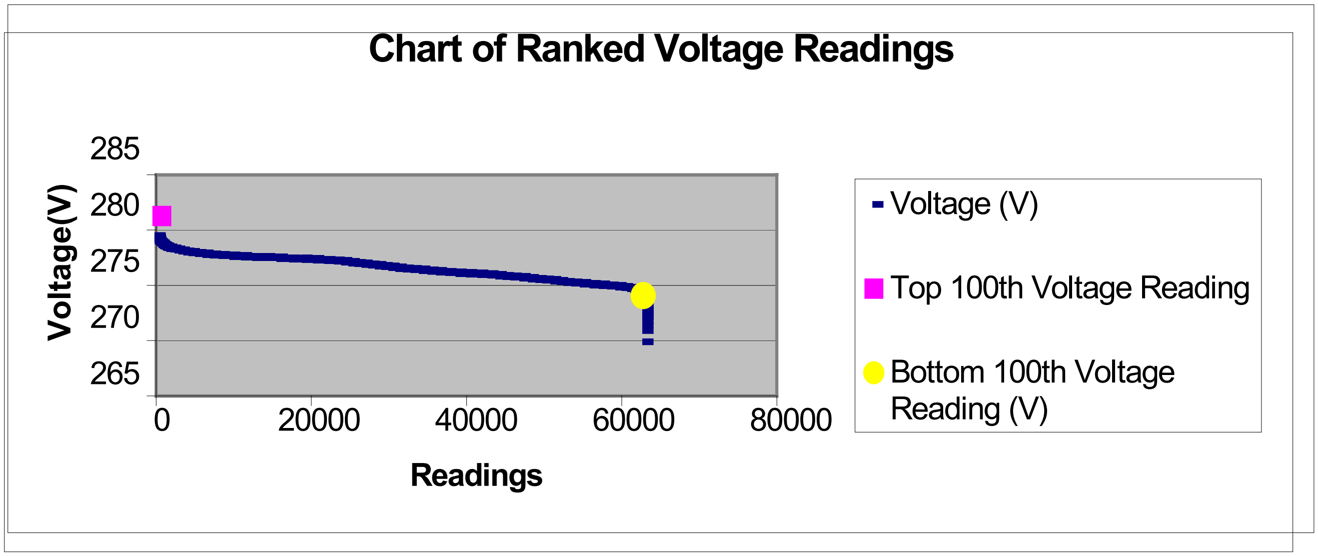
From the 2nd subtask, it was found that the maximum and minimum voltage are all fairly close for the downstream of the UPS, PDU#1 and PDU#2. Hence we are fairly confident that the electrical system in Cyert Hall is a stable system and there are no serious disability with the power quality. The detailed documents are in Annex E.

From Table 5.2, it is evident from the charts that all the voltages are within the boundaries set by the ITIC curve for all four location of measurements[3], indicating that the system is reliable. It is noteworthy that readings at higher frequency would be more indicative. Instantaneous spikes of duration in the range of ms may occur between the measurements as the interval between the measurements is 1 second.

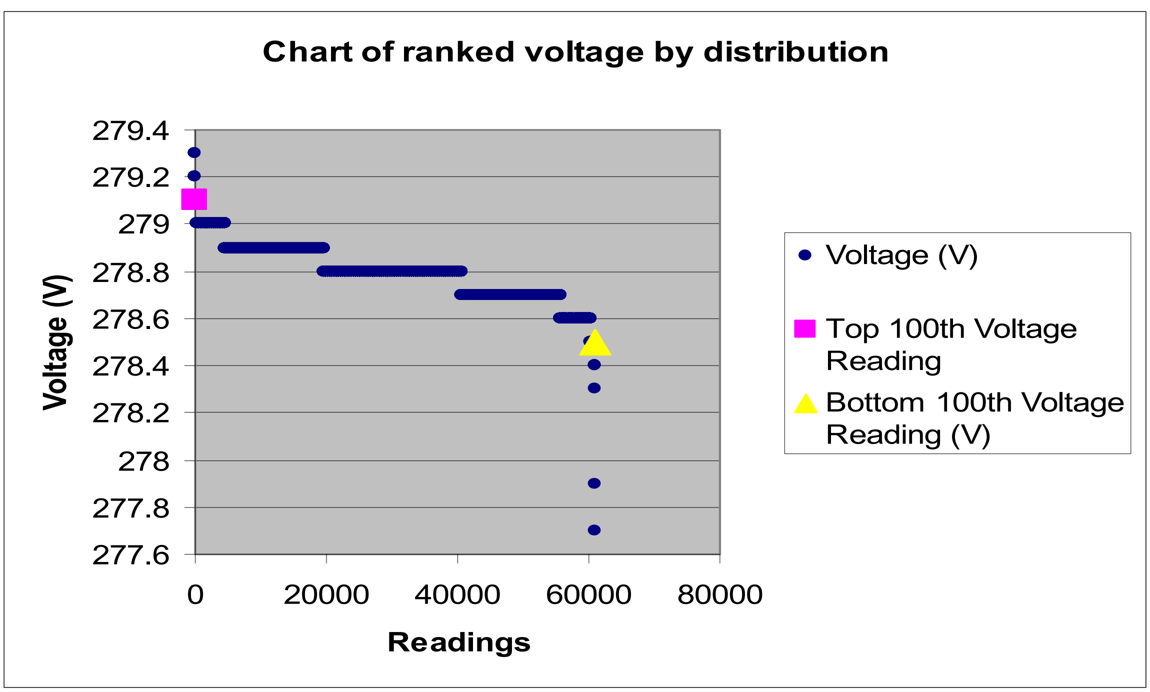
[3] For a 480V Y-connection, the upper bound of the ITIC curve for a stable state voltage is 110% x 280V = 308V, the lower bound is 90% x 280V = 252V. For a 208V Y connection, the upper bound is 120V x 110% = 132 V, the lower bound is 90% x 120V = 108 V.

Table 5.2
Charts of Ranked Voltage Distribution

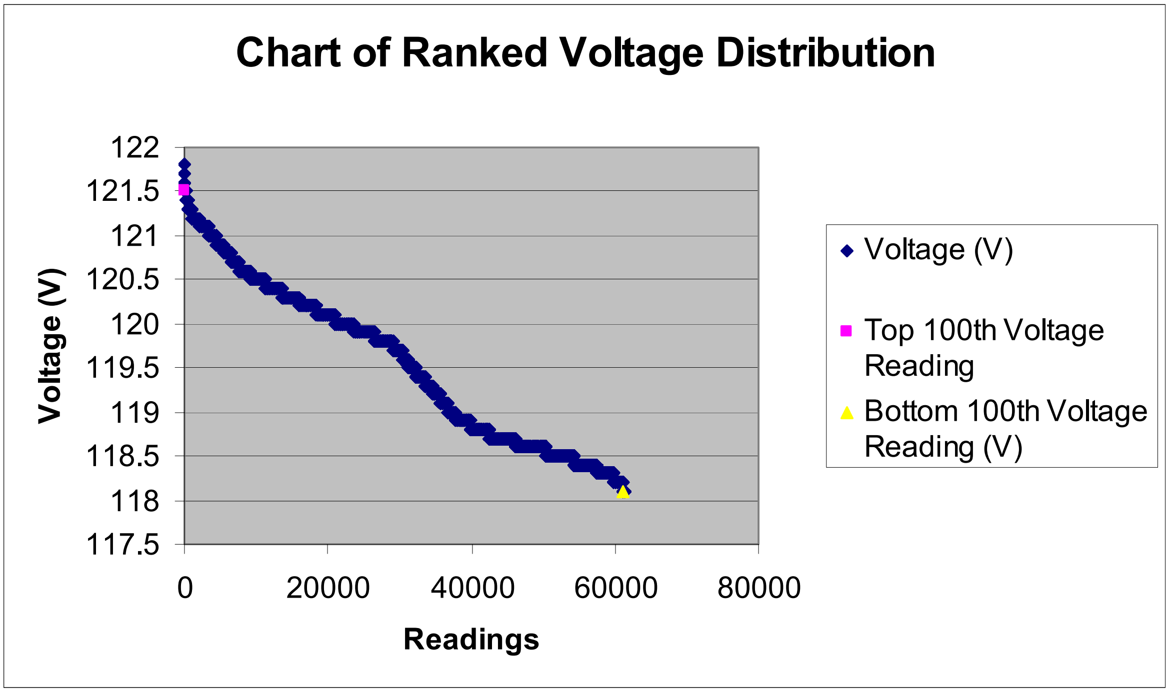
Input Side of 480V UPS



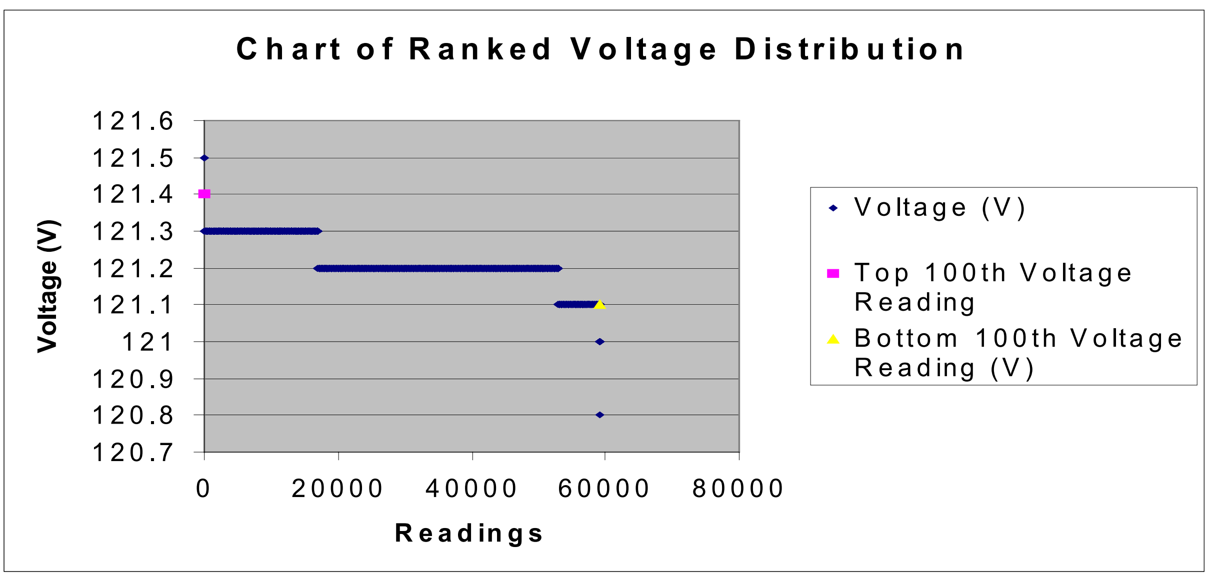
Downstream of 480V UPS



Output of PDU #1 (208V)



Output of PDU #2 (208V)



5. Discussion of Limitations

The method of investigation has several caveats. These limitations of the experiment in particular need to be kept in mind. Firstly, survey methods are often criticized as unreliable. One concern is that participants may strategically misrepresent their costs. For example, they may believe that exaggerating their costs will spur their utility company to improve reliability, or they may fear that their willingness to pay would be used to justify an increase in rates. In addition, participants often lack recent experience with the events being studied, which reduces the reliability of their responses. Participants with recent outage experience, for example, sometimes report lower interruption costs than customers who lack such experience, although there is also anecdotal information to the contrary. Moreover, the survey do not consider the frequency of occurrences of outages based on actual log files but only rely on the memory of the administrator which may be inaccurate.

Secondly, traditional metrics for power system reliability (eg. MAIFI or SAIDI) tend to focus on large outages. However, estimates of costs associated with these events are not well documented and generally not useful for identifying the type of power supply problems that can affect modern businesses and universities.

Thirdly, since outages are often caused by weather (e.g. lightning) or natural disasters (e.g. earthquakes), it is often impossible to isolate the effects of the outage from the other effects of these initiating events.

A fourth point is that analysis to synthesize and extrapolate from these surveys is difficult, due to inconsistencies in sampling, study design, and reporting conventions. Although the inconsistencies have been kept to a minimal throughout the experiment, inconsistencies in reporting is inevitable due to human error.

A fifth point is that a Digital Trip Analyser manufactured by Dranetz or a harmonics meter would have been more ideal because it is capable of measuring at intervals of cycles and microsecond and be able to capture spikes which lasts only a few cycles, however we are limited by budget and time constrain. This is definitely a consideration for future study and suggests further lines of enquiry in the future.

Lastly, the tradeoff in capturing all the information regarding the power supply is whether an affordable device exists to make the measurement. The less expensive a device is, the more likely it will be applied at many locations, more completely representing the voltage quality electricity users are experiencing. However, such a device might not meet the needs of some of the more sensitive users.

6. Conclusion

The key findings of the study are multi-faceted. Firstly, it was found that the key components of the cost due to power quality problems are unmeasurable productivity losses and real equipment losses. Using the model we have devised in this study, we have found the annual costs accruing to Carnegie Mellon University to be in the range of **5 million dollars to 15 million dollars.**

Secondly, the perception of administrators regarding the cost of power quality can be an overestimate of significantly glaring magnitude (**an overestimate in the range of 1 to 3.5**). Furthermore, in the method derived from EPRI's CEIDS survey, administrators were asked to consider costs to **others**. We can clearly see that this would result in underestimating the cost based on the survey of faculty, staff and graduate students in which they were asked them to consider costs to **themselves**. The administrators are not fully aware of the details of the lost cost incurred by individuals ex-ante, while the evaluation by individuals is likely to comprise of other incidents that the administrators have overlooked.

This result introduces ambiguity in the EPRI's CEIDS study of industries because the survey component was derived from the survey used in the CEIDS study – which requested administrators to extrapolate costs to their respective companies. In addition, the result of the CEIDS study was given as a point estimate of 3 significant figures which is nebulous in the terms of accuracy and significance. It is recommended that future survey-based research (eg. CEIDS) provide a range of their results to account for the inaccuracies and errors in reporting as well as the tendencies of over-estimating.

Thirdly, it was found that the department of Social and Decision Science, contrary to hypothesis, has a higher overall cost due to power quality problems compared to the department of Electrical and Computer Engineering. Although the number of computers in ECE greatly outnumbers that in SDS, it is noteworthy that faculty in ECE have daily backup of their work on a separate ECE server so any work that is lost can be recovered from the server; the maximum they can lose in a power outage is a day's worth of work. For SDS, the work of faculty is stored in their personal computers. In the case of power outages causing data corruption, the loss of data is significant, with up to two week's worth of work lost. The loss cost greatly increases in magnitude if the power quality problem corrupts data. The time needed to recover the lost data is minimal if the computer is supported by a UPS.

Lastly, the power quality measurements in Cyert Hall indicates that the power quality in Carnegie Mellon University falls within the benchmarks of the ITIC curve and is therefore a stable system with no serious disability. However, a device which could measure voltage more frequently would give us better data. This suggests a line of inquiry in the future.

Recommendations for the University and Directions for Further Research

Even though our findings derive from an ex post evaluation of power quality losses, they offer useful guidelines for the university if the working patterns of staff, faculty and students do not alter much, in which case, they are unlikely to be.

Based on this study's results, we can clearly see that UPS servers reduce the volatility of voltage and reduce lost productivity time as well as minimize data loss. It was also found that the UPS coverage of the ECE department is clearly insufficient. The probability for desktops going down in the event of a power outage is about 70%. Although installations charges for a UPS costs between $700 to $2000, this is a case of a large spending at the start, but the savings reaped from the reduced losses due to lost productivity more than offsets the initial capital investment. If we equip all 1300 personal computers in ECE with UPS, we can have potential savings of about $10,000 in the first year (after deducting labor cost), and potential savings of about $50,000 annually.

There are also potential savings we can make in the SDS department. Unlike ECE which has a backup server for faculty's daily work, SDS does not. It is suggested that separate backup servers/AFS servers should be installed. The cost of installation is minimal in terms of additional infrastructure and this would substantially bring down the power quality losses in SDS faculty by a factor of **4 or more** (i.e. about $20,000 for the department per annum).

For computationally-intensive experiments or projects involving multiple-terminal collaboration, it is advocated that the computers be placed on UPS and have frequent periodic backups on AFS servers. Disruptions to these experiments were found to have the next highest cost to the university apart from work by faculty. It is advocated that checkpoints be placed in this experiments so that there is minimal data loss when a power quality problem.

The extent of which different departments consult and utilize Cyert Computing Services with regards to power quality issues is uncertain. There are currently a variety of liability-reduction equipment provided by Cyert Computing Services. An option for the university and departments would be to make use of this existing resources. Hence, it is not clear whether the university should invest in power quality devices and if so, whether it should invest in more centralized power-saving devices or in distributed devices in different departments. The recommendations we have proposed pertains to the department of ECE and SDS specifically and cannot be and should not be generalized for other departments. This would suggest future lines of inquiry in the future.

The most practical solution is not necessarily technical in nature but is human behavior based. It is important to create incentives where people back up work regularly or use servers in specific departments. A good backup strategy balances need against practicality and time against cost. It is recommended that faculty and staff to back up on a daily to weekly basis, and fortunately, timesaving methods make the process easy. Education and shifting of mindsets is pertinent to reduce the cost of power quality.

The study helps to clarify certain issues in prior survey-based research and points to a number of potentially fruitful avenues for further research. Firstly, measurements by a Digital Trip Analyser or a harmonics meter would shed more light on the power quality because it is capable of measuring at intervals of cycles and microsecond and be able to capture spikes which lasts only a few cycles. It would be fruitful to look at measurements taken over a larger period of time to fully capture the changes in power and voltage variability over time. When better technology and data becomes available, they should be taken into account when planning the power quality infrastructure of Carnegie Mellon.

Secondly, the dynamics of how power quality problems affect each department precisely is not fully explored ie. how the relationship of location, academic and research activity and density of electrical devices affect the power quality costs directly or indirectly. Further research is needed to shed light on this important relationship.[4]

[4] The author gratefully acknowledge the support of the Facilities Management Services, Cyert Computing Services and the Engineering and Public Policy Department at Carnegie Mellon.

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SDS Graduate Students: Janice Golenbock, Uri Simonsohn
SDS Staff: Amy patterson and Marilyn Walgora

X. References

Apostolov Alexander, Guillot David" Power Quality Monitoring in Substations Based on Advanced Protection and Control Devices", 2000

Arnold, Ray "Solutions to the power quality problem", Power Engineering Journal, April 2001

Bonneville Power Administration 2000 Annual Report

B.W. Kennedy, *Power Quality Primer*. New York: McGraw-Hill, 2000.

Chowdhury Badrul, "Power Quality", IEEE May 2001

D. L. Brooks, R. C. Dugan, Waclawiak, Marek, Sundaram, Ashok
"Indices for Assessing Utility Distribution System
RMS Variation Performance", *IEEE Transactions on Power Delivery*, vol. 13,
no. 1, January 1998, pp. 254-259.

D. Sabin, "Indices Used to assess RMS Voltage Variation", Electrotek Concepts Issue 51 pg 2, July 2000

EPRI TR-106294-V2, "*An Assessment of Distribution System Power Quality; Volume 2: Statistical Summary Report"*, May 1996.

G. Heydt, *Electric Power Quality*, 2nd ed. Scottsdale AZ: Stars in a Circle Publications, 1995.

Guillot, David " Power Quality Monitoring", ALSTOM Transmission and Distribution, April 2001

Heydt, "Power Quality Engineering", *IEEE Power Engineering Review, September 2001*

IEEE Std.1159-1995, "*Recommended Practice on Monitoring Electric Power Quality"*, Working Group on Monitoring Electrical Power Quality of SCC22 - Power Quality, Draft 6, November, 1994.

J.Driesen, T.Van Craenenbroeck, D.Van Dommelen, "The Development of Power Quality Markets", IEEE 2002

J. J. Burke, D. C. Griffith, and D. J. Ward, "Power quality-Two different perspectives," *IEEE Trans. Power Delivery*, vol. 5, pp.
1501-13, July 1990.

Kandil, Farghal and Elmitwally, "Refined power quality statistics", IEE 2001, Feb 2001

McGranaghan, Mark "Trends in Power Quality Monitoring", *IEEE Power Engineering Review, October 2001*

Meyer, Winkler, Muhlwitz, "Advanced Power Quality Rating under the Conditions of Regulated Markets", Apr 2000

M. F. McGranaghan, D. R. Mueller, M. J. Samotyj, "Voltage Sags in Industrial Systems," *IEEE Transactions on Industry Applications*, Vol 29, No. 2, March/April 1993.

M.H.J. Bollen, *Understanding Power Quality Problems -Voltage Sags and Interruptions*. Piscataway, NJ: IEEE Press, 2000.

Stones, John, Collinson Alan, "Power Quality", Power Engineering Journal April 2001

Primen, Lawrence Berkeley National Laboratory, "The Cost of Power Disturbances to Industrial & Digital Economy Companies", EPRI Journal, July 2001

V. J. Gosbell, Perera, Sarath, Smith, Vic "Voltage Sag Measurement and Characterization" Power Quality Centre, Technical Note No. 4, June 2001

V. Wagner, A. Andreshak, and J. Staniak, "Power Quality and Factory Automation, " Proceedings of
the IAS Annual Meeting, vol. 35, no. 6, pp. 1391-1396.

Annex A

Survey on Power Quality

1) **About how many outages has the facility experienced in the last 12 months?**

    ______ outages in the past 12 months

2) **About how many outages does the facility experience in a single year?**

    ______ outages in a typical year

3) **What percent of the outages you listed in Question 2 typically falls into each of the following categories?**

Less than 1 second	**_____ %**
1 second to less than 60 seconds	**_____ %**
1 minute to less than 3 minutes	**_____ %**
3 minute to less than 5 minutes	**_____ %**
5 minute to less than 1 hour	**_____ %**
1 hour to less than 4 hours	**_____ %**
4 hours or longer	**_____ %**
	100%

4) **About how many times in a typical year does the following occur at this facility? The power goes off for a second or two, comes back on for a few seconds, then goes back off again.**

    ______ outages in a typical year

5) **In general, how long would activities stop or slow down as a result of this 1 sec outage**

    Activities would slow down for:

    _____ Seconds OR _____ Minutes OR _____ Hours

The next few pages describe three different outage case studies. Each case describes an outage that your firm might experience and provides you with several details about the outage. (eg. when it occurs, how long it lasts, whether or not you have any advance warning that the outage might occur.)

For each case, please imagine that the outage described actually occurs at this facility in exactly the manner described, and think about how this particular outage would affect your operations. Several of the questions will ask about specific dollar amounts which you will save (or lose) as a result of the particular outage.

Length of outage:	**1 second**
Time when Outage occurs:	**Summer weekday starting 2pm**
Warning or prior notification:	**None**

6) Please give an estimate of the costs and savings you would generally expect your organization to experience due to the outage of this duration (1 sec). If you think there would not be no cost of savings for a specific item, please put zero in the blank.

Labor Costs

Estimated Costs

Salaries and wages paid to staff who are unable to work $____________
Labor costs to make up lost work $____________

Material Costs

Damage or spoilage to materials,
ongoing projects, inventory $____________

Additional Costs

Extra restart costs $____________

Ongoing overhead expenses incurred
during the outage and restart period $____________

Damage to organization's building and equipment $____________

Cost to run/and or rent backup equipment **$____________**

Others (please specify: _____________) **$____________**

Savings

Savings from unused materials or inventory **$____________**

Savings on energy bill **$____________**

Savings on wages that were not paid **$____________**

Other (please specify : ____________) **$____________**

7) **What is the value of work that would be lost while activities are slowed down or stopped due to this 1 second outage**

$____________ Value of lost work

Length of outage:	**3 minutes**
Time when Outage occurs:	**Summer weekday starting 2pm**
Warning or prior notification:	**None**

8) **Please give an estimate of the costs and savings you would generally expect your organization to experience due to the outage of this duration (3 minutes). If you think there would not be no cost of savings for a specific item, please put zero in the blank.**

Labor Costs

Estimated Costs

Salaries and wages paid to staff who are unable to work **$____________**
Labor costs to make up lost work **$____________**

Material Costs

Damage or spoilage to materials,
ongoing projects, inventory **$____________**

Additional Costs

Extra restart costs **$____________**

Ongoing overhead expenses incurred during the outage and restart period **$____________**

Damage to organization's building and equipment **$____________**

Cost to run/and or rent backup equipment **$____________**

Others (please specify: _____________) **$____________**

Savings

Savings from unused materials or inventory **$____________**

Savings on energy bill **$____________**

Savings on wages that were not paid **$____________**

Other (please specify : ____________) **$____________**

9) What is the value of work that would be lost while activities are slowed down or stopped due to this 3 minute outage

$____________ Value of lost work

Length of outage:	**1 hour**
Time when Outage occurs:	**Summer weekday starting 2pm**
Warning or prior notification:	**24 hours before the outage, you are notified that "rotating outages are possible"**

10) Please give an estimate of the costs and savings you would generally expect your organization to experience due to the outage of this duration (1 hour). If you think there would not be no cost of savings for a specific item, please put zero in the blank.

Labor Costs

Estimated Costs

Salaries and wages paid to staff who are unable to work $____________
Labor costs to make up lost work $____________

Material Costs

Damage or spoilage to materials,
ongoing projects, inventory $____________

Additional Costs

Extra restart costs $____________
Ongoing overhead expenses incurred
during the outage and restart period $____________

Damage to organization's building and equipment $____________

Cost to run/and or rent backup equipment $____________

Others (please specify: _____________) $____________

Savings

Savings from unused materials or inventory $____________

Savings on energy bill $____________

Savings on wages that were not paid $____________

Other (please specify : ____________) $____________

Length of outage:	1 hour
Time when Outage occurs:	Summer weekday starting 2pm
Warning or prior notification:	None

11) Please give an estimate of the costs and savings you would generally expect your organization to experience due to the outage of this duration (1 hour). If you think there would not be no cost of savings for a specific item, please put zero in the blank.

Labor Costs

Estimated Costs

Salaries and wages paid to staff who are unable to work $____________
Labor costs to make up lost work $____________

Material Costs

Damage or spoilage to materials,
ongoing projects, inventory $____________

Additional Costs

Extra restart costs $____________

Ongoing overhead expenses incurred

during the outage and restart period $____________

Damage to organization's building and equipment $____________

Cost to run/and or rent backup equipment $____________

Others (please specify: _____________) $____________

Savings

Savings from unused materials or inventory $____________

Savings on energy bill $____________

Savings on wages that were not paid $____________

Other (please specify : ____________) $____________

12) What is the value of work that would be lost while activities are slowed down or stopped due to this 1 second outage

$____________ Value of lost work

Which of the following typically occurs at your faculty when power quality events occur? (CIRCLE ALL THAT APPLY)

1 Light flicker, blink, or dim
2 Circuit breakers or power strips trip
3 Computer lock up or reboot themselves
4 Motors or other process equipment start or stop by themselves
5 Motors or other process equipment slows down or speeds up unexpectedly
6 Motors or other process equipment are damaged
7 Computers or other electronics are damaged
8 Employees receive electric shocks when touching equipment
9 Other (specify: ________________)

Approximately how much money does the facility lose annually as a result of the power quality events that occur in the precious question. (DO NOT INCLUDE LOSSES THAT RESULT FROM POWER OUTAGES, EVEN THOSE THAT ONLY LAST FOR ONLY A SECOND)

$____________________

13) **Which of the following has the facility installed to deal with power quality or reliability concerns? (CIRCLE ALL THAT APPLY)**

1 Surge protectors
2 Uninterruptible power supply (UPS) devices
3 Line conditioners or filters
4 Back-up generator(s)
5 A co-generation system capable of generating most or all of your power needs on-site
6 Other (Please specify ___________)
7 None of the above

14) **Approximately how much money has the university invested in the purchase and installation of the equipment described in question 8 for this facility?**

$ _________

15) **Approximately what percentage of your facility's total electrical load is currently covered by … ? (WRITE IN A PERCENTAGE FOR EACH ITEM)**

Percent of Load Covered

A standby or backup generator __________ **%**

UPS devices, line conditioners, or filters __________ **%**

We would like to thank you in advance for your time and help. The survey results would be invaluable in the investigation of power quality in Carnegie Mellon University.

Thanks and have a good day.

Annex B

ANNEX B Type and Frequency of Outage

Type of Outage	Duration of Outage	#times	The times at which the problem occurred	Information about the equipment affected	Information about the equipment nearby	Facility Restarted?	Duration Facility was down if restarted
Power Flicker	< 1 second (Lights flicker - Momentary Outage) - No restart	1	1/9/01	Everything went black, major power hit	Alarms sounded, affected the chilled water plant, reduction in cooling capacity	Yes; #1 required restarting	2 hrs
	< 1 second (Lights flicker - Momentary Outage) -restart	3	9/14/2001, 3/9/2001			No	
(PDU #1 Alarm)	1+Sec (PDU #1 Alarm)	5	1/22/2002, 4/30/2002,9/27/2001,1/5	Lights flicker a few times		No	
Alarm on EDPAC #1 and #6 - power loss	1+Sec (EDPAC #1 and #6 Alarm)	2	4/28/2002, 5/10/2002	power loss		No	20 minutes
	1+ Sec Printer Reboot	1	20-Nov	Rebooted; it was in a crashed state		No	
EDPAC2 Alarm	3 minute to less than 5 minutes	1	5-Jan	UPS fixed by battery guys		Yes	4 hrs

Total approximate outage time from 27th August 2001 to 24th May 2002

6 hrs 40 minutes and 9 seconds

6.67 hrs

Sources:

Cyert Environment Malfunction Log	8/29 /2001-5/23/2002
Cyert Miscellaneous Malfunction Log	8/27/2001 - 5/24/2002

Annex C

To calculate the costs of the power quality problems: the following methods and calculations were employed.

Lost Production

Lost production was calculated by taking the costs of lost production minus the cost of production that would be made up over time.

Cost Variables

Several factors were considered when calculating total cost of an outage.

1 **Labor Costs**
   - **Idle Labor:** Salaries and wages paid to staff who are unable to work
   - **Additional Labor:** Labor costs to make up lost production and services

2 **Material Costs:** Damage or spoilage to materials, finished products, or inventory

3 **Additional Costs**

4 **Extra restart Costs**
   - **Overhead:** Ongoing overhead expenses incurred during the outage and restart period
   - **Equipment damages:** Damages to an organization's building or equipment
   - **Extra Backup Costs:** Costs to run and/or rent backup equipment.
   - **Other:** costs identified by respondents as a result of outage

Savings Variables

In addition, possible savings realized during an outage were also considered:

1 Unused Material - Savings from unused materials or inventory
2 Energy Savings - Realized savings on their energy bill
3 Labor Unpaid - Savings from wages that were not paid
4 Other - Other savings identified by respondents as a result of outage

Missing cost values for given scenarios were estimated to be zero. Using $0 estimates due to lack of information of costs resulting from an outage provides a more conservative estimate than other methods of estimation.

Net Cost

Net Cost for individual outages were calculated by subtracting total savings from total costs. Negative net costs were recoded as $0

Overall power quality costs were assessed based on average overall annual cost.

Average Annual Outage Costs

First the average number of each type of outage (eg, 1 second, 3 minute, 1 hour) was calculated. Then the average cost for each type of outage was calculated. The product of the total number of each type of outage and the average corresponding cost of the outage was calculated.

Methodology for investigation

Equipment failure/malfunction logs files of Cyert Hall Power Source [Environment and Miscellaneous] were obtained courtesy of Carnegie Mellon Computing Services and these documents provided relevant information of loads affected and detailed information of suspect loads. The following values can be obtained from the documents: the type of outage, the frequency of occurrence, the times at which the problem occurred, information about the equipment affected and information about the nearby equipment. The log files were dated from 29th August 2001 to 23th of May of 2002 for Environment and 27th August 2001 to 24th of May 2002.A total of 13 power quality occurred over the semester period. There were two instances when the facility had to be restarted due to power quality incidents; once on the first of September 2001 for a period of 2 hours and another on the 5th of January for a period of 4 hours.

Another source is the electricity bill of Cyert Hall. The electricity usage of Cyert can be determined and the annual cost of electricity usage of Cyert Hall can be determined. From Appendix B, the annual cost of Cyert Electrical Usage is $260422 per year for the year of 2001.

The payroll of faculty, technicians and administrators would have been an ideal source to compute the cost of lost salary, but this was strictly confidential. Hence, an alternative strategem is proposed. Considering the average wage of Carnegie Mellon is $25 per worker per hour, the cost of the loss can be computed by this formula:

Lost working time **x** Number of staff working in Cyert **x** Average wage per hr
= 6.67 hrs x 145 staff x 25
= $24178.75

The cost of re-starting the facility can also be determined but with a certain degree of ambiguity. The official charge-out rate = $39.42 for high-level technicians and facilities maintenance operators. There are no detailed documentation of the duration of work done.

The mean duration provided by Mr. Burner was 3 to 4 man working-days (i.e. 3.5 x 8 man-hours = 28 man-hours) for every instance they are activated. Mr Altschul's best estimate is 4 workers of 6 hrs each (i.e. 4 x 6 man-hours = 24 man-hours)
Hence the cost of restarting the facility

= Mean duration of work to restart facility **x** Mean number of technicians
x official charge out rate

$$= (\frac{24+28}{2} man-hours)\times \$39.42 = \$1024.92$$

To compute the cost of backup (UPS), 100.1 kvA (Kilo-volt Amperes) of Cyert total electrical load is devoted to UPS devices, line conditioners and filters. This would translate to
100.1 kvA **x** 24 hrs **x** 365 days **=** 876876 kwh

Considering the 5274418 kwh per annum consumed by Cyert Hall (Appendix B).

Cost of backup power = $\frac{876876}{5274418}\times \$260422$ (Annual Electrical Cost by Cyert)= \$43295

Installation Costs: 1 x Surge Protectors = 1 x \$5000
3 x Dual Conversion UPS devices = 3 x \$34000 = \$102000
8 x Harmonic Traps = 8 x \$3000 = \$24000

This are derived from the best estimate of the purchase price of the power reliability devices. Review of site circuit diagrams was also conducted. Several of these devices were installed a few years ago. There are no official records.

Results of Data Analysis

Calculations based on survey results of Mr Marty Altschul, FMS (Facilities Management Services) University Engineer

Total costs of a 1 sec outage = \$12700
Total costs of a 3 minute outage = \$18500
Total costs of a 1 hr outage (with pre-notification) = \$417000
Total costs of a 1 hr outage (without pre-notification) = \$597000

Average number of a 1 sec outage per annum = 1 x 9% = 0.09
Average number of a 3 min outage per annum = 1 x 91% = 0.91
Average number of a 1 hr outage per annum (with pre-notification) = 0
Average number of a 1 hr outage per annum (without pre-notification) = 0

Average Annual Outage Costs (outages only) = 0.09 x \$12700 + 0.91 x \$18500 = \$17978

Total cost of power quality events (excluding outages) = \$50000

Average Annual Outage Costs (total) = 0.09 x \$12700 + 0.91 x \$18500 + \$50000 = **\$67978**

Cost of installation of power maintenance facilities = N.A.

Calculations based on survey results of Kenneth Burner, Assistant Director for Hardware, Carnegie Mellon Computing Services.

Total costs of a 1 sec outage = N.A.
Total costs of a 3 minute outage = N.A.
Total costs of a 1 hr outage (with pre-notification) = N.A
Total costs of a 1 hr outage (without pre-notification) = N.A.

Average number of a 1 sec outage per annum = 12 x 90% = 10.8
Average number of a 3 min outage per annum = 12 x 9% = 1.08
Average number of a 1 hr outage per annum (with pre-notification) = 12 x 1% = 0.12
Average number of a 1 hr outage per annum (without pre-notification) = 0

Average Annual Outage Costs (outages only) = N.A

Total cost of power quality events (excluding outages) = N.A

Average Annual Outage Costs (total) = N.A.

Cost of installation of power maintenance facilities = **$200, 000**

Annex D

Questions on Power Quality on Campus

1. Can I make a count of the number of computers, printers that you have in the building? Do you keep records of the number of computers in the building?

2. Do you have a record of the UPS servers in the building; if so, how many are there?

3. How many servers are running in the building?

4. If there was a power outage in Cyert Hall server, which of the following would occur?

    i) How many computers would go down (connection to server lost)?

    ii) For the computers that go down; what loss of functionality (i.e. which aspect of your work is affected? For example: email or capability of telneting to unix server or failure to backup)

    iii) For the aspect of work that is affected, how long would you take to recover the lost work done?

    iv) What is the average hourly wage of the worker/researcher who is working?

    v) If the lost work done cannot be recovered, what is the value of the lost work/research?

5. If there was a power outage in Hammersclag Hall for ECE participants or Baker Hall for H&SS participants, which of the following would occur?

    vi) How many computers would go down?

    vii) For the computers that go down; what loss of functionality (i.e. which aspect of your work is affected. For example: email or capability of telneting to unix server)

    viii) For the aspect of work that is affected, how long would you take to recover the lost work done?

    ix) What is the average hourly wage of the worker/researcher who is working?

x) If the lost work done cannot be recovered, what is the value of the lost work/research?

6. Would lab equipment, experiments, image-rendering etc be affected?

   xi) For the aspect of work that is affected, how long would you take to recover the lost work done?

   xii) What is the average hourly wage of the worker/researcher who is working?

   xiii) If the lost work done cannot be recovered, what is the value of the lost work/research?

   xiv) Would these apparatus be damaged due to the power outage? If so, what is the cost needed to repair or replace them?

7. Would fax machines and telephone be affected ?(Cordless phones will not work without electricity)

   xv) For the aspect of work that is affected, how long would you take to recover the lost work done?

   xvi) What is the average hourly wage of the worker/researcher who is working?

   xvii) If the lost work done cannot be recovered, what is the value of the lost work/research?

8. If the outage occurred at night, outages would lead to loss of lights.

   xviii) For the aspect of work that is affected due to loss of lights, how long would you take to recover the lost work done?

   xix) What is the average hourly wage of the worker/researcher who is working? (includes overtime)

   xx) If the lost work done cannot be recovered, what is the value of the lost work/research?

9. **Miscellaneous .** Would people be trapped in elevators if there was a power outage (for Hammersclag Hall participants only)

   xxi) What is the value of the work they could have done if they were not trapped?

xxii) What would be the value of lost leisure due to the loss of power outage due to television, radio defunctionality? If your building have refrigerators equipped, what is the cost due to perishable food being damaged in the power outage?

We would like to thank you in advance for your time and help. The survey results would be invaluable in the investigation of power quality in Carnegie Mellon University.

Thanks and have a good day.

List of personnel surveyed

ECE staff :Kenny Mckinney, Louis J Anschuetz (Network Manager), Mat Grosland, (User Consultant) and Elaine Zurcher (Store Room Supervisor)

ECE faculty, James C. Hoe (Assistant Professor of Electrical and Computer Engineering and Computer Science)

Charles P. Neuman (Professor of Electrical and Computer Engineering)

ECE Graduate students, Jessica R. Kreger and Soji Yamakawa (Computer Integrated Systems)

SDS Graduate Students: Janice Golenbock, Uri Simonsohn

SDS Faculty: Dr Julie Downs, Dr John Miller

SDS Staff: Amy patterson and Marilyn Walgora

Projection Results

Calculations of Cost of power outage by Department

	Staff	Faculty	Most Like	Cost Associated with a one-second outage associated with building	Cost Associated with a one-minute outage associated with building	Cost Associated with a one-hour outage associated with building
Airforce ROTC	6	3	SDS	3809.22	3809.22	5606.22
Architecture	21	16	ECE	5223.75	5223.75	10766.25
Army ROTC	1	8	SDS	10062.37	10062.37	13954.37
Art	10	19	SDS	23946.7	23946.7	33647.7
Biological Sciences	61	30	ECE	13443.75	13443.75	24106.25
Biomedical	6	4	ECE	1432.5	1432.5	2827.5
CALD: Center For Automated Learning & Discovery	3	5	ECE	1031.25	1031.25	2718.75
Civil Engineering	19	21	ECE	5411.25	5411.25	12578.75
Center For Bone Tissue Engineering	0	9	ECE	945	945	3915
Chemical Engineering	19	22	ECE	5516.25	5516.25	13013.75
Chemistry	20	28	ECE	6315	6315	15805
CNBC: Center For The Neural Basis Of Cognition	24	2	ECE	4260	4260	5220
Computer Science	109	128	ECE	31833.75	31833.75	75436.25
Design	44	15	SDS	19135.28	19135.28	28960.28
Drama	204	36	SDS	46551.48	46551.48	76035.48

ECE	133	56	ECE	28323.75	28323.75	48466.25
English	28	28	SDS	35374.36	35374.36	50466.36
EPP	20	14	SDS	17725.4	17725.4	25631.4
ETC: Entertainment Technology Center	3	1	ECE	611.25	611.25	978.75
GSIA	174	95	SDS	120523.38	120523.38	176468.38
H&SS Dean's Office	9	3	SDS	3828.33	3828.33	5805.33
HCII: Human Computer Interaction	59	21	SDS	26772.83	26772.83	40371.83
Heinz	182	44	SDS	56467.34	56467.34	88463.34
HIBD:Hunt Institute For Botanical Documentation	24	14	ECE	5520	5520	10440
History	66	20	SDS	25560.42	25560.42	39100.42
ICES:Institute For Complex Engineered Systems	35	6	ECE	6536.25	6536.25	8953.75
IS Program In H&SS	2	2	SDS	2526.74	2526.74	3604.74
ISRI: Institute For Software Research International	67	9	ECE	12251.25	12251.25	16058.75
LTI Research	65	10	ECE	12018.75	12018.75	16131.25
Mathematical Sciences	34	33	SDS	41697.58	41697.58	59544.58
Mechanical Engineering	84	11	ECE	15330	15330	20010
Modern Languages	31	22	SDS	27851.47	27851.47	40249.47
MSE: Materials Science & Engineering	73	18	ECE	14208.75	14208.75	21061.25
Music	74	27	SDS	34410.38	34410.38	51783.38

Navy Rotc	5	7	SDS	8830.85	8830.85	12483.85
Philosophy	21	20	SDS	25273.77	25273.77	36113.77
Physics	59	35	SDS	44370.83	44370.83	64675.83
PSC-Pittsburgh Supercomputer Center	93	1	ECE	15798.75	15798.75	17291.25
Psychology	143	24	SDS	31078.91	31078.91	51154.91
REC:Robotics Engineering Consortium	42	3	ECE	7402.5	7402.5	8917.5
Robotics Institute	44	50	ECE	12675	12675	29725
SDS	15	18	SDS	22721.55	22721.55	32243.55
SEI Director's Office	17	1	ECE	2973.75	2973.75	3516.25
Statistics	38	15	SDS	19097.06	19097.06	28562.06
STC Administration	21	1	SDS	1390.77	1390.77	3129.77
				858069.52	858069.52	1335994.52
General Administration (using a evenly-weighted average of staff wages from ECE and SDS)				210932.04	210932.04	298258.29
				1069001.6	1069001.6	1634252.81

Total Annual Cost of Outages in Carnegie Mellon University*

Duration of Outages	Frequency of outages	Cost of outages	Total Cost of Outages by duration of outages
Approximately 1 hour	2	1634252.81	3268505.62
1-min	2	1069001.56	2138003.12
Approximately 1 second	9	1069001.56	9621014.04
Total Annual Cost of Outages in Carnegie Mellon University*			15027522.78
* the effects of a 4-hr outage is similar to a 1-hr outage			
* using log files of Cyert Hall as model			

Annex E

Minimum and Maximum Voltage Measurements

Input of UPS (480V)

VA Min (V)			IA Min (A)	VB Min (V)			IB Min (A)
6/18/02 14:38	267.9	6/18/02 8:15	30.1	6/18/02 14:38	267.2	6/18/02 8:15	31.4
6/18/02 14:39	268	6/18/02 16:13	30.4	6/18/02 14:39	267.4	6/18/02 23:06	31.9
6/18/02 14:38	268.9	6/18/02 13:51	31.1	6/18/02 14:38	268.2	6/18/02 16:13	31.9
6/18/02 14:49	269.3	6/18/02 7:05	31.4	6/18/02 14:49	268.5	6/18/02 7:05	32.9
6/18/02 14:51	269.4	6/18/02 23:06	31.6	6/18/02 14:51	268.7	6/18/02 13:51	32.9
6/18/02 15:17	269.5	6/18/02 22:58	32	6/18/02 15:17	268.8	6/18/02 22:58	33.4
VA max (V)			IA MAX (A)	VB max (V)			IB MAX (A)
6/18/02 6:34	279.5	6/18/02 13:17	39.6	6/18/02 6:47	279	6/18/02 13:17	41
6/18/02 6:32	279.4	6/18/02 15:00	39.4	6/18/02 6:47	279	6/18/02 8:41	40.9
6/18/02 6:34	279.4	6/18/02 8:41	39.2	6/18/02 6:47	279	6/18/02 15:00	40.9
6/18/02 6:34	279.4	6/18/02 9:33	39.1	6/18/02 6:35	278.9	6/18/02 10:54	40.7
6/18/02 6:34	279.4	6/18/02 10:54	39	6/18/02 6:34	278.9	6/18/02 10:53	40.6
6/18/02 6:34	279.4	6/18/02 10:23	38.9	6/18/02 6:32	278.9	6/18/02 10:23	40.5
VC Min (V)			IC Min (A)		Real Power Min (Watts)		Reactive Power Min (Watts)
6/18/02 14:39	268.5	6/18/02 8:15	31.4	6/18/02 8:15	18.6	6/18/02 16:13	14.4
6/18/02 14:38	268.5	6/18/02 16:13	32	6/18/02 16:13	18.9	6/18/02 8:15	14.6
6/18/02 14:38	269.4	6/18/02 7:05	32.8	6/18/02 23:06	19.2	6/18/02 13:51	14.7
6/18/02 14:49	269.6	6/18/02 23:06	32.8	6/18/02 13:51	19.5	6/18/02 23:06	15.1
6/18/02 15:17	269.8	6/18/02 13:51	32.9	6/18/02 7:05	19.5	6/18/02 13:22	15.3
6/18/02 14:51	269.9	6/18/02 22:58	33.8	6/18/02 22:58	20	6/18/02 7:05	15.4
VC max (V)			IC Max (A)		Real Power Max (Watts)		Reactive Power Max (Watts)
6/18/02 6:34	279.8	6/18/02 15:00	41	6/18/02 15:00	24.9	6/18/02 8:41	19.2
6/18/02 6:34	279.8	6/18/02 13:17	40.9	6/18/02 13:17	24.8	6/18/02 22:23	19.1
6/18/02 6:32	279.8	6/18/02 9:33	40.8	6/18/02 9:33	24.7	6/18/02 21:32	19
6/18/02 6:32	279.7	6/18/02 8:41	40.6	6/18/02 10:54	24.7	6/18/02 22:22	19
6/18/02 6:34	279.7	6/18/02 10:54	40.6	6/18/02 8:41	24.6	6/18/02 13:17	18.9
6/18/02 6:34	279.7	6/18/02 10:53	40.4	6/18/02 10:53	24.5	6/18/02 10:54	18.9
	Apparent		Power				

	Power Min (Watts)		Factor Min (Watts)				
6/18/02 8:15	23.6	6/18/02 21:32	0.78				
6/18/02 16:13	23.8	6/18/02 22:22	0.78				
6/18/02 23:06	24.4	6/18/02 22:23	0.78				
6/18/02 13:51	24.4	6/18/02 22:07	0.78				
6/18/02 7:05	24.8	6/18/02 21:48	0.78				
6/18/02 22:58	25.5	6/18/02 7:02	0.78				
	Apparent Power Max (Watts)		Power Factor Max (Watts)				
6/18/02 8:41	31.2	6/18/02 14:39	0.82				
6/18/02 13:17	31.2	6/18/02 10:16	0.81				
6/18/02 10:54	31.1	6/18/02 14:50	0.81				
6/18/02 9:33	31	6/18/02 10:49	0.81				
6/18/02 15:00	30.9	6/18/02 14:38	0.81				
6/18/02 9:17	30.8	6/18/02 10:49	0.81				
Downstream of UPS (480V)							
VA Min			IA Min	VB Min			IB Min
6/20/02 14:38	277.6	6/20/02 12:33	23.9	6/20/02 13:41	279.7	6/20/02 14:38	21.2
6/20/02 8:11	277.7	6/20/02 14:38	23.9	6/20/02 14:38	279.8	6/20/02 7:56	21.3
6/20/02 16:25	277.7	6/20/02 13:13	24	6/20/02 8:11	279.9	6/20/02 16:10	21.3
6/20/02 13:41	277.9	6/20/02 13:14	24	6/20/02 16:25	279.9	6/20/02 13:24	21.3
6/20/02 12:33	278.1	6/20/02 13:15	24	6/20/02 12:33	280.1	6/20/02 7:55	21.3
6/20/02 9:49	278.3	6/20/02 13:16	24	6/20/02 14:42	280.4	6/20/02 16:10	21.3
VA max			IA MAX	VB max			IB MAX
6/20/02 7:22	279.3	6/21/02 0:00	24.9	6/20/02 7:22	281.5	6/20/02 23:59	22.3
6/20/02 11:38	279.3	6/20/02 23:26	24.8	6/20/02 15:36	281.5	6/20/02 23:26	22.2
6/20/02 12:20	279.3	6/20/02 6:43	24.8	6/20/02 10:05	281.4	6/20/02 21:03	22.2
6/20/02 15:36	279.3	6/20/02 10:44	24.8	6/20/02 14:17	281.4	6/21/02 0:00	22.2
6/20/02 23:37	279.3	6/20/02 10:57	24.8	6/20/02 11:38	281.4	6/20/02 23:26	22.2
6/20/02 8:18	279.2	6/20/02 14:58	24.8	6/20/02 19:03	281.3	6/20/02 23:59	22.2
VC Min			IC Min		Real Power Min		Reactive Power Min
6/20/02 14:38	274.1	6/20/02 9:33	21.4	6/20/02 6:43	-12.6	6/20/02 13:27	18
6/20/02 13:41	274	6/20/02 17:47	21.4	6/20/02 14:58	-12.6	6/20/02 13:20	17.9
6/20/02 8:11	273.9	6/20/02 8:07	21.4	6/20/02 21:03	-12.6	6/20/02 13:20	17.7
6/20/02 16:25	272	6/20/02 16:22	21.4	6/21/02 0:00	-12.6	6/20/02 13:16	17.6
6/20/02 12:33	271	6/20/02 12:33	21.4	6/21/02 0:00	-12.6	6/20/02 13:27	17.5
6/20/02 14:42	271	6/20/02 13:41	21.4	6/20/02 20:38	-12.5	6/20/02 13:20	17.5
VC max			IC Max		Real Power Max		Reactive Power Max

6/20/02 7:22	277.1	6/20/02 20:38	22.1	6/20/02 14:38	-12.1	6/20/02 23:40	20
6/20/02 15:36	276.9	6/20/02 6:43	22.1	6/20/02 12:33	-12.1	6/20/02 22:22	19.9
6/20/02 10:05	276.8	6/20/02 14:58	22.1	6/20/02 13:41	-12.1	6/20/02 22:35	19.9
6/20/02 11:38	276.7	6/20/02 14:20	22.1	6/20/02 13:13	-12.2	6/20/02 22:01	19.9
6/20/02 10:54	275.1	6/20/02 21:03	22.1	6/20/02 13:13	-12.2	6/20/02 18:59	19.9
6/20/02 9:46	275.1	6/21/02 0:00	22.1	6/20/02 13:14	-12.2	6/20/02 18:30	19.9
	Apparent Power Min		Power Factor Min				
6/20/02 13:41	12.1	6/21/02 0:00	-1				
6/20/02 12:33	12.1	6/20/02 21:04	-1				
6/20/02 14:38	12.1	6/21/02 0:00	-1				
6/20/02 8:11	12.2	6/21/02 0:00	-1				
6/20/02 16:25	12.2	6/20/02 8:13	-1				
6/20/02 7:56	12.2	6/20/02 16:27	-1				
	Apparent Power Max		Power Factor Max				
6/21/02 0:00	12.6	6/21/02 0:00	-1				
6/20/02 21:04	12.6	6/20/02 21:04	-1				
6/21/02 0:00	12.6	6/21/02 0:00	-1				
6/21/02 0:00	12.6	6/21/02 0:00	-1				
6/20/02 8:13	12.6	6/20/02 8:13	-1				
6/20/02 16:27	12.6	6/20/02 16:27	-1				
PDU #1 (208V)							
VA Min			IA Min	VB Min			IB Min
6/21/02 10:48	116.2	6/21/02 15:00	1.76	6/21/02 10:48	116	6/21/02 16:11	3.75
6/21/02 10:48	116.5	6/21/02 15:50	1.85	6/21/02 10:48	116.2	6/21/02 22:00	3.77
6/21/02 11:47	116.7	6/21/02 15:54	1.87	6/21/02 11:47	116.6	6/21/02 18:02	3.82
6/21/02 13:51	116.8	6/21/02 7:25	1.94	6/21/02 13:51	116.8	6/21/02 23:46	3.83
6/21/02 11:32	117	6/21/02 8:45	1.94	6/21/02 11:32	116.8	6/21/02 22:02	3.83
6/21/02 11:02	117.2	6/21/02 8:45	1.94	6/21/02 16:48	117	6/21/02 22:02	3.84
VA max			IA MAX	VB max			IB MAX
6/21/02 6:32	121.8	6/21/02 14:16	34.1	6/21/02 6:32	121.9	6/21/02 20:36	21.1
6/21/02 6:32	121.8	6/21/02 13:19	32.5	6/21/02 6:32	121.9	6/21/02 10:52	20.8
6/21/02 6:32	121.8	6/21/02 13:48	31.8	6/21/02 6:32	121.9	6/21/02 8:21	19.5
6/21/02 6:32	121.8	6/21/02 14:14	31.5	6/21/02 6:32	121.9	6/21/02 22:55	19.2
6/21/02 6:32	121.8	6/21/02 7:40	31.3	6/21/02 6:32	121.8	6/21/02 14:13	18.8
6/21/02 6:32	121.7	6/21/02 18:59	30.9	6/21/02 6:32	121.8	6/21/02 22:38	18.6
VC Min			IC Min		Real Power Min		Reactive Power Min
6/21/02 10:48	116	6/21/02 15:50	8.6	6/21/02 15:35	1.31	6/21/02 18:04	-215.4
6/21/02 10:48	116.2	6/21/02 11:38	8.61	6/21/02 15:50	1.31	6/21/02 18:02	-180.6
6/21/02 11:47	116.4	6/21/02 11:41	8.61	6/21/02 15:54	1.32	6/21/02 23:54	-33.9

6/21/02 11:32	116.6	6/21/02 11:43	8.61	6/21/02 15:54	1.32	6/21/02 11:16	49.3
6/21/02 13:51	116.6	6/21/02 12:03	8.62	6/21/02 15:38	1.32	6/21/02 16:33	57.1
6/21/02 16:48	116.9	6/21/02 11:38	8.62	6/21/02 15:54	1.32	6/21/02 15:18	75.5
VC max			IC Max		Real Power Max		Reactive Power Max
6/21/02 6:32	121.7	6/21/02 23:17	49.5	6/21/02 20:37	7.57	6/21/02 7:56	1472.7
6/21/02 6:32	121.7	6/21/02 17:56	47.2	6/21/02 11:09	7.1	6/21/02 21:22	1397.8
6/21/02 6:32	121.7	6/21/02 21:25	44.9	6/21/02 17:56	6.8	6/21/02 23:17	1307.2
6/21/02 6:32	121.7	6/21/02 18:03	44.4	6/21/02 20:40	6.77	6/21/02 16:40	1264.3
6/21/02 6:32	121.7	6/21/02 11:09	44.2	6/21/02 23:16	6.73	6/21/02 16:45	1254.1
6/21/02 6:32	121.7	6/21/02 11:15	42.6	6/21/02 20:36	6.68	6/21/02 18:36	1250.4
	Apparent Power Min		Power Factor Min				
6/21/02 15:50	1.41	6/21/02 20:49	0.88				
6/21/02 15:52	1.42	6/21/02 7:56	0.89				
6/21/02 15:52	1.42	6/21/02 22:24	0.89				
6/21/02 15:52	1.42	6/21/02 9:57	0.89				
6/21/02 15:35	1.42	6/21/02 17:36	0.89				
6/21/02 15:52	1.42	6/21/02 7:26	0.89				
	Apparent Power Max		Power Factor Max				
6/21/02 20:37	7.6	6/21/02 20:37	1				
6/21/02 11:09	7.2	6/21/02 20:40	1				
6/21/02 17:56	6.87	6/21/02 23:20	1				
6/21/02 20:40	6.79	6/21/02 20:37	1				
6/21/02 20:36	6.77	6/21/02 23:12	1				
6/21/02 23:16	6.76	6/21/02 20:37	1				
PDU #2							
VA Min			IA Min	VB Min			IB Min
6/19/02 6:23	120.7	6/19/02 11:49	54.9	6/19/02 13:01	119.9	6/19/02 11:49	47.5
6/19/02 13:01	120.8	6/19/02 16:04	55.1	6/19/02 11:49	119.9	6/19/02 18:51	47.7
6/19/02 11:49	120.9	6/19/02 13:01	55.1	6/19/02 6:23	120	6/19/02 19:55	47.7
6/19/02 6:31	121	6/19/02 7:45	55.2	6/19/02 15:41	120.2	6/19/02 19:59	47.7
6/19/02 6:31	121	6/19/02 15:30	55.2	6/19/02 8:11	120.2	6/19/02 19:50	47.7
6/19/02 6:31	121	6/19/02 8:45	55.2	6/19/02 9:46	120.2	6/19/02 19:36	47.8
VA max			IA MAX	VB max			IB MAX
6/19/02 6:55	121.5	6/19/02 10:46	56.9	6/19/02 7:45	120.8	6/19/02 10:16	50
6/19/02 7:45	121.5	6/19/02 10:46	56.9	6/19/02 7:47	120.7	6/19/02 10:17	50
6/19/02 13:20	121.5	6/19/02 19:06	56.9	6/19/02 6:55	120.6	6/19/02 8:49	49.8
6/19/02 13:38	121.5	6/19/02 8:53	56.9	6/19/02 21:02	120.6	6/19/02 10:17	49.8
6/19/02 15:55	121.5	6/19/02 15:59	56.8	6/19/02 13:20	120.6	6/19/02 10:07	49.8
6/19/02 6:46	121.4	6/19/02 10:49	56.8	6/19/02 23:16	120.6	6/19/02 9:31	49.8

VC Min			IC Min		Real Power Min		Reactive Power Min
6/19/02 13:01	118.9	6/19/02 7:45	61.4	6/19/02 11:49	17.1	6/19/02 10:38	-3.32
6/19/02 11:49	118.9	6/19/02 7:49	61.5	6/19/02 19:50	17.2	6/19/02 16:55	-3.32
6/19/02 6:23	119	6/19/02 7:44	61.5	6/19/02 16:05	17.2	6/19/02 12:52	-3.32
6/19/02 14:36	119.2	6/19/02 6:23	61.5	6/19/02 17:04	17.2	6/19/02 22:41	-3.31
6/19/02 12:14	119.2	6/19/02 23:18	61.5	6/19/02 19:49	17.2	6/19/02 19:44	-3.31
6/19/02 13:48	119.2	6/19/02 7:44	61.6	6/19/02 16:46	17.2	6/19/02 18:08	-3.31
VC max			IC Max		Real Power Max		Reactive Power Max
6/19/02 6:55	119.8	6/19/02 9:47	64.2	6/19/02 15:59	17.7	6/19/02 6:23	-3.22
6/19/02 7:45	119.8	6/19/02 9:51	64.2	6/19/02 10:03	17.7	6/19/02 7:46	-3.23
6/19/02 13:20	119.7	6/19/02 9:51	64.2	6/19/02 9:47	17.6	6/19/02 11:49	-3.23
6/19/02 7:03	119.7	6/19/02 9:51	64.1	6/19/02 9:51	17.6	6/19/02 17:14	-3.24
6/19/02 7:47	119.7	6/19/02 8:04	64.1	6/19/02 9:51	17.6	6/19/02 18:17	-3.24
6/19/02 10:17	119.6	6/19/02 9:45	64.1	6/19/02 9:51	17.6	6/19/02 18:19	-3.24
	Apparent Power Min		Power Factor Min		Apparent Power Max		Power Factor Max
6/19/02 11:49	17.4	6/19/02 15:59	0.98	6/19/02 15:59	18	6/19/02 15:59	0.98
6/19/02 6:23	17.5	6/19/02 10:03	0.98	6/19/02 10:03	18	6/19/02 10:03	0.98
6/19/02 19:50	17.5	6/19/02 10:02	0.98	6/19/02 10:02	18	6/19/02 10:02	0.98
6/19/02 16:07	17.5	6/19/02 15:41	0.98	6/19/02 15:41	17.9	6/19/02 15:41	0.98
6/19/02 19:50	17.5	6/19/02 8:12	0.98	6/19/02 8:12	17.9	6/19/02 8:12	0.98
6/19/02 19:50	17.5	6/19/02 9:56	0.98	6/19/02 9:56	17.9	6/19/02 9:56	0.98