UNIVERSITY OF ALBERTA

POWER SYSTEM MODELING OF A COMPUTER SYSTEM

by

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DEDICATIONS

To my loving wife Tara, for all her patience and understanding in helping me to fulfill my goals.

To my family for giving me the strength and courage to venture into the world.

POWER SYSTEM MODELING OF A COMPUTER SYSTEM

ABSTRACT

Various computer workstation configurations and test patterns are used to collect a comprehensive and controlled set of data from a computer laboratory on the first floor of the Cameron Library at the University of Alberta A power system study is completed on this computer laboratory. The computers in the laboratory are not protected by an uninterruptible power supply, so a Dranetz 658 Powerline Monitor was used to determine the effects of the power system on the computer laboratory. Using this data, a set of models is established for an individual computer, and a group of computers, to illustrate these effects. The results of the predictive models are used to make decisions as to the necessity of computer protection, isolation or both. Circuit models are used to illustrate the interaction of a power system with an individual computer and a computer laboratory consisting of many computers.

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GLOSSARY OF TERMS

When possible, definitions are referred to a bibliographic source using a superscript.

AC [3]**:**	Alternating Current. AC current is a waveform which regularly reverses in positive and negative directions. The normal electrical power alternates 60 times per second (60 Hz.).
Ampere [3]**:**	A unit of electrical current or rate of flow of electrons. One volt across one ohm of resistance causes current flow of one ampere. A flow of one coulomb per second equals one ampere.
ANSI:	American National Standards Institute
Apparent Power [3]**:**	The product of voltage and current in a circuit.
Attenuation [3]**:**	The reduction of a signal from one point to another. For an electrical surge, attenuation refers to the reduction of an incoming surge by a limiter (attenuator). Wire resistance, arrestors, and power conditioners attenuate surges to varying degrees.
AWG [3]**:**	American Wire Gauge. This term refers to the US standard for wire size.
Balanced Load [3]**:**	An alternating current power system consisting of more than two current-carrying conductors in which these conductors all carry the same current.
Blackout [3]**:**	Total loss of commercial power.
Brownout [3]**:**	A reduction of voltage by a utility in response to a power demand in excess of its generation capability. Nominal reductions are 3, 5, or 8 percent.
Capacitance [18]**:**	Capacitance is that property of a system of dielectrics and conductors that allows for the storage of

electrically separated charges when a potential difference exists between the conductors.

CEA: Canadian Electrical Association

CSA: Canadian Standards Association

DC [3]: Direct Current. Current which flows in only one direction.

Dropout [3]: A discrete voltage loss. A voltage sag (complete or partial) for a very short period of time (milliseconds) constitutes a dropout.

Frequency [3]: The number of complete cycles of sinusoidal variation per unit time. For AC power lines, the most widely used frequencies are 60 and 50 hertz (Hz.).

Ground [3]: A conducting connection, whether intentional or accidental, between an electrical circuit or equipment and the earth, or to some conducting body that serves in place of the earth.

Harmonic [3]: A sinusoidal component of an AC voltage that is a multiple of the fundamental waveform frequency.

Harmonic Distortion [3]: The presence of harmonics which change an AC waveform from sinusoidal to complex.

IEEE: Institute of Electrical and Electronic Engineers

Inductance [18]: Represents the propensity of a conductor to store energy in an associated magnetic field.

LC Circuit [3]: An electrical network containing both inductive and capacitive elements.

Linear Load [3]: Those electrical loads in which the impedance is constant regardless of the voltage, so that if voltage is sinusoidal the current drawn is also sinusoidal.

Load [3]: The driven device that uses the power supplied form the source.

NEC: National Electrical Code

Nominal Voltage [18]: Actual line voltage; may vary by location and by time of day as loads change. A 120 V nominal voltage may vary by 10% or more.

Nonlinear Load [3]: Electrical loads in which the instantaneous current is not proportional to the instantaneous voltage, or, effectively, the load impedance varies with voltage.

Outage [3]: An outage is a long term power interruption. From the utility perspective, an outage occurs when a component of the distribution system is not available to provide its normal function (i.e., the generator cannot supply power.) Normally, utility companies do not include short power interruptions (grid switching) in their classification of outage history and also may only count power interruptions with a duration longer than 1 to 5 minutes.

Overvoltage [3]: A voltage greater than the rating of a device or component. Normally overvoltage refers to long term events (several AC cycles and longer). The term can also apply to transients and surges.

Power [18]: Fundamental power is the rate of energy transfer or consumption. Power is equal to voltage times current (times displacement power factor in AC circuits.) Units are Watts.

(Displacement) Power Factor [13]: The displacement component of power factor; the ratio of the active power of the fundamental wave, in Watts, to the apparent power of the fundamental wave in Volt-Amperes.

(True) Power Factor [18]: The true power factor is the ratio of Watts to volt amperes in an alternating current setting including all calculable harmonics.

Reactance [18]: The opposition to the flow of alternating current by the inductance or capacitance of a component or circuit.

Resistance [18]: A physical property of a circuit that impedes the portion of alternating current which is directly in phase with its associated voltage, and restricts the flow of direct current.

Resonance [18]: Resonance of a circuit or system refers to the enhancement of its response to a periodic excitation. The frequency at which the inductive and capacitive components of an electrical circuit have equal reactance is the resonant frequency. Resonance occurs when a harmonic frequency coincides with the resonant frequency, resulting in a very high currents and voltages in the circuit.

RLC Circuit: An electrical network consisting of resistive, inductive, and capacitive elements.

RMS: RMS is the root mean square of a magnitude. It is usually referenced to power, voltage and current.

Sag [3]: A reduction in a voltage envelope. The duration is usually from one cycle to a few seconds. Sags are usually caused by fault clearing or heavy load startup.

Surge [14]: Momentary overvoltage typically above 105% V RMS . It lasts from one cycle to a few seconds.

Swell [14]: Increased voltage usually resulting from faults on a system with subsequent fuse or high-speed circuit breaker action and reclosing. Usually seen on unloaded phases. Typically above 105% V RMS . It lasts from one cycle to a few seconds.

Total Harmonic Distortion (THD) [18]: THD is the sq. root percentage of the sum of squares of all RMS magnitudes of harmonics except the first harmonic divided by the square of the RMS magnitude of the first harmonic.

Transient [3]: A high amplitude, short duration impulse superimposed on the normal voltage or current.

Undervoltage [3]: Negative change in amplitude of a voltage.

UPS [3]: Uninterruptible Power Source.

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Chapter 1

INTRODUCTION

Computer systems play an important role in individual and commercial facilities. With so many facilities relying on these machines, their correct and continuous operation is necessary. The operator of these facilities should be aware of the effects that computers have on their power supply and of the impact that their power supply has on the operation of their computers' processes. As a result, power system reliability has become an integral part of design and layout of these systems. It is important to know that a system will not fail and that measures can be taken to ensure this. However, to what extent should companies protect these systems from power supply anomalies? Do these systems pollute their electrical environments and affect other electrical devices connected to the same power system? Can computers create problems in a power system, if so, should measures be taken to deal with these problems? Do other devices on the power systems cause the power required for the computers to be less than the specified minimum standards? These questions can be answered by modeling a computer system with respect to its power system operating characteristics. The set of models, based on information gathered from power line monitoring of a computer laboratory power supply will be presented in this thesis.

1.1 Project History:

This thesis was implemented, based on new questions and ideas that arose during a previous study 'Fluorescent Ballast Study' [10] on the lighting system of the Cameron library on the University of Alberta Campus. Fluorescent lighting ballast failures had increased dramatically within the Cameron library and a solution was sought to reduce these failures. A Dranetz 658 Powerline Monitor was used to collect data from various electrical panels within the library. This information was used to resolve problems associated with the lighting system. Results of the study showed increased harmonics present in the voltage and current waveforms of the power supply. This power supply is also connected to the power supply for the main computer laboratory within the Cameron Library. Some concerns regarding power fluctuations within the main computer laboratory were raised (i.e., CSA standards summarized in Tables 1 and 2). Do these power fluctuations cause computer terminals to fail? Unfortunately, the scope of the lighting project did not include detailed power fluctuation analysis, or any other question, concerning the computers in the laboratory. With these concerns in mind, an idea for a new study, based entirely on the computers and their interaction with their power supply, was developed. Numerous studies such as 'Predicting Net Harmonic Currents Produced by Large Numbers of Distributed Single Phase Computer Loads' [19] have been completed dealing with the effects of power systems on power supplies but none have shown these effects as they translate to a computer containing such power supplies.

1.2 Power Quality:

Power quality as defined in the 'Power Quality Reference Guide' [18] by CEA as the degree to which both the utilization and delivery of electric power affects the performance of electrical equipment. From a consumer perspective, power quality is more simplistic. The power being delivered is considered to be "perfect" so long as it is available. If power is interrupted, it is considered to have failed. More complex methods of defining power quality are required when doing a quantitative analysis. Power quality involves six major areas: Power Factor, Power System Disturbances, Frequency, Load Balancing, Harmonics, and Reliability (including stability). Some of the significant power quality issues are discussed in this thesis to help understand the process of developing a model for the interaction of computers with their power system.

Displacement Power Factor is a measure of the efficiency of the power being delivered to a facility. This factor is a direct result of the types of equipment using power and any in-line modifications made to improve the power factor.

Power system disturbances are anomalies in the voltage and current waveforms that occur in a power system. These can range from a major black-out (total power failure) to a minor voltage sag (drop in voltage just below CSA, ANSI, NEC or other commonly accepted standards for normal operation of a power system). Other common types of power system disturbances include voltage swells- minor increase in voltage just above commonly accepted standards (i.e. 125V), voltage surge- major increase in voltage above commonly accepted standards for a short period of time, usually less than one half cycle, and brown-out- major decrease in voltage below commonly accepted standards. These power system disturbances create distortions in both voltage and current waveforms. CSA RMS voltage standards are summarized in Tables 1 and 2; provided by Electrical Engineering 421 Notes [4] Information regarding ANSI, NEC or other commonly accepted standards is available through organizations such as the IEEE.

Table 1: CSA:CAN3-235-83 (service entrances)

NOMINAL SYSTEM VOLTAGES	<<<<	EXTREME OPERATING CONDITIONS < NORMAL OPERATING CONDITIONS >		>>>>
Single-Phase				
120/240	106/212	110 / 220	125 / 250	127/254
240	212	220	250	254
480	424	440	500	508
600	530	550	625	635
Three-Phase 4 - Conductor				
120 / 208 Y	110 / 190	112 / 194	125 / 216	127 / 220
240 / 416 Y	220 / 380	224 / 388	250 / 432	254 / 440
277 / 480 Y	245 / 424	254 / 440	288 / 500	293 /508
347 / 600 Y	306 / 530	318 / 550	360 / 625	367 / 635
Three-Phase 3- Conductor				
240	212	220	250	254
480	424	440	500	508
600	530	550	625	635

Table 2: CSA: CAN3-C235-83 (utilization points)

NOMINAL SYSTEM VOLTAGES	<<<<	EXTREME OPERATING CONDITIONS < NORMAL OPERATING CONDITIONS >		>>>>
Single-Phase				
120/240	104/208	108 / 216	125 / 250	127/254
240	208	216	250	254
480	416	432	500	508
600	520	540	625	635
Three-Phase 4 - Conductor				
120 / 208 Y	108 / 187	110 / 190	125 / 216	127 / 220
240 / 416 Y	216 / 374	220 / 380	250 / 432	254 / 440
277 / 480 Y	240 / 416	250 / 432	288 / 500	293 /508
347 / 600 Y	300 / 520	312 / 540	360 / 625	367 / 635
Three-Phase 3- Conductor				
240	208	216	250	254
480	416	432	500	508
600	520	540	625	635

Frequency describes the number of times a periodic sinusoidal voltage or current waveform repeats itself within a second. The North American Standard for power supply is sixty times per second or 60 Hz.

Balancing loads is accomplished by having the same magnitude of current drawn from each of the three phases of a three phase power system by utilizing identical loads on each phase. When identical loads are not available, balancing loads becomes more difficult. The combination of the three phase impedances should be arranged such that the neutral current is kept to a minimum. A three phase power system supplies three sinusoidal waveforms each 120 degrees apart from each other. This is a common power supply characteristic for the delivery of commercially available energy within North America.

Distortions of the sinusoidal voltage and current waveforms can be modeled by harmonic analysis. If the distortion repeats over time (i.e. periodic) it can be described by a Fourier Series. A Fourier Series is a mathematical procedure used to sum frequency multiples of the fundamental sinusoid. Harmonics are exact numerical multiples of the original sinusoidal waveform. The first harmonic (i.e. the fundamental) is located at the original frequency of 60 Hz. The second harmonic is 120 Hz; the third harmonic is 180 Hz. Any periodic voltage or current waveform distortion based on a periodic pattern can be modeled using harmonics.

Power factor and harmonics are rarely considered within the reliability parameters, as it requires specialized monitoring instruments not available to most people. This leads to a simpler and more common method of defining reliability for power quality. Any company purchasing power generally considers the percentage of time that power is delivered in a given time period to be power delivery reliability. In essence, companies are only impacted when they get either no power at all or their processes have been interrupted by power supply anomalies. Although this perspective is valid, it does not deal with aspects of power quality that are necessary for the proper functioning of a computer. However, reliability as seen from a power delivery perspective deals with the overall quality of the power being supplied. One simple method of defining power system performance (i.e. reliability) uses the percentage of time that the power system supplies power within the voltage tolerance levels indicated in the standard [CSA-CAN3-C235-83]. Power companies are expected to deliver power at 60 Hz +/- .02 Hz. The magnitude of voltage and current depends on the types of loads connected to a power system. Most household plugs deliver effectively 120 V_{RMS} +/- ~6 Volts and up to 200 Amps. There is an expectation that power companies provide distortion-free voltage waveforms. Distortion may be caused by individual users of power using loads that distort the voltage and current waveforms supplied. These distortions are discussed in the following chapters.

1.3 Site Description:

The location used for monitoring the power system of a computer laboratory was the computer laboratory on the first floor of Cameron Library at the University of Alberta. The laboratory consists of thirty computer terminals, one server terminal and one laser printer. Each terminal is connected via a bus to the power system. Each bus connects to a single phase voltage supply on an electrical power panel. Three terminals are connected to each bus in a parallel manner. Terminals are also connected via a modem cable to a network hub. Each terminal is connected to this hub in a parallel fashion. The computer laboratory physical layout can be seen in Figure 1. This figure is a cropped portion of the blueprints to the first floor of Cameron library. The blueprints provide a pictorial method of describing how the computer laboratory is laid out and where its associated power supply panel is located. Figure 2 illustrates the computer terminals set up with respect to powerline monitoring from the computer power supply panel. The power supply panel setup showing the association of each wire to its corresponding load can be seen in Figure 3. Some phase connections such as 11C 'receptacle' are used for plugging in miscellaneous devices temporarily used in the computer laboratory.

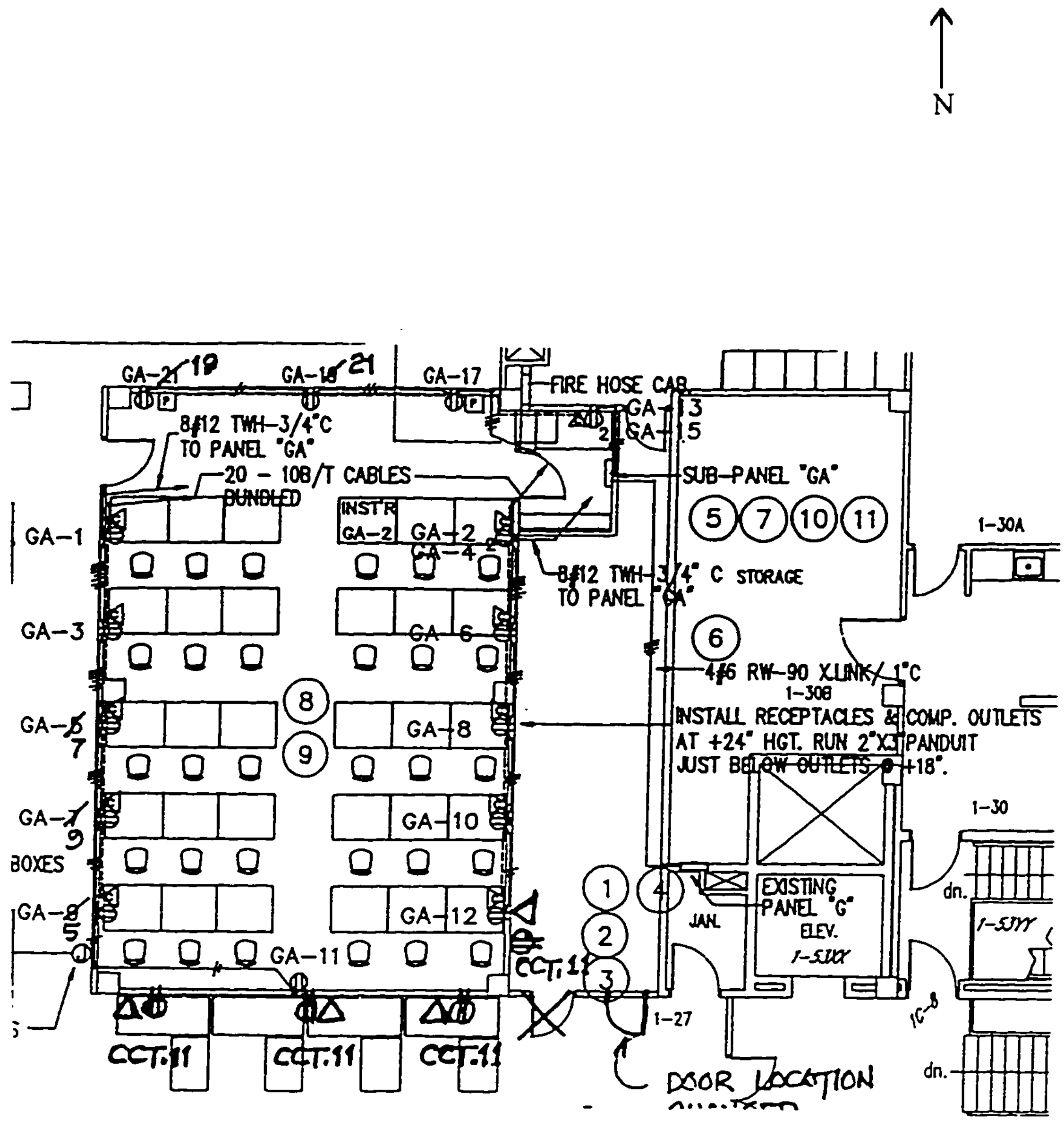
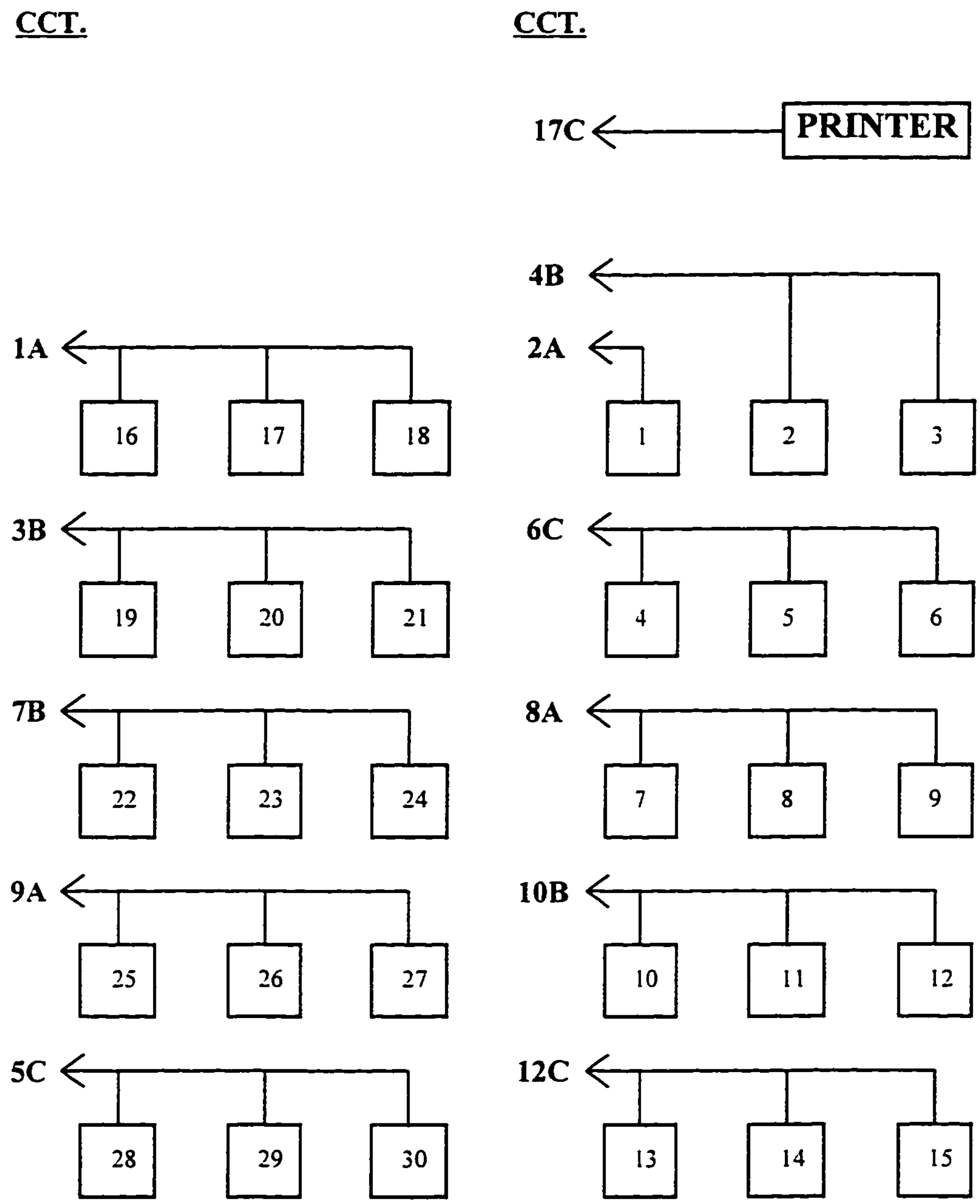


Figure 1: Computer laboratory physical layout



Legend

i_a = circuit breaker "i" on "A" phase

i_b = circuit breaker "i" on "B" phase

i_c = circuit breaker "i" on "C" phase

Figure 2: Computer laboratory power supply setup

Westinghouse Canada Inc.			
Panel GA rm. 1-20G			
Circuit	**PH**	**ABC PH**	**Circuit**
row #1 west	1A	2A	row #1 east
row #2 west	3B	4B	row #1 east
row #5 west	5C	6C	row #2 east
row #4 west	7A	8A	row #3 east
row #3 west	9B	10B	row #4 east
receptacle	11C	12C	row #5 east
file server	13A	14A	receptacle south
file server	15B	16B	power pole south
printer	17C	18C	power pole south
projector	19A	20A	s.w. from 1-20G
printer	21B	22B	outside 1-20G
file server ex. fan	23C	24C	

Figure 3: Computer laboratory power supply panel

1.4 Purpose:

Once a computer is installed and operational, it is expected to perform without failure. If the computer is placed in an environment to which it is not suited or designed for, it may fail prematurely. Such environments include dirty working conditions, wet/humid environments and connections to power systems where the delivered power is not what the computer manufacturer expected. If a system is placed in dirty or wet areas special air-filtering/drying can be used to circumvent problems. However, how does one know if the computer system is connected to a power system containing undesirable power problems? Are there ways of predicting the possibility of problems?

By modeling the interaction of a computer system with its power supply, one may make an educated hypothesis of the relevance and necessity of protecting the computer system from undesirable power supply. Information gathered from monitoring the computer laboratory in Cameron library enables the development of such a model.

1.5 Scope:

The objective of the thesis is to develop a composite model of a computer system using a computer laboratory with thirty computers as a basis for data collection. Circuit models are used to describe how power systems affect computers receiving power from the power system. A simple single line diagram of the computer lab can be seen in Figure 2. Power supply input was monitored for the entire lab over a specific period of time. A group of three terminals is then monitored for power input over the same time set as previously determined. A group of two terminals and a single terminal were also monitored in the same manner. Different terminals can be used to repeat the test to maintain a level of control. Analyzing this data using reliability, statistics, and mathematical modeling enables the development of a model for the interaction of a computer and its power environment. This model is limited to a maximum of thirty computer terminals as data for a greater number of terminals is unavailable and is considered beyond the scope of this thesis.

Chapter 2

DRANETZ 658 POWERLINE MONITOR AND HARMONICS

2.1 Dranetz 658 Powerline Monitor:

To monitor a system for voltage and current harmonics, a powerline monitor is required. One such device is the Dranetz 658 Powerline Monitor which connects directly to the electrical panel associated with the area requiring the powerline monitoring. The powerline monitor records daily voltage and current waveforms and captures any events outside specified tolerances. System monitoring includes individual harmonics (up to the 50th), total harmonic distortion, frequency, amplitudes and waveforms. This information can be stored on 3.5" floppy disks and processed in the Dranetz program available for installation on most types of computers. Using these data, circuit models can be developed illustrating a computers' effects on a power system's voltage and current characteristics. These models can be used to extrapolate data to include multiple computers at individual locations.

2.2 Dranetz 658 Powerline Monitor Characteristics:

A Dranetz 658 powerline monitor can record up to 4 separate and distinct sets of waveforms, simultaneously, over long periods of time. For example, one can monitor two phases of current and two phases of voltage at the same time. To represent a complete set of connections on a three phase system, two separate sets of connections are necessary to view all eight possible monitoring combinations. The three phases require voltage and current monitoring; and the recording of neutral to ground voltage and neutral current. Each channel of the powerline monitor can be set for various tolerance levels, each independent of the other three channels. The monitor collects data on anomalies, line harmonics, waveforms, and comparisons between different inputs. All information collected is time-referenced to help reveal operational patterns within a power system. An example of such an operational pattern would be the daily startup of a specific piece of equipment which creates a power system problem elsewhere in the power system. By correlating the time of a power system problem and the daily usage of power system connected devices, possible origins of the problem can be identified and solutions to many concerns can be readily identified.

2.3 Dranetz 658 Powerline Monitor Setup:

Available settings for the Dranetz 658 powerline monitor include high and low limits for voltage and current, sensitivity of measurement, wave setting, impulse magnitude, and frequency deviation. The settings can be changed for each channel separately in order to monitor four different types of waveforms simultaneously. Information collected by the Dranetz 658 powerline monitor is presented initially as a waveform. Information concerning harmonics can be shown in graphical and tabular format as well.

2.4 Sample Dranetz output waveform:

Sample output voltage and current waveforms from the Dranetz 658 powerline monitor measuring the power supply panel for the Cameron Library computer laboratory in a single computer terminal configuration (See Chapter 3 for details) can be seen in Figures 4 and 5. Figure 4 shows the voltage output waveform of a single computer terminal power supply. Figure 5 shows the current output waveform of a single computer terminal power supply. For each waveform recorded by the Dranetz 658 Powerline Monitor, there is also a table of harmonic data and a summary bar graph. Samples of these can be seen in Table 3 and Figure 13 in Section 2.6.

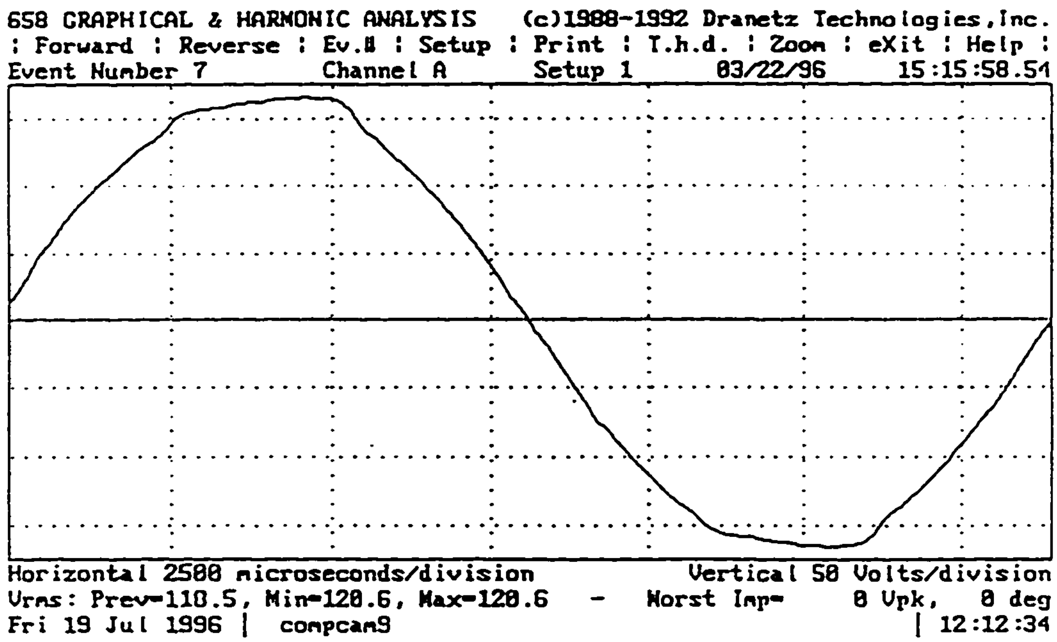


Figure 4: Sample Dranetz output voltage waveform

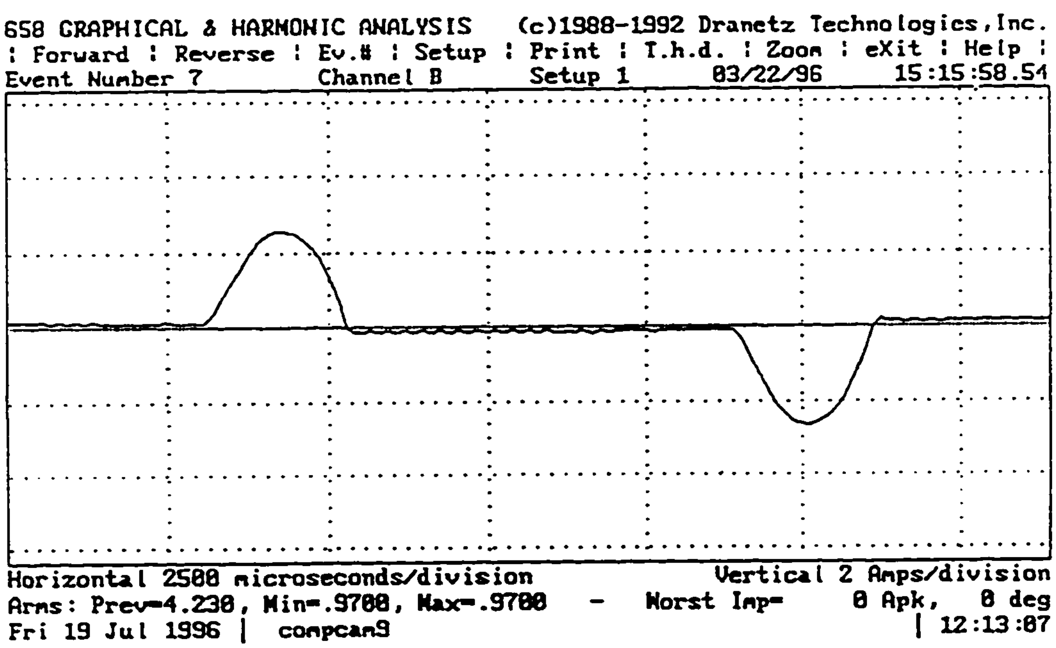


Figure 5: Sample Dranetz output current waveform

2.5 Definition of Harmonics:

What are harmonics? As defined by the Power Quality Reference Guide [18], harmonics are sinusoidal currents and voltages with frequencies that are integral multiples of the fundamental power line frequency which is 60 Hz in North America. Harmonics combine with the fundamental sinusoidal waveform to produce a distorted waveform. Each harmonic present is given a number directly related to the ratio of its frequency with respect to the fundamental frequency. For example, the second harmonic is located at 120 Hz which is exactly twice the fundamental frequency of 60 Hz. The third harmonic is located at 180 Hz which is exactly three times the fundamental frequency. All subsequent harmonics follows the same pattern.

2.6 Mathematical Representation:

A periodic waveform can be described by the complete set of harmonics including the fundamental using a Fourier Series. A Fourier series is a mathematical procedure used to sum frequency multiples of the original sinusoid to represent a particular waveshape. Given that the sinusoid repeats over a time period 2π/ω (where ω = 2πf rad/sec), the Fourier series is:

$$f(t) = \sum_{n=0}^{\infty} (a_n \cos(nwt) + b_n \sin(nwt)) \qquad (2\text{-}1)$$

Extracting constant a_0 from equation (2-1) yields equation (2-2).

$$f(t) = a_0 + \sum_{n=1}^{\infty} (a_n \cos(nwt) + (b_n \sin(nwt)) \qquad (2\text{-}2)$$

Where:

$$a_0 = \frac{w}{2\pi} \int_{-\pi/w}^{\pi/w} f(t)dt \qquad (2\text{-}3)$$

$$a_n = \frac{w}{\pi} \int_{-\pi/w}^{\pi/w} f(t)\cos(nwt)dt \qquad (2\text{-}4)$$

$$b_n = \frac{w}{\pi} \int_{-\pi/w}^{\pi/w} f(t)\sin(nwt)dt \qquad (2\text{-}5)$$

$$g(t) = \sqrt{a_n^2 + b_n^2}\cos(wt + \psi) \qquad (2\text{-}6)$$

Where $\psi = -\phi_n$

$$\phi_n = \tan^{-1}\left(\frac{b_n}{a_n} \right) \qquad \text{(Pythagorean' theorem)}$$

$\omega = 2\pi f$ (rad/sec)

f= frequency of the supply voltage (Hz)

n= harmonic order of signal

t= time in seconds (s)

a_n=n^{th} Fourier coefficient of the cosine term

b_n=n^{th} Fourier coefficient of the sine term

2.7 1/N theorem and Resonance:

The 1/N theorem, expressed mathematically in equation 2-7, constrains the magnitude of non-resonance harmonics with respect to their harmonic number. Each harmonic is expressed as a percentage of the magnitude of the fundamental divided by its harmonic number. For example, the fifth harmonic is no greater than 100/5 or 20% of the fundamental harmonic. Using this theory, these numbers are maximum possible values and they are usually much smaller. However, the percentage of the harmonics can rise above the calculated maximum if two or more loads are constructively producing similar harmonics or if there is harmonic resonance present within the site.

$$H_n = \frac{|Fundamental Harmonic|}{n} \qquad (2\text{-}7)$$

where, H_n= the magnitude of the n^{th} harmonic

n= the harmonic order

|Fundamental Harmonic| = the magnitude of the fundamental harmonic

Harmonic resonance is a phenomenon seen as a capacitive short circuit for harmonic current to flow. It can be either parallel or series. This capacitance is usually due to power factor correction capacitor banks in place either at the load (parallel) or at the end of the distribution feeder (series). The capacitors provide a lower impedance path for the higher frequency harmonics. Capacitance and inductance are present in any power system. However, their magnitude is often negligible with respect to any added capacitance or inductance such as power factor correction capacitors. Using various methods, resonance points can be calculated. If these points are approximately equal to the frequency of a harmonic present, resonance can occur. During resonance, the affected harmonics increase significantly in magnitude. Application of the 1/N theorem was not used in this thesis due to its overly simplistic approach to calculating harmonics. Detailed harmonic data from the Dranetz 658 Powerline Monitor was also available. Additional information regarding the 1/N theorem is available in the Power Quality Reference Guide [Ontario Hydro., 1989] [18].

2.8 Symmetry and Phase Alignment:

Harmonics can have several different types of characteristics. Harmonics can be either symmetrical or asymmetrical. Asymmetrical harmonics are even numbered with respect to the fundamental. This can be seen in Figures 6 and 7. Figure 6 represents the summation of the fundamental and second harmonic; producing an overall waveform. Figure 7 is similar except the second harmonic is replaced by the fourth harmonic. The fundamental waveform in Figures 6 and 7 contain one maximum peak and one minimum peak. The n^{th} harmonic waveform contains n maximum peaks of the same magnitude and n minimum peaks of the same magnitude. The x-axis margin is labeled in units of 2.5 Milliseconds/Division for easy comparison to the Dranetz 658 Powerline Monitor waveforms. (i.e. 6.28 (approximately 2π) times 2.5 Milliseconds/Division is one 60 Hz cycle.)

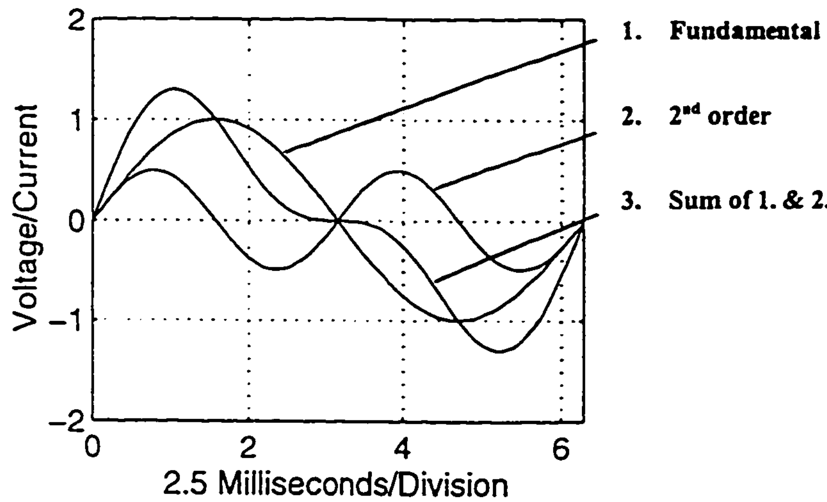


Figure 6: Summation of first and second harmonic waveforms

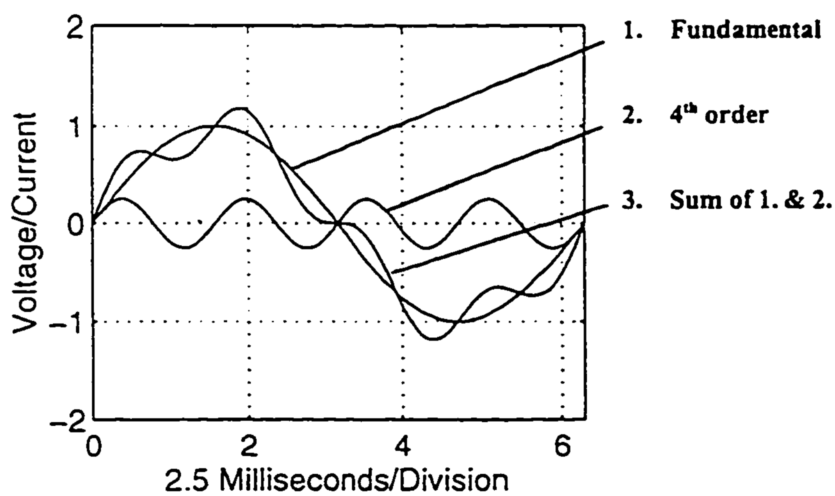


Figure 7: Summation of first and forth harmonic waveforms

Symmetrical harmonics are the odd numbered harmonics greater than 1. Symmetrical harmonics can be any angle, with respect to the fundamental. To illustrate their properties, two examples show them as in-phase and out-of-phase initially with respect to the fundamental. These can be seen in Figures 8-11. Figures 8 and 9 represent the summation of the fundamental and third harmonic; producing an overall waveform. Figure 8 shows the third harmonic initially in phase while Figure 9 illustrates the third harmonic initially out of phase. Figures 10 and 11 are similar to Figures 8 and 9 except the third harmonic is replaced by the fifth harmonic.

Regardless of the phase alignment or symmetry, the combination of the fundamental harmonic with subsequent harmonics have a greater peak magnitude than that of the fundamental by itself.

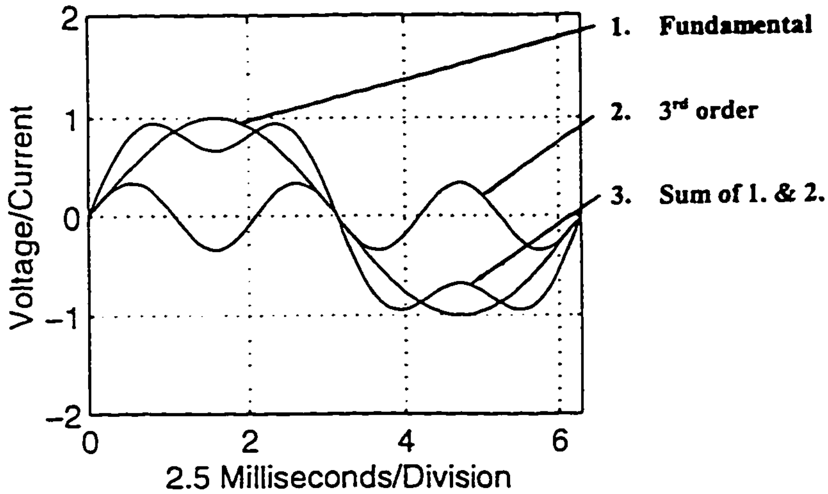


Figure 8: Summation of first and third harmonic waveforms (in phase)

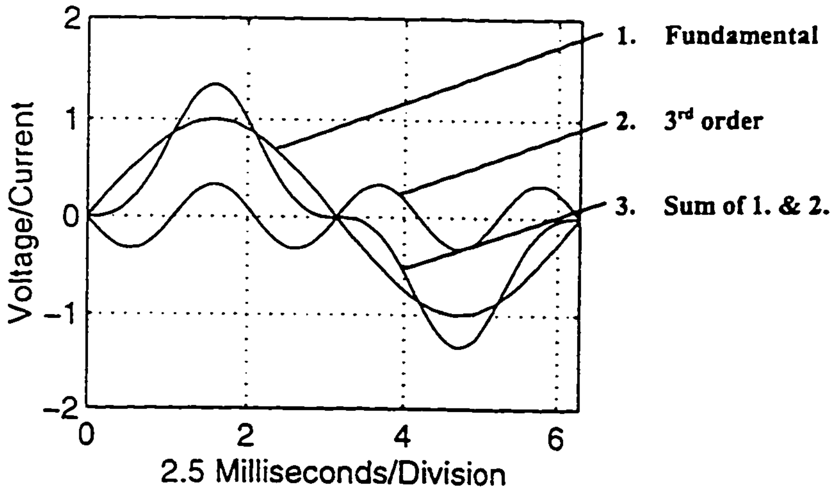


Figure 9: Summation of first and third harmonic waveforms (out of phase)

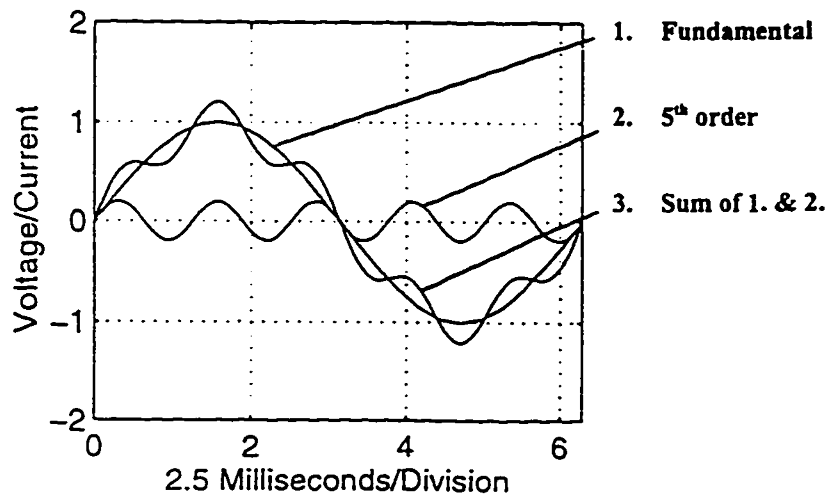


Figure 10: Summation of first and fifth harmonic waveforms (in phase)

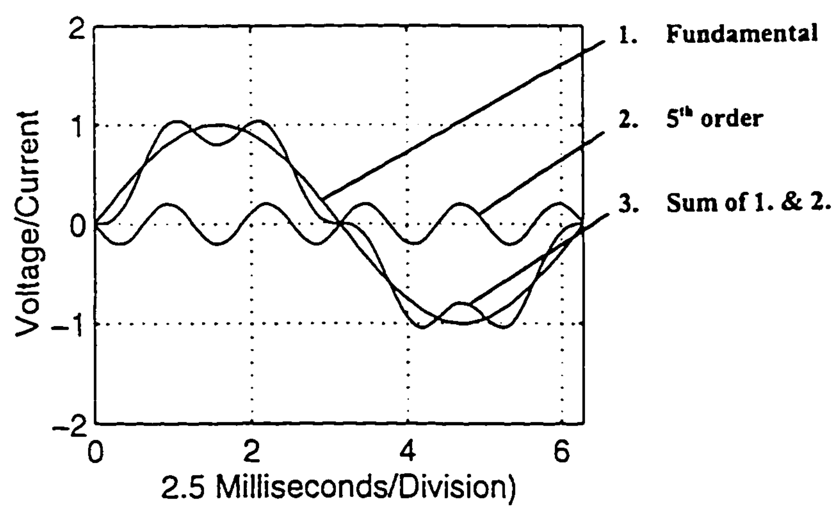


Figure 11: Summation of first and fifth harmonic waveforms (out of phase)

2.9 Total Harmonic Distortion (THD):

Total Harmonic Distortion or THD is a mathematical representation of the combination of all the harmonics present. To calculate the THD, for a voltage waveform:

$$V_{THD} = 100\%\left(\frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + V_n^2 + \cdots}}{V_1}\right)$$

V_1= Fundamental Voltage (RMS)

V_2 to V_n = Voltage Harmonics (RMS)

If the impedance of the network is known, the voltage and current can be related by:

$V_n = Z_n I_n$ where $Z_n = R_n + jX_n$ is the impedance of the network.

R_n is the resistance of the network.

$X_n = 2\pi fL$ is the reactance of the network.

f= the frequency of the voltage

L= equivalent system inductance

Similar calculations can be done for THD of current (I_{THD}).

$$I_{THD} = 100\%\left(\frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + I_n^2 + \cdots}}{I_1}\right)$$

Presentations of both THD equations can be altered to better suit the available data given by the Dranetz 658 Powerline Monitor. The magnitude of each harmonic is expressed as a percentage of the fundamental harmonic magnitude. This changes the equation in such a manner:

$$I_{THD} = 100\%(\frac{\sqrt{I_1^2(\%I_2^2 + \%I_3^2 + \%I_4^2 + \%I_n^2 + \cdots}}{I_1}) \qquad (2\text{-}8)$$

Where $\%I_n$ are the harmonic magnitude levels of individual current harmonics expressed as a percentage of the fundamental.

The V_{THD} equation can be modified in the same manner when using data from the Dranetz 658 Powerline Monitor to calculate THD.

2.10 Causes of Harmonics:

There are many causes of harmonics when dealing with power systems. Most commonly, the presence of harmonics is due to a power system connection with a non-linear load or a non-sinusoidal supply voltage. A non-linear load is any power device in which applied current is not directly proportional to applied voltage. Common examples of such devices are computers, laser printers, photocopiers, and uninterruptible power supplies. Conversely, a linear load draws current directly proportional to voltage. This is seen in pure resistance devices such as some plug-in kettles.

Voltage and current harmonics can be seen in the following examples. The first example, Table 3, illustrates the summation of harmonics from a table of current harmonics to produce its total harmonic distortion. The second example, Figures 12-15, shows the voltage harmonic characteristics of a laser printer associated with the computer laboratory while idle and during start up.

Data provided for the following example is located in Table 3. Sample calculation for I_{THD} RMS given a series of RMS harmonics from 1 to 50. An approximate summation of all significant RMS harmonics (above ten percent of the fundamental) can be seen as follows:

$$I_{THD} = 100\% \left(\frac{\sqrt{.22^2(\ .988^2 + .925^2 + .842^2 + .726^2 + .610^2 + .507^2 + .368^2 + .259^2 + .152^2)}}{.22} \right)$$

$$I_{THD} = 198.05\%$$

Without using the approximation and including all fifty RMS harmonics for the laser printer:

$$I_{THD} = 199.11\%$$

Table 3: Harmonic spectrum of a computer laser printer power supply.

658 GRAPHICAL & HARMONIC ANALYSIS (c)1988-1992 Dranetz Technologies,Inc.
¦ Print ¦ eXit ¦
Event Number 22 Channel B Setup 1 04/07/96 10:03:27.72

Fnd:	0.22A	81 deg	18th:	1.6%	111 deg	35th:	4.7%	209 deg
2nd:	2.4%	176 deg	19th:	15.2%	342 deg	36th:	0.8%	174 deg
3rd:	98.0%	276 deg	20th:	0.5%	270 deg	37th:	4.0%	30 deg
4th:	3.9%	343 deg	21st:	8.6%	176 deg	38th:	0.6%	355 deg
5th:	92.5%	183 deg	22nd:	0.8%	170 deg	39th:	2.3%	235 deg
6th:	3.2%	164 deg	23rd:	3.5%	41 deg	40th:	1.1%	23 deg
7th:	84.2%	291 deg	24th:	0.5%	311 deg	41st:	0.9%	251 deg
8th:	2.8%	322 deg	25th:	2.9%	288 deg	42nd:	0.5%	102 deg
9th:	72.6%	116 deg	26th:	0.4%	69 deg	43rd:	1.6%	32 deg
10th:	2.6%	158 deg	27th:	6.3%	150 deg	44th:	0.6%	130 deg
11th:	61.0%	303 deg	28th:	1.9%	39 deg	45th:	2.7%	170 deg
12th:	2.7%	9 deg	29th:	5.9%	345 deg	46th:	2.7%	125 deg
13th:	50.7%	131 deg	30th:	1.3%	0 deg	47th:	1.5%	65 deg
14th:	2.5%	168 deg	31st:	7.2%	185 deg	48th:	1.4%	176 deg
15th:	36.8%	319 deg	32nd:	1.2%	109 deg	49th:	0.8%	231 deg
16th:	3.1%	299 deg	33rd:	3.7%	4 deg	50th:	3.7%	85 deg
17th:	25.9%	146 deg	34th:	0.5%	284 deg			

T.H.D.: 199.1% ODD CONTRIB.: 198.8% EVEN CONTRIB.: 10.3%
Frequency: 60.0 Hz
Thu 16 May 1996 | Printing screen... (Press Esc to abort) | 16:25:51

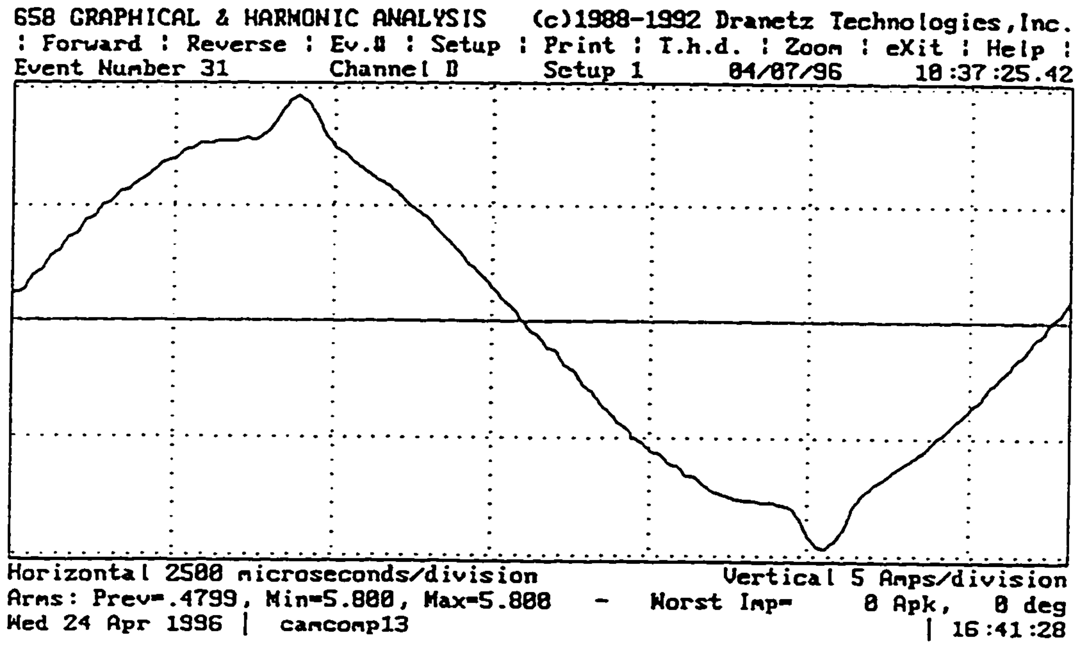


Figure 12: Laser printer power supply current waveform (idle)

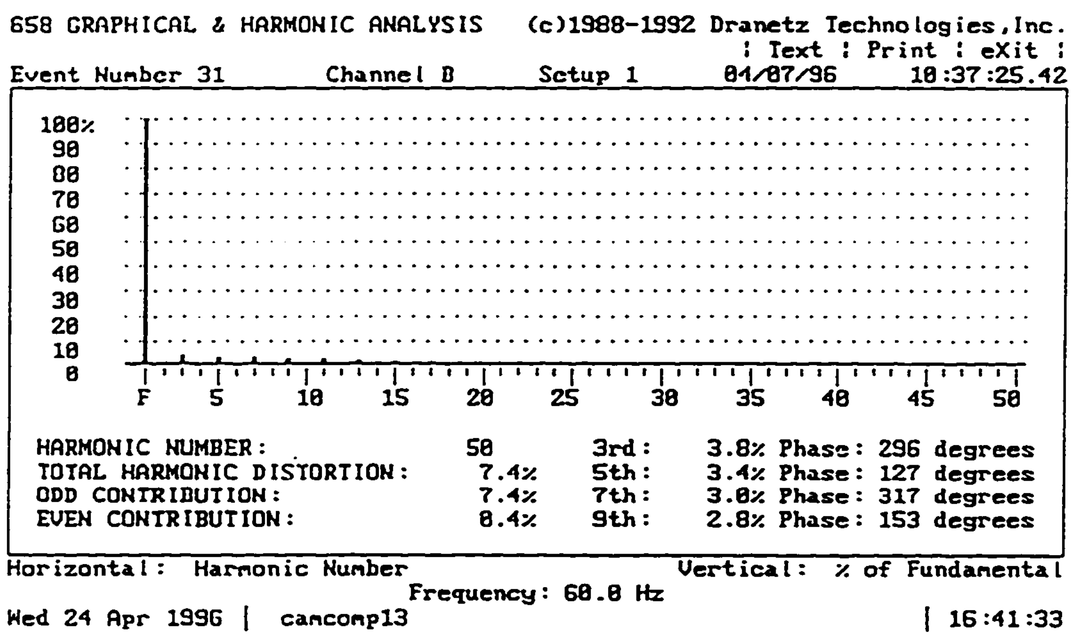


Figure 13: Laser printer power supply graphic spectrum (idle)

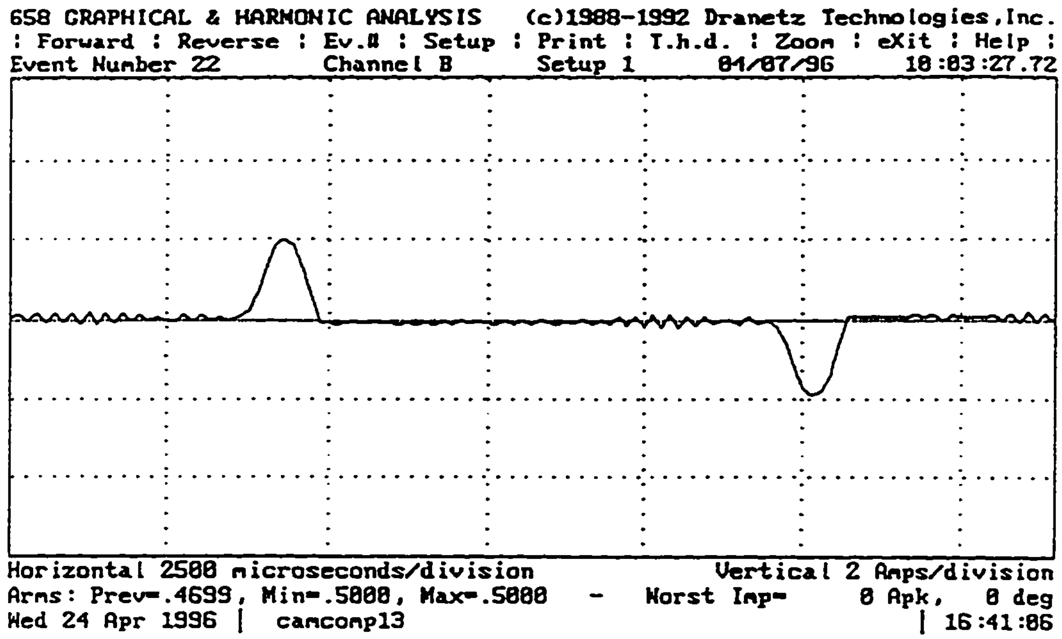


Figure 14: Laser printer power supply current waveform (printing)

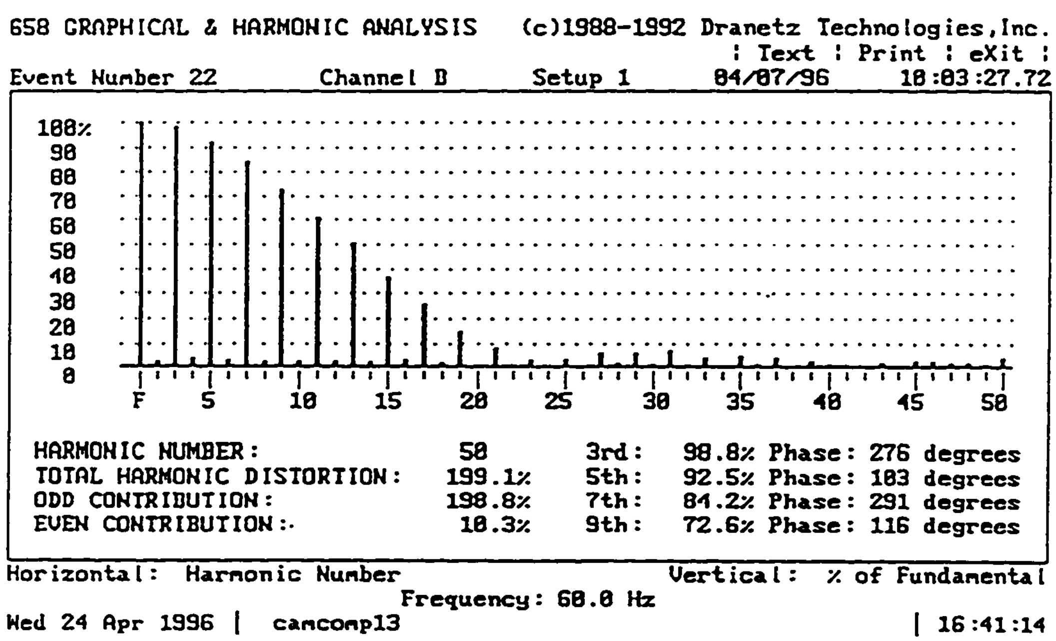


Figure 15: Laser printer power supply graphic spectrum (printing)

The Figures 12 through 15 represent a laser printer under two separate conditions. Figures 12 and 13 illustrate when the laser printer requires steady current for the duration of each cycle of the input signal. The total harmonic distortion (7.4%) observed is below the standards found in IEEE 519 (8%) shown as Table 4. Figures 14 and 15 illustrate the harmonic characteristics of the laser printer as it regulates (selectively uses current) from the input signal drawing current during the peaks of each cycle. The harmonic distortion is much greater than expected (199.1%). IEEE 519 standard shown as Table 4 permits a maximum of 8%. Resonance occurs in more than one harmonic therefore these harmonics do not follow the 1/N theorem. The harmonics created by the device couple into the system via the input voltage and current as well as the neutral voltage and current.

2.11 Effects of Harmonics:

Harmonics can cause many problems. As seen in Figures 6 through 11, harmonics can increase the peak amplitude of the input voltage. This may cause problems for devices relying on a specified input voltage. Individual harmonics can cause specific problems for certain types of devices. Capacitors directly connected to a power system are rated for the specified voltage and frequency. If a high frequency and high magnitude current harmonic is present, it increases heating of the capacitor. The capacitor, originally rated for the lower temperature, may no longer be sufficient to handle energy passed through it and may fail much faster than normal. Harmonics also cause stress on circuit breakers, motors, transformers, induction relays, and computer equipment. This stress can include overheating, vibrations, power quality loss, nuisance trips, and erratic failures. The Institute of Electrical and Electronics Engineers Inc. (IEEE) has published a set of standards [14] for industry to follow relating to voltage and current harmonic content of power systems. These can be seen in Table 4.

Point of Common Coupling (PCC) is defined for the duration of the data collection in Cameron Library Computer Laboratory as the power supply panel. Maximum short circuit current for the power supply panel is less the rating of the panel itself. The panel is rated for 20kA fault current. The maximum demand load current is 24 breakers times 20A per breaker which is equal to 480A. The short circuit to demand load current factor is 20kA/480A = 41.7. A factor of 41.7 falls into the 20<50 category in the IEEE Standard 519. This category allows for a maximum of 8.0% Total Demand Distortion.

Table 4: Maximum Harmonic Current Distortion in % of I_L

Maximum Harmonic Current Distortion in % of I_L						
Individual Harmonic Order (Odd Harmonics)						
I_{sc}/I_L	<11	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Even harmonics are limited to 25% of the odd harmonic limits. TDD refers to Total Demand Distortion and is based on the average maximum demand current at the fundamental frequency, taken at the PCC.

* All power generation equipment is limited to these values of current distortion regardless of I_{sc}/I_L.

PCC = Point of Common Coupling
I_{sc} = Maximum short circuit current at the PCC
I_L = Maximum demand load current (fundamental) at the PCC
h = Harmonic Order

Chapter 3

Individual Computer Performance Model

3.1 Dranetz 658 Powerline Monitor Setup:

Data collection involving an individual computer terminal required a single connection of one computer terminal to one phase of the three phase power supply electrical panel. The terminal was also connected in parallel with twenty-nine other terminals to a central modem hub via modem lines. Powerline monitoring consisted of voltage and current connections to the associated phase of the power supply electrical panel as well as ground to neutral voltage measurement and neutral current measurement also located within the power supply electrical panel. The ground connection is made of electro-metallic tubing (i.e.. conduit).

The Dranetz 658 Powerline Monitor connections were as follows:

Disk 8 Computer # 5 solely energized by circuit 6C while the other two computers normally energized by circuit 6C are energized using circuit 4B.

Channel A: circuit 6C voltage to neutral

Channel B: circuit 6C phase current

Channel C: circuit 6C neutral to ground voltage.

Channel D: circuit 6C neutral current

Disk 9 Computer # 4 with the other two computers connected to an alternate bus.

Channel A: circuit 6C voltage to neutral

Channel B: circuit 6C phase current

Channel C: circuit 6C neutral to ground voltage.

Channel D: circuit 6C neutral current

The Dranetz 658 Powerline Monitor settings were as follows:

Channels A and C were measured in V; B and D were measured in A.

Setup #1	A	B	C	D
Range	VH	I30	VL	I30
Hi Lim	125	15.0	12.5	15.0
Low Lim	110	0.0	0.0	0.0
Sens.	50	5.0	5.0	5.0
Imp.	100	11.0	10.0	11.0
Wave	100	10.0	10.0	10.0
Frequency	0.5	(All Channels)		

Disks 8 and 9 refer to physical disk numbers containing sections of the data collected from the Cameron Library computer laboratory. Each disk number is directly referenced to the names seen in each waveform. As an example, Table 5 is from file compcam8 which is data located on disk 8. Individual computer numbers reference Figure 2. Hi Lim and Low Lim specify the maximum and minimum levels the channel characteristics may vary before causing the monitor to produce a disturbance record. Sens. is instrument sensitivity. Imp. is the maximum transient impulse level the system can have without causing the monitor to produce a disturbance record. Wave is the wave distortion level. Frequency is the frequency variation possible before the monitor produces a disturbance record. Units for each channel parameter are dependent on the setup configuration of the monitor.

3.2 Startup Transients:

During start-up of a computer terminal, transient voltage and current waveforms occur. Transient voltage may include a decrease in magnitude as well as a flattening of the voltage supply peaks. This is due to increased loading during the startup phase causing the power supply panel to decrease voltage when instantaneous current demands can not be fully met. Transient current includes an increase in magnitude as well as spiking (sharp increase in peak current value) during the peaks of the current waveform. An illustration of these types of transients can be seen from the startup of the laser printer. (The laser printer illustrates start-up transients more effectively than a computer terminal because its transient waveforms are much more pronounced). The transient current waveform of the laser printer beginning a print cycle is shown in Figure 14.

3.3 Harmonics (Single Terminal):

Current and voltage harmonics of the individual computer as measured at its associated phase of the three phase power supply electrical panel can be seen in Tables 5-8. Neutral current and ground to neutral voltage are also included because harmonic coupling through a power system can be significant in both the ground and neutral conductors. Emphasis is placed on the neutral conductor as it interconnects directly with the power system in the same manner as the phase conductors.

3.3.1 Voltage Harmonics:

Harmonic levels associated with a single terminal were higher in magnitude for currents than they were for voltage. The mean total harmonic distortion for the phase voltage is approximately 2.1% of the fundamental voltage magnitude. Percentages are based on sample waveforms (10% of 5000 waveforms) captured by the Dranetz 658 Powerline Monitor. The waveforms selected matched the time of day and relative loading of the other computer terminal configurations as closely as possible. The total odd harmonics contribution comprises approximately 95% (20 times the magnitude of the total even harmonic contribution) of the THD. Table 5 shows THD levels at 3.1% and the total odd harmonic contribution levels at 3.1% although this percentage level is only approximately 15 times the total even harmonic contribution level of 0.2%. Neutral to ground voltage contains higher levels of harmonic content as a percentage of its fundamental voltage. This is attributed to the significantly lower fundamental harmonic voltage magnitude in the neutral to ground voltage compared to the phase voltage. This can be seen in Table 6. (Tables 5 and 6 are sample data taken within 1 minute and 4 seconds of each other.) Tables 5 and 6 show the following:

Fundamental phase voltage magnitude from Table 5 is 120.31V. The third harmonic as a percentage of the fundamental is 2.3%. This translates to a voltage level of 2.77V. The fundamental neutral to ground voltage magnitude from Table 6 is 0.27V. The third harmonic as a percentage of the fundamental is 364.1%. This translates to a voltage level of 0.98V. It is evident that the voltage harmonic magnitude level is actually lower in the neutral to ground voltage than in the phase voltage even though voltage seen on a percentage basis would appear otherwise. This does, however lead to the possibility of extremely large harmonic levels in the neutral conductor in comparison to its fundamental if, as an example, there is a third harmonic in the phase voltage of 90%. This harmonic would couple into the neutral to ground voltage producing harmonic magnitude levels that would make the neutral to ground fundamental harmonic voltage seem insignificant. These high harmonic levels could reciprocate in other conductors such as communication wires creating a variety of potentially hazardous problems such as signal interference.

Table 5: Harmonic spectrum of a single computer terminal (phase to neutral voltage)

658 GRAPHICAL & HARMONIC ANALYSIS (c)1988-1992 Dranetz Technologies, Inc.
: Print : eXit :

Event Number 4 | Channel A | Setup 1 | 03/19/96 | 11:09:19.00

Harmonic	Magnitude	Phase	Harmonic	Magnitude	Phase	Harmonic	Magnitude	Phase
Fnd:	120.31V	88 deg	18th:	0.0%	310 deg	35th:	0.2%	70 deg
2nd:	0.0%	170 deg	19th:	0.2%	345 deg	36th:	0.0%	72 deg
3rd:	2.3%	52 deg	20th:	0.1%	275 deg	37th:	0.0%	341 deg
4th:	0.1%	118 deg	21st:	0.3%	227 deg	38th:	0.0%	70 deg
5th:	1.0%	206 deg	22nd:	0.1%	258 deg	39th:	0.1%	139 deg
6th:	0.1%	85 deg	23rd:	0.0%	315 deg	40th:	0.0%	67 deg
7th:	1.5%	58 deg	24th:	0.0%	222 deg	41st:	0.1%	33 deg
8th:	0.1%	61 deg	25th:	0.1%	309 deg	42nd:	0.0%	30 deg
9th:	0.7%	241 deg	26th:	0.0%	187 deg	43rd:	0.1%	321 deg
10th:	0.1%	34 deg	27th:	0.2%	190 deg	44th:	0.0%	330 deg
11th:	0.2%	221 deg	28th:	0.0%	204 deg	45th:	0.0%	66 deg
12th:	0.1%	19 deg	29th:	0.1%	46 deg	46th:	0.1%	319 deg
13th:	0.3%	4 deg	30th:	0.0%	198 deg	47th:	0.0%	325 deg
14th:	0.1%	16 deg	31st:	0.1%	332 deg	48th:	0.0%	285 deg
15th:	0.5%	243 deg	32nd:	0.0%	154 deg	49th:	0.1%	278 deg
16th:	0.0%	2 deg	33rd:	0.1%	120 deg	50th:	0.0%	275 deg
17th:	0.1%	326 deg	34th:	0.0%	97 deg			

T.H.D.: 3.1% ODD CONTRIB.: 3.1% EVEN CONTRIB.: 0.2%
Frequency: 60.0 Hz
Fri 05 Jul 1996 | compcam8 | 15:18:55

Table 6: Harmonic spectrum of a single computer terminal (neutral to ground voltage)

658 GRAPHICAL & HARMONIC ANALYSIS (c)1988-1992 Dranetz Technologies, Inc.
: Print : eXit :

Event Number 4 | Channel C | Setup 1 | 03/19/96 | 11:09:19.00

Harmonic	Magnitude	Phase	Harmonic	Magnitude	Phase	Harmonic	Magnitude	Phase
Fnd:	0.27V	41 deg	18th:	8.8%	182 deg	35th:	10.4%	314 deg
2nd:	11.6%	357 deg	19th:	23.6%	240 deg	36th:	3.7%	297 deg
3rd:	364.1%	240 deg	20th:	7.8%	163 deg	37th:	14.7%	197 deg
4th:	11.8%	329 deg	21st:	30.5%	77 deg	38th:	5.6%	268 deg
5th:	69.5%	49 deg	22nd:	6.4%	138 deg	39th:	1.9%	356 deg
6th:	13.2%	302 deg	23rd:	7.7%	307 deg	40th:	4.3%	105 deg
7th:	68.1%	289 deg	24th:	5.5%	113 deg	41st:	6.5%	291 deg
8th:	10.4%	282 deg	25th:	17.2%	219 deg	42nd:	3.4%	105 deg
9th:	100.4%	83 deg	26th:	4.8%	87 deg	43rd:	14.8%	156 deg
10th:	11.7%	264 deg	27th:	16.4%	46 deg	44th:	5.2%	206 deg
11th:	15.3%	338 deg	28th:	5.5%	66 deg	45th:	3.6%	153 deg
12th:	9.0%	246 deg	29th:	12.3%	314 deg	46th:	9.1%	166 deg
13th:	33.1%	267 deg	30th:	5.0%	40 deg	47th:	1.8%	235 deg
14th:	9.5%	224 deg	31st:	16.9%	205 deg	48th:	5.8%	112 deg
15th:	62.8%	88 deg	32nd:	2.1%	348 deg	49th:	15.6%	124 deg
16th:	8.8%	212 deg	33rd:	11.8%	345 deg	50th:	8.6%	166 deg
17th:	6.1%	283 deg	34th:	4.9%	5 deg			

T.H.D.: 403.1% ODD CONTRIB.: 401.2% EVEN CONTRIB.: 39.2%
Frequency: 60.0 Hz
Fri 05 Jul 1996 | compcam8 | 15:19:59

3.3.2 Current Harmonics:

The mean total harmonic distortion for the phase current is approximately 91% of the fundamental current magnitude. Percentages are based on sample waveforms (10% of 5000 waveforms) captured by the Dranetz 658 Powerline Monitor. The total odd harmonic contribution comprises approximately 96% (25 times the magnitude of the total even harmonic contributions) of the THD. Table 7 shows THD levels at 119.5% and the total odd harmonic contribution levels at 119.4% although this percentage level is approximately 30 times the total even harmonic contribution level of 3.8%. Neutral current contained similar levels of harmonic content on a percentage basis. This is attributed to the similarities in the fundamental harmonic current magnitude of the phase and neutral conductors. This can be seen in Table 8.

The harmonic levels in the current follow patterns similar to the voltage due to the V=IZ relationship (Z is the system impedance). The basic harmonic levels expressed as a current do not change significantly from one conductor to another. As an example, the data seen in Tables 7 and 8 contain fundamental currents for the phase conductor and the neutral conductor that are 0.61A and 0.60A respectively. The third harmonic for each is 87.9% and 87.2% respectively. Both translate into third harmonic currents of approximately 0.5A. Again, harmonics coupling into the neutral conductor could create potential problems even though the fundamental harmonic current levels are not much lower than the higher order odd harmonic levels. Current harmonics, in this respect, differ from voltage harmonics.

Table 7: Harmonic spectrum of a single computer terminal (phase current)

658 GRAPHICAL & HARMONIC ANALYSIS (c)1988-1992 Dranetz Technologies,Inc.
: Print : eXit :
Event Number 4 Channel B Setup 1 03/19/96 11:09:19.00

Fnd:	0.60A	84 deg	18th:	0.2%	193 deg	35th:	0.2%	300 deg
2nd:	1.7%	349 deg	19th:	1.9%	251 deg	36th:	0.2%	354 deg
3rd:	87.9%	282 deg	20th:	0.5%	291 deg	37th:	0.8%	193 deg
4th:	1.9%	131 deg	21st:	2.7%	152 deg	38th:	0.4%	33 deg
5th:	65.9%	112 deg	22nd:	0.6%	311 deg	39th:	1.6%	61 deg
6th:	1.6%	308 deg	23rd:	3.5%	357 deg	40th:	0.3%	41 deg
7th:	40.7%	305 deg	24th:	0.5%	229 deg	41st:	0.6%	310 deg
8th:	1.1%	92 deg	25th:	2.2%	214 deg	42nd:	0.5%	103 deg
9th:	10.3%	140 deg	26th:	0.3%	224 deg	43rd:	0.4%	142 deg
10th:	0.6%	277 deg	27th:	0.5%	123 deg	44th:	0.3%	314 deg
11th:	3.3%	29 deg	28th:	0.3%	243 deg	45th:	0.7%	66 deg
12th:	0.6%	25 deg	29th:	1.9%	349 deg	46th:	0.4%	167 deg
13th:	7.3%	311 deg	30th:	0.4%	104 deg	47th:	0.8%	297 deg
14th:	0.5%	166 deg	31st:	1.8%	207 deg	48th:	0.7%	314 deg
15th:	7.8%	153 deg	32nd:	0.4%	64 deg	49th:	0.8%	169 deg
16th:	0.7%	346 deg	33rd:	1.5%	81 deg	50th:	0.3%	220 deg
17th:	5.1%	356 deg	34th:	0.4%	117 deg			

T.H.D.: 119.5% ODD CONTRIB.: 119.4% EVEN CONTRIB.: 3.8%
Frequency: 60.0 Hz
Fri 05 Jul 1996 | compcam8 | 15:19:25

Table 8: Harmonic spectrum of a single computer terminal (neutral current)

658 GRAPHICAL & HARMONIC ANALYSIS (c)1988-1992 Dranetz Technologies,Inc.
: Print : eXit :
Event Number 4 Channel D Setup 1 03/19/96 11:09:19.00

Fnd:	0.61A	264 deg	18th:	0.8%	315 deg	35th:	0.7%	146 deg
2nd:	2.0%	171 deg	19th:	2.1%	31 deg	36th:	0.5%	350 deg
3rd:	87.2%	98 deg	20th:	0.3%	14 deg	37th:	0.8%	6 deg
4th:	1.9%	320 deg	21st:	3.1%	306 deg	38th:	0.3%	234 deg
5th:	64.7%	286 deg	22nd:	0.2%	265 deg	39th:	0.8%	200 deg
6th:	1.5%	126 deg	23rd:	2.8%	142 deg	40th:	0.3%	346 deg
7th:	40.6%	115 deg	24th:	0.5%	333 deg	41st:	0.2%	1 deg
8th:	1.1%	265 deg	25th:	2.2%	348 deg	42nd:	0.2%	103 deg
9th:	17.8%	307 deg	26th:	0.3%	1 deg	43rd:	0.4%	287 deg
10th:	1.1%	71 deg	27th:	0.8%	261 deg	44th:	0.5%	4 deg
11th:	3.1%	185 deg	28th:	0.6%	285 deg	45th:	0.6%	209 deg
12th:	0.3%	192 deg	29th:	1.6%	137 deg	46th:	0.6%	322 deg
13th:	6.9%	114 deg	30th:	0.2%	297 deg	47th:	0.4%	340 deg
14th:	0.8%	335 deg	31st:	1.9%	350 deg	48th:	0.4%	160 deg
15th:	8.1%	315 deg	32nd:	0.0%	116 deg	49th:	0.4%	312 deg
16th:	0.7%	107 deg	33rd:	1.0%	209 deg	50th:	0.7%	352 deg
17th:	4.6%	152 deg	34th:	0.2%	326 deg			

T.H.D.: 118.1% ODD CONTRIB.: 118.1% EVEN CONTRIB.: 4.1%
Frequency: 60.0 Hz
Fri 05 Jul 1996 | compcam8 | 15:20:24

3.4 Verification of Dranetz Powerline Harmonics Waveforms:

The Dranetz 658 Powerline Monitor provides information concerning waveforms on three different levels. These include a graphic representation of the voltage or current waveform, a table of harmonic magnitudes and phase angles, and a bar graph visibly comparing relative harmonic magnitudes. The bar graph does not show phase angles thus providing insufficient information to reproduce a graphic waveform. However,, the table of magnitudes and phase angles does provide sufficient information to reproduce a graphic waveform. Aside from the table providing the magnitudes and phase angles, information concerning the type of sinusoidal waveform (cosine or sine) and the starting location of the phase angles are required. The manufacturers provided the following information:

Type of waveform used for calculating waveforms:	**Cosine**
Starting location of phase angles:	**Negative of the magnitude shown in their output tables.**

Equations developed for reproducing the waveforms can be seen in section 2.2. Figure 16 illustrates the reproduction of an arbitrarily chosen Dranetz waveform seen as Table 3 containing harmonic magnitudes and phase angles producing Figure 14, the waveform produced by the Dranetz 658 Powerline Monitor. A visual comparison confirms the accuracy of the Dranetz 658 Powerline Monitor. The waveform in Figure 16 was produced by inputing a set of data from an arbitrarily choosen Dranetz output waveform and table and inputting the information into Matlab. See Appendix A for programming details.

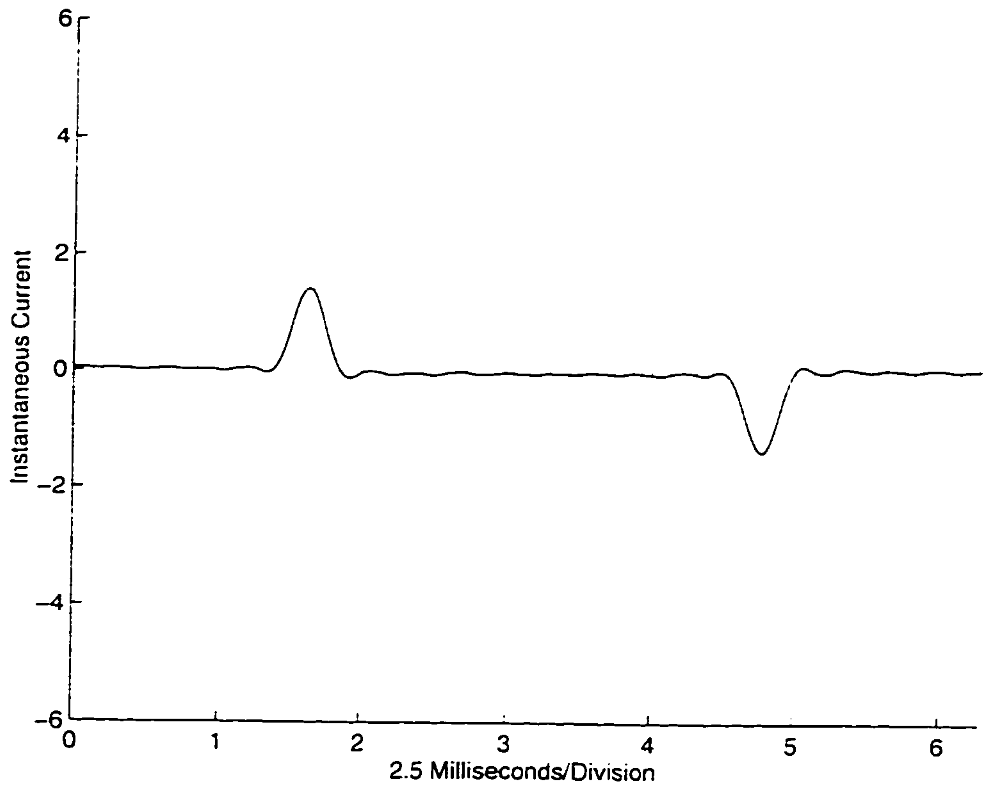


Figure 16: Voltage harmonic waveform developed from harmonic spectrum data.

3.5 Voltage Drop in Cable:

Voltage drop within a power supply cable is characterized by a percentage voltage drop per unit length of cable. Percent voltage drop varies with the cable operating temperature, magnitude of the current and size (AWG) of cable. The ambient temperature remains constant inside the computer laboratory within several degrees centigrade leaving voltage drop variation dependent only on the magnitude of the current and AWG of the cable. Calculation of voltage drop per unit length can be completed using the per foot impedance values specified by Okonite Company EHB-81 1994 [7].

Two cables are used within the power supply electrical panel and associated areas that were connected to the Dranetz 658 Powerline Monitor. Both cables are of similar insulation, shielding, and temperature ratings. The cables are RW90, XLPE rated to -40 degrees centigrade with an ambient cable temperature of 90°C.

The first cable is 12 AWG 600V. The impedance ratings are as follows:

Positive / negative sequence cable impedance:

R = 0.0008110 ohms/ft X = 0.0000736 ohms/ft at 60 Hz

Zero sequence cable impedance:

R = 0.0025547 ohms/ft X = 0.0001735 ohms/ft at 60 Hz

The second cable is 6 AWG 1000V. The impedance ratings are as follows:

Positive / negative sequence cable impedance:

R = 0.0005100 ohms/ft X = 0.0000680 ohms/ft at 60 Hz

Zero sequence cable impedance:

R = 0.0016065 ohms/ft X = 0.0001673 ohms/ft at 60 Hz

These impedance values can be used to calculate complete voltage drop over a given length of cable. As harmonic order increases, equivalent reactive impedance also increases, thus decreasing the magnitude of voltage harmonics present in the power system over extended lengths of cable. The given reactance $X_n = 2\pi fL$ in the preceding tables is provided at a frequency (f) of 60 Hz. As the harmonic order increases, X_n also increases in the same linear fashion. Cable length within the power supply electrical panel and the computer laboratory is quite limited. Cable lengths range from 15 feet from the power supply electrical panel to the nearest set of three computer terminals, to 45 feet from the power supply electrical panel to the furthest set of computer terminals. Sample calculations for both 15 and 45 ft. 12 AWG Cable, illustrate the significance of the voltage drop (V). V = IZ, where Z = R+jX and I = conductor current.

(R+jX)15 (ft) of cable +/- sequence =

$$15(0.0008110) + j15(0.0000736) = 0.0122 + j\,0.0011$$

(R+jX) 45 (ft) of cable +/- sequence =

$$45(0.0008110) + j45(0.0000736) = 0.0365 + j\,0.0033$$

With a current of 1A at approximately 120V fundamental in a single phase of a three phase conductor, the voltage drop would be approximately 0.012V at 15 feet and 0.036V at 45 feet.

With a current of 1A at approximately 120V at the fifth harmonic in a single phase of a three phase conductor would see a voltage drop of approximately 0.013V at 15 feet and 0.040V at 45 feet. This can be seen by taking the root sum of squares of $R+jX_5$, where $X_5 = 5X$.

A voltage drop between 0.11 and 0.33 percent is present from the power supply electrical panel to its associated loads (Percentage voltage drop calculated by dividing the voltage drop by the fundamental voltage). These approximations are based on majority of power coming from the first five harmonics and a maximum individual cable length of 45 feet. Voltage drop of between 0.11 and 0.33 percent is quite minimal when considering the overall voltage levels of the power system and would likely be considered during theoretical analysis only.

3.6 Circuit Model of a single computer terminal power supply:

Performance modeling of an individual computer requires both the knowledge of voltage and current characteristics as well as internal structuring of a computer terminal. An equivalent circuit model includes voltage and current input, components representing the changes performed on the input signal, and voltage and current output.

The input signal is a voltage source equivalent to voltage seen at the phase connection to the power supply electrical panel. Following IEEE Standard 519-1992 Section 8.1, non-linear devices (such as a computer terminal power supply) can be replaced with a current source. Standard 519 also includes a limitation: the voltage source must contain harmonic levels less than approximately ten percent. For the purpose of developing this model, these standards are used. The voltage source contains impedance, although in this instance, the impedance is governed by the cable impedance from the power supply panel to the distribution transformer (within Cameron Library) and the distribution transformer itself.

The voltage input signal (and neutral to ground voltage output signal) travels along a cable seen as a series inductance and resistance (Figure 17). The inductance and resistance is calculated from the voltage drop characteristics seen in Section 2.11. IEEE Standard 519 also provides a cable line impedance approximation as an alternate method of determining line inductance when cable data is not available. Per-phase line inductance on a three-phase ac line can be considered to be 1 μH/m.

After traversing the cable, the voltage and current signals enter the computer power supply. The characteristics of the computer power supply vary depending on the harmonic order in question. The fundamental harmonic is represented as a simple impedance where power, including the full range of harmonics provided from the power supply panel voltage source, is being absorbed by the computer power supply to operate the computer and its peripheral devices.

The computer power supply output includes several different components. The fundamental voltage harmonic of the computer power supply through Z_{CPU1}. The rest of the harmonics are seen individually as current sources providing direct coupling to the power supply electrical panel. For each harmonic order above 1, there is a current source which is directly proportional in magnitude to the percentage harmonic level with respect to the fundamental harmonic magnitude. The model shows only a few current sources, representing the highest percentage harmonic levels with respect to the fundamental harmonic magnitude. Current sources representing various harmonics are dependent on the relative magnitudes of harmonics present within the circuit being modeled. For example, a large harmonic magnitude in the 4th harmonic would require a current source to represent it. The example seen in Figure 18 does not contain a large harmonic magnitude in the 4th harmonic relative to the 3rd, 5th, 7th, and 9th harmonics and is therefore not included in the model.

The computer terminal impedance at the fundamental harmonic can be calculated using the following equations:

$$V_{CPU1} = I_{CPU1} x Z_{CPU1} \tag{3-1}$$

$$|Z_{CPU1}| = |V_{CPU1}| / |I_{CPU1}| \tag{3-1a}$$

$$W_{CPU1} = (I_{CPU1})^2 x R_{CPU1} \tag{3-2}$$

$$Z_{CPU1} = R_{CPU1} + jX_{CPU1} \tag{3-3}$$

V_{CPU1} = Computer terminal input voltage at the fundamental harmonic.

I_{CPU1} = Computer terminal input current at the fundamental harmonic.

W_{CPU1} = Computer terminal real power absorbed.

R_{CPU1} = Computer terminal resistance at the fundamental harmonic.

X_{CPU1} = Computer terminal inductance (+jX) or capacitance (-jX) at the fundamental harmonic.

Z_{CPU1} = Computer terminal impedance at the fundamental harmonic.

Voltage and current relationships are calculated using the following equations:

$$V_n = I_n x Z_n \qquad (3\text{-}4)$$

V_n = the circuit model voltage at harmonic n.

I_n = the circuit model current at harmonic n.

Z_n = the circuit model equivalent impedance at harmonic n.

The circuit model is developed using two sets of equations. Initial calculations are required to determine the impedance of the computer terminal at the fundamental harmonic. Equation (3-1a) can be used to calculate the impedance Z_{CPU1} from the magnitude of the voltage and current. Equation (3-2) may be used to calculate the resistive component of the impedance Z_{CPU1} from the magnitude of current and power. Equation (3-2) is an approximation as it assumes the total watts of power used by the computer terminal are seen within the fundamental harmonic. Equation (3-3) is used to calculate the inductive or capacitive portion of the impedance Z_{CPU1}. The imaginary portion of the computer terminal impedance is a function of harmonic order and can be re-calculated for each harmonic order using the n as a multiplying factor. A second set of equations is necessary for determining overall voltage and current relationships for the circuit model. Equation (3-4) is applied at each harmonic which is relevant to the circuit model. This includes the fundamental harmonic and any subsequent harmonic for which there is an associated current source.

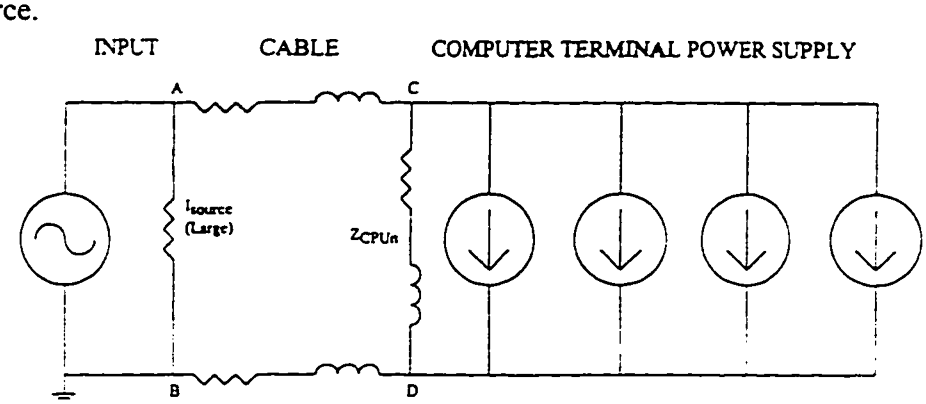


Figure 17: Circuit model diagram (single computer terminal)

3.6.1 Single Computer Terminal Circuit Model:

An example of this circuit model was developed using data from cable voltage drop (Section 3.5), voltage characteristics from Table 6 and current characteristics from Table 8. The voltage source is 120.31V RMS at 88° at the fundamental (but still containing all input harmonics). The voltage source impedance (in parallel with the voltage source itself) is considered to be large due to the extensive cable length to the distribution transformer and large size of the distribution transformer relative to the small amount of power being used by the computer power supply. The cable impedances for the phase and neutral cables, (a length of 15 feet) for the fundamental (positive sequence) are 0.0122 + j0.0011n ohms each. Resistance is considered to be constant over the range of frequencies used in this harmonic analysis. The imaginary portion of impedance contains the multiplying factor n = harmonic order. The computer power supply is represented by Z_{CPU1} and several current sources. For a comprehensive model, a current source should be included for each harmonic being considered. To illustrate the application of the model, current sources are shown for harmonics containing at least 10% of the magnitude of the fundamental harmonic current. These values are:

3rd Harmonic:	0.53A RMS at 282°
5th Harmonic:	0.40A RMS at 112°
7th Harmonic:	0.24A RMS at 305°
9th Harmonic:	0.11A RMS at 140°

Application of equation (3-1) yields $Z_{CPU1} = 120.31V\angle 88/0.60A\angle 84 = 200.5$ ohms.

Equation (3-2), given that real power (from computer specifications) is 68 Watts, $R_{CPU1} = 68/((.6)^2) = 188.89$ ohms and $X_{CPU1} = (Z_{CPU1}^2 - R_{CPU1}^2)^{1/2} = 67.24$ ohms.

The resulting impedance (equation (3-3))is $Z_{CPU1} = 188.89 + j67.24$ ohms.

The magnitude of Z_{CPUn} (n>1) = (nth voltage across Z_{CPUn}) / (nth harmonic current)

The equivalent circuit model impedance $Z_{equivalent}$ (n>1) = $Z_{neutralcable}$ // ($Z_{CPUn} + Z_{phasecable}$)

$Z_{CPUn} >> Z_{phasecable}$ therefore Z_{CPUn} is approximately negligible.

The application of equation (3-4) for the fundamental harmonic includes cable impedance as well as the computer terminal impedance. The resulting equations are:

$V_1 = I_1 \times (Z_{CPU1} + Z_{phasecable} + Z_{neutralcable})$

$V_3 = (I_3)(Z_{equivalent})$, where $Z_{equivalent} = Z_{neutralcable} // (Z_{CPU3} + Z_{phasecable})$

$V_5 = (I_5)(Z_{equivalent})$, where $Z_{equivalent} = Z_{neutralcable} // (Z_{CPU5} + Z_{phasecable})$

$V_n = (I_n)(Z_{equivalent})$, where $Z_{equivalent} = Z_{neutralcable} // (Z_{CPUn} + Z_{phasecable})$

Where $_n$ is the harmonic order.

3.6.2 Application of the Single Computer Terminal Circuit Model:

Fundamental voltage and current levels can be calculated to demonstrate the application of the single computer terminal circuit model. Voltage levels are calculated across the branches corresponding to the nodes, A, B, C, and D seen in Figure 18. Current levels are calculated along the branches in-between the nodes in the direction of first to second node. For example, current I_{AB} is the current along the branch from node A to node B.

$V_{AB} = \sim 120.31V \angle 88°$ (same as input)

$I_{AB} = \sim 0A$ (large impedance)

$I_{AC} = I_{CD} = I_{DB} = I_{SOURCE} = 0.60A \angle 84°$

$V_{AC} = I_{AC} \times 0.0122+j0.0011\Omega = 0.60A \angle 84° \times 0.0122+j0.0011\Omega = 0.007V \angle 89.2°$

$V_{AC} = V_{DB} = \sim$ negligible with respect to voltage levels across other segments in the circuit model.

$V_{CD} = Z_{CPU1} \times I_{CD} = 188.89+j67.04\Omega \times 0.60A \angle 84° = -120.32V \angle 76.5°$

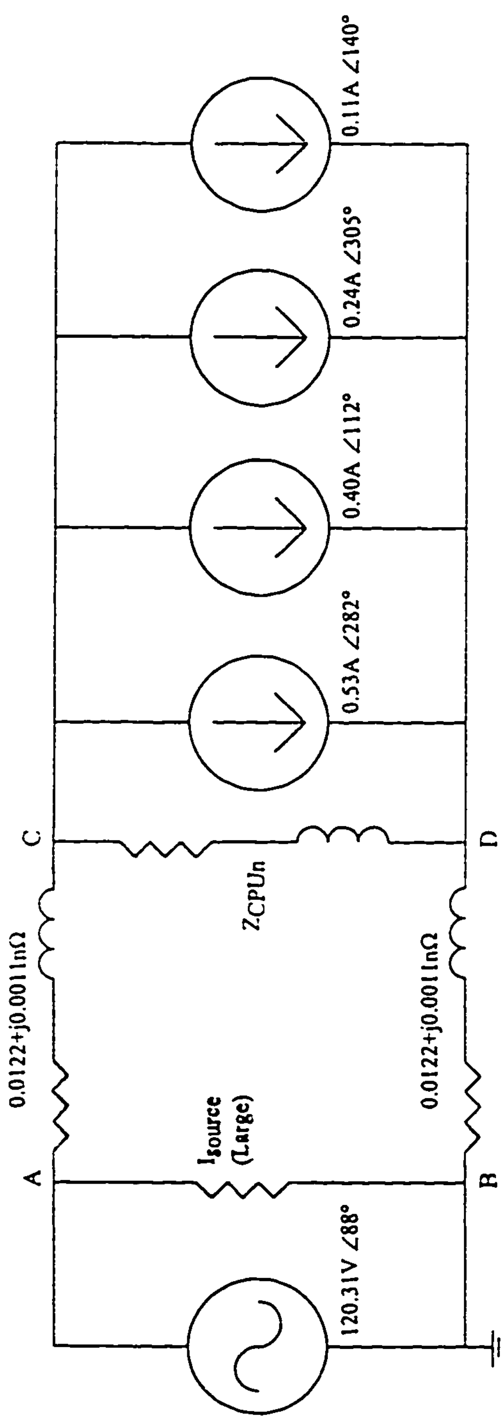


Figure 18: Circuit model (single computer terminal configuration)

Chapter 4

Multiple Computer Performance Model

4.1 Dranetz 658 Powerline Monitor Setup (Two Terminals):

Data collection involving two computer terminals required a parallel connection of two computer terminals to one phase of the three phase power supply electrical panel. The terminals were also connected in parallel with twenty-eight other terminals to a central modem hub via modem lines. Powerline monitoring consisted of voltage and current connections to the associated phase of the power supply electrical panel as well as ground to neutral voltage measurement and neutral current measurement also located within the power supply electrical panel. The ground connection is made of electro-metallic tubing (i.e., conduit).

Powerline monitor connections were as follows:

Disk 10 Computer #'s 4 and 5 with the other computer connected to an alternate bus.

Channel A: circuit 6C line to neutral voltage

Channel B: circuit 6C phase current

Channel C: circuit 6C neutral to ground voltage.

Channel D: circuit 6C neutral current

Disk 11 Computer #'s 10 and 11 with the other computer connected to an alternate bus.

Channel A: circuit 10B line to neutral voltage

Channel B: circuit 10B phase current

Channel C: circuit 10B neutral to ground voltage.

Channel D: circuit 10B neutral current

Powerline monitor settings were as follows:

Channels A and C were measured in V; B and D were measured in A.

Setup #1	A	B	C	D
Range	VH	I30	VL	I30
Hi Lim	125	15.0	12.5	15.0
Low Lim	110	0.0	0.0	0.0
Sens.	50	5.0	5.0	5.0
Imp.	100	11.0	10.0	11.0
Wave	100	10.0	10.0	10.0
Frequency	0.5	(All Channels)		

Disks 10 and 11 refer to physical disk numbers containing sections of the data collected from the Cameron Library computer laboratory. Each disk number is directly referenced to the names seen in each waveform. As an example, Table 9 refers to compcam10 which is data located on disk 10. Computer numbers reference Figure 2.

4.2 Dranetz 658 Powerline Monitor Setup (Three Terminals):

Data collection involving three computer terminals required a parallel connection of three computer terminals to one phase of the three phase power supply electrical panel. The terminals were also connected in parallel with twenty-seven other terminals to a central modem hub via modem lines. Powerline Monitoring consisted of voltage and current connections to the associated phase of the power supply electrical panel as well as ground to neutral voltage measurement and neutral current measurement also located within the power supply electrical panel. The ground connection is made of electro-metallic tubing (i.e., conduit).

Powerline monitor connections were as follows:

Disk 5 Computer #'s 4, 5, and 6.

Channel A: circuit 6C line to neutral voltage

Channel B: circuit 6C phase current

Channel C: circuit 6C neutral to ground voltage.

Channel D: circuit 6C neutral current

Disk 6 Computer #'s 7, 8 and 9.

Channel A: circuit 8A line to neutral voltage

Channel B: circuit 8A phase current

Channel C: circuit 8A neutral to ground voltage.

Channel D: circuit 8A neutral current

Disk 7 Computer #'s 10, 11 and 12.

Channel A: circuit 10B line to neutral voltage

Channel B: circuit 10B phase current

Channel C: circuit 10B neutral to ground voltage.

Channel D: circuit 10B neutral current

Powerline monitor settings were as follows:

Channels A and C were measured in V; B and D were measured in A.

Setup #1	A	B	C	D
Range	VH	I30	VL	I30
Hi Lim	125	15.0	12.5	15.0
Low Lim	110	0.0	0.0	0.0
Sens.	50	5.0	5.0	5.0
Imp.	100	11.0	10.0	11.0
Wave	100	10.0	10.0	10.0
Frequency	0.5	(All Channels)		

Disks 5, 6 and 7 refer to physical disk numbers containing sections of the data collected from the Cameron Library computer laboratory. Each disk number is directly referenced to the names seen in each waveform. As an example, Table 13 refers to compcam6 which is data located on disk 6. Computer numbers reference Figure 2.

4.3 Dranetz 658 Powerline Monitor Setup (Thirty Terminals):

Data collection involving all thirty computer terminals required 10 parallel connections of groups of three computer terminals. Each group of terminals was connected to a separate single phase of the three phase power supply electrical panel. The terminals were also connected in parallel to a central modem hub via modem lines. Powerline monitoring consisted of voltage and current connections to all three of the associated phases of the power supply electrical panel as well as ground to neutral voltage measurement and neutral current measurement also located within the power supply electrical panel. The ground connection is made of electro-metallic tubing (i.e., conduit).

Powerline monitor connections were as follows:

Disk 1 All thirty computers.

Channel A: electrical panel phase A line to neutral voltage

Channel B: electrical panel phase A phase current

Channel C: electrical panel phase B line to neutral voltage

Channel D: electrical panel phase B phase current

Disks 2 and 4 All thirty computers.

Channel A: electrical panel phase C line to neutral voltage

Channel B: electrical panel phase C current

Channel C: electrical panel neutral to ground voltage.

Channel D: electrical panel neutral current

Disk 1 settings include monitoring of voltage and current for phases A and B.

Powerline monitor settings were as follows:

Setup #1	A	B	C	D
Range	VH	I30	VL	I30
Hi Lim	125	30.0	125	30.0
Low Lim	110	0.0	110	0.0
Sens.	50	5.0	50	5.0
Imp.	100	11.0	100	11.0
Wave	100	10.0	100	10.0
Frequency	0.5	(All Channels)		

Disks 2 and 4 settings including monitoring of voltage and current for phase C as well as neutral current and neutral to ground voltage.

Powerline monitor settings were as follows:

Channels A and C are measured in V; channels B and D are measured in A.

Setup #1	A	B	C	D
Range	VH	I300	VL	I300
Hi Lim	125	50	12.5	50
Low Lim	110	0	0	0
Sens.	50	50	5.0	50
Imp.	100	110	10.0	110
Wave	100	100	10.0	100
Frequency	0.5	(All Channels)		

Disks 1, 2 and 4 refer to physical disk numbers containing sections of the data collected from the Cameron Library computer laboratory. Each disk number is directly referenced to the names seen in each waveform. As an example, Table 17 refers to compcam1 which is data located on disk 1. Computer numbers reference Figure 2.

4.4 Harmonics (Two Terminals):

Current and voltage harmonics of two computer terminals measured at their associated phase of the three phase power supply electrical panel can be seen in Tables 9-12. Neutral current and ground to neutral voltage have also been included because harmonic coupling through a power system can be significant in both the ground and neutral conductors. Emphasis is placed on the neutral conductor as it interconnects with the power system in the same manner as the phase conductors.

4.4.1 Voltage Harmonics:

Harmonic levels associated with two terminals were higher in magnitude for currents than they were for voltage. The mean total harmonic distortion for the phase voltage is approximately 2.3% of the fundamental voltage magnitude. Percentages are based on sample waveforms (10% of 5000 waveforms) captured by the Dranetz 658 Powerline Monitor. The total odd harmonic contribution comprises approximately 3% (20 times the magnitude of the total even harmonic contribution) of the THD. Table 9 shows THD levels at 3.2% and the total odd harmonic contribution levels at 3.1% although this percentage level is merely 5 times the total even harmonic contribution level of 0.6%. Neutral to ground voltage contained much higher levels of harmonic content on a percentage basis. This is attributed to the significantly lower fundamental harmonic voltage magnitude in the neutral to ground voltage compared to the phase voltage. This can be seen in Table 10. (Both Tables 9 and 10 are sample data taken within 1 minute and 18 seconds of each other.) Tables 9 and 10 show the following:

Fundamental phase voltage magnitude in Table 9 is 116.79V. The third harmonic is 2.5% of the fundamental. The magnitude of the third harmonic phase voltage is 2.92V. The fundamental neutral to ground voltage magnitude from Table 10 is 1.44V. The third harmonic is 76.4% of the fundamental. The magnitude of the third harmonic neutral to ground voltage is 1.10V.

Table 9: Harmonic spectrum of two computer terminals (phase to neutral voltage)

658 GRAPHICAL & HARMONIC ANALYSIS (c)1988-1992 Dranetz Technologies, Inc.
: Print : eXit :

Event Number 4 | Channel A | Setup 1 | 03/26/96 | 09:00:56.03

Fnd:	116.79V 87 deg	18th:	0.1% 43 deg	35th:	0.1% 329 deg
2nd:	0.3% 311 deg	19th:	0.1% 356 deg	36th:	0.1% 232 deg
3rd:	2.5% 35 deg	20th:	0.1% 120 deg	37th:	0.1% 212 deg
4th:	0.3% 12 deg	21st:	0.3% 162 deg	38th:	0.1% 281 deg
5th:	0.6% 191 deg	22nd:	0.1% 156 deg	39th:	0.0% 343 deg
6th:	0.2% 85 deg	23rd:	0.1% 239 deg	40th:	0.0% 300 deg
7th:	1.3% 49 deg	24th:	0.1% 235 deg	41st:	0.1% 350 deg
8th:	0.2% 134 deg	25th:	0.2% 265 deg	42nd:	0.0% 342 deg
9th:	0.9% 213 deg	26th:	0.1% 317 deg	43rd:	0.0% 303 deg
10th:	0.1% 170 deg	27th:	0.1% 126 deg	44th:	0.0% 107 deg
11th:	0.3% 206 deg	28th:	0.1% 322 deg	45th:	0.0% 111 deg
12th:	0.1% 246 deg	29th:	0.1% 348 deg	46th:	0.1% 123 deg
13th:	0.3% 306 deg	30th:	0.0% 21 deg	47th:	0.1% 145 deg
14th:	0.1% 287 deg	31st:	0.0% 291 deg	48th:	0.1% 166 deg
15th:	0.5% 215 deg	32nd:	0.1% 95 deg	49th:	0.1% 201 deg
16th:	0.1% 0 deg	33rd:	0.1% 69 deg	50th:	0.1% 223 deg
17th:	0.1% 34 deg	34th:	0.0% 141 deg		

T.H.D.: 3.2% ODD CONTRIB.: 3.1% EVEN CONTRIB.: 0.6%
Frequency: 60.0 Hz
Fri 05 Jul 1996 | compcam10 | 15:22:57

Table 10: Harmonic spectrum of two computer terminals (neutral to ground voltage)

658 GRAPHICAL & HARMONIC ANALYSIS (c)1988-1992 Dranetz Technologies, Inc.
: Print : eXit :

Event Number 4 | Channel C | Setup 1 | 03/26/96 | 09:00:56.03

Fnd:	1.44V 69 deg	18th:	1.9% 291 deg	35th:	1.1% 148 deg
2nd:	8.4% 152 deg	19th:	0.9% 223 deg	36th:	1.4% 160 deg
3rd:	76.4% 222 deg	20th:	2.0% 8 deg	37th:	0.5% 330 deg
4th:	9.1% 225 deg	21st:	5.7% 343 deg	38th:	0.9% 240 deg
5th:	5.0% 34 deg	22nd:	1.4% 75 deg	39th:	1.7% 179 deg
6th:	8.8% 295 deg	23rd:	2.1% 156 deg	40th:	1.5% 286 deg
7th:	13.0% 298 deg	24th:	2.2% 147 deg	41st:	1.9% 336 deg
8th:	6.1% 1 deg	25th:	3.9% 139 deg	42nd:	1.0% 4 deg
9th:	23.4% 38 deg	26th:	2.1% 212 deg	43rd:	1.8% 356 deg
10th:	4.2% 56 deg	27th:	4.6% 238 deg	44th:	1.3% 54 deg
11th:	3.3% 52 deg	28th:	1.5% 261 deg	45th:	1.9% 77 deg
12th:	3.8% 116 deg	29th:	1.2% 231 deg	46th:	0.5% 197 deg
13th:	4.4% 175 deg	30th:	1.2% 335 deg	47th:	0.8% 274 deg
14th:	2.6% 165 deg	31st:	2.5% 43 deg	48th:	0.8% 181 deg
15th:	8.6% 3 deg	32nd:	1.1% 7 deg	49th:	1.6% 255 deg
16th:	2.6% 240 deg	33rd:	2.8% 131 deg	50th:	1.5% 315 deg
17th:	4.8% 272 deg	34th:	0.7% 114 deg		

T.H.D.: 84.7% ODD CONTRIB.: 82.6% EVEN CONTRIB.: 18.6%
Frequency: 60.0 Hz
Fri 05 Jul 1996 | compcam10 | 15:24:15

4.4.2 Current Harmonics:

The mean total harmonic distortion for the phase current is approximately 98% of the fundamental current magnitude. Percentages are based on sample waveforms (10% of 5000 waveforms) captured by the Dranetz 658 Powerline Monitor. The total odd harmonic contribution comprises approximately 23% (1.5 times the magnitude of the total even harmonic contribution) of the THD. Table 11 shows THD levels at 28.5% and the total odd harmonic contribution levels at 22.3%. Neutral current contained similar levels of harmonic content on a percentage basis. This is attributed to the similarities in the fundamental harmonic current magnitude of the phase and neutral conductors. This can be seen in Table 12.

The harmonic levels in the current follow patterns similar to the voltage due to the V=IZ relationship (Z is the system impedance). The basic harmonic levels expressed as a current do not change significantly from one conductor to another. As an example, the data seen in Tables 11 and 12 contain fundamental currents for the phase conductor and the neutral conductor which are 12.83A and 12.90A respectively. The third harmonic for each is 19.3% and 19.5% respectively. Both translate into third harmonic currents of approximately 2.5A. Again, harmonics coupling into the neutral conductor could create potential problems even though the fundamental harmonic current levels are not much lower than the higher order odd harmonic levels. Current harmonics, in this respect, differ from voltage harmonics.

Table 11: Harmonic spectrum of two computer terminals (phase current)

658 GRAPHICAL & HARMONIC ANALYSIS (c)1988-1992 Dranetz Technologies,Inc.
¦ Print ¦ eXit ¦

Event Number 4 Channel B Setup 1 03/26/96 09:00:56.03

Fnd:	12.83A	78 deg	18th:	1.9%	308 deg	35th:	0.8%	105 deg
2nd:	10.5%	151 deg	19th:	1.6%	344 deg	36th:	0.7%	147 deg
3rd:	19.3%	216 deg	20th:	1.4%	19 deg	37th:	0.8%	175 deg
4th:	9.2%	231 deg	21st:	1.0%	57 deg	38th:	0.7%	204 deg
5th:	6.6%	228 deg	22nd:	1.2%	73 deg	39th:	0.7%	232 deg
6th:	7.6%	303 deg	23rd:	1.2%	94 deg	40th:	0.8%	265 deg
7th:	6.2%	342 deg	24th:	1.0%	138 deg	41st:	0.8%	302 deg
8th:	4.7%	359 deg	25th:	1.0%	170 deg	42nd:	0.8%	327 deg
9th:	2.3%	21 deg	26th:	0.8%	198 deg	43rd:	0.8%	358 deg
10th:	3.2%	47 deg	27th:	1.0%	223 deg	44th:	0.8%	32 deg
11th:	3.3%	81 deg	28th:	1.0%	258 deg	45th:	0.8%	65 deg
12th:	2.6%	122 deg	29th:	0.9%	298 deg	46th:	0.7%	95 deg
13th:	2.4%	157 deg	30th:	0.9%	311 deg	47th:	0.8%	128 deg
14th:	2.0%	181 deg	31st:	0.9%	345 deg	48th:	0.8%	164 deg
15th:	2.6%	214 deg	32nd:	0.9%	24 deg	49th:	0.7%	190 deg
16th:	1.8%	258 deg	33rd:	0.8%	53 deg	50th:	0.7%	225 deg
17th:	1.6%	295 deg	34th:	0.7%	79 deg			

T.H.D.: 28.5% ODD CONTRIB.: 22.3% EVEN CONTRIB.: 17.8%

Frequency: 60.0 Hz

Fri 05 Jul 1996 | compcam10 | 15:23:40

Table 12: Harmonic spectrum of two computer terminals (neutral current)

658 GRAPHICAL & HARMONIC ANALYSIS (c)1988-1992 Dranetz Technologies,Inc.
¦ Print ¦ eXit ¦

Event Number 4 Channel D Setup 1 03/26/96 09:00:56.03

Fnd:	12.90A	258 deg	18th:	2.1%	120 deg	35th:	0.9%	296 deg
2nd:	10.5%	330 deg	19th:	1.9%	157 deg	36th:	1.0%	335 deg
3rd:	19.5%	33 deg	20th:	1.8%	193 deg	37th:	0.9%	3 deg
4th:	9.4%	48 deg	21st:	1.4%	235 deg	38th:	0.8%	37 deg
5th:	6.4%	46 deg	22nd:	1.5%	250 deg	39th:	0.8%	66 deg
6th:	7.8%	119 deg	23rd:	1.3%	273 deg	40th:	0.9%	95 deg
7th:	6.5%	157 deg	24th:	1.3%	317 deg	41st:	0.9%	132 deg
8th:	4.9%	174 deg	25th:	1.3%	347 deg	42nd:	0.8%	160 deg
9th:	2.4%	204 deg	26th:	1.2%	20 deg	43rd:	0.7%	189 deg
10th:	3.4%	223 deg	27th:	1.2%	43 deg	44th:	0.8%	220 deg
11th:	3.5%	255 deg	28th:	1.2%	80 deg	45th:	0.8%	254 deg
12th:	2.8%	296 deg	29th:	1.2%	117 deg	46th:	0.7%	288 deg
13th:	2.6%	330 deg	30th:	1.0%	140 deg	47th:	0.7%	312 deg
14th:	2.2%	355 deg	31st:	1.1%	172 deg	48th:	0.7%	345 deg
15th:	2.7%	24 deg	32nd:	1.2%	205 deg	49th:	0.7%	20 deg
16th:	2.1%	71 deg	33rd:	1.0%	239 deg	50th:	0.8%	55 deg
17th:	2.0%	107 deg	34th:	0.9%	270 deg			

T.H.D.: 29.2% ODD CONTRIB.: 22.8% EVEN CONTRIB.: 18.3%

Frequency: 60.0 Hz

Fri 05 Jul 1996 | compcam10 | 15:24:41

4.5 Harmonics (Three Terminals):

Current and voltage harmonics of three computer terminals as measured at their associated phase of the three phase power supply electrical panel can be seen in Tables 13-16. Neutral current and ground to neutral voltage have also been included because harmonic coupling through a power system can be significant in both the ground and neutral conductors. Emphasis is placed on the neutral conductor as it interconnects with the power system in the same manner as the phase conductors.

4.5.1 Voltage Harmonics:

Harmonic levels associated with three terminals were higher in magnitude for currents than they were for voltage. The mean total harmonic distortion for the phase voltage is approximately 2.5% of the fundamental voltage magnitude. Percentages are based on sample waveforms (10% of 5000 waveforms) captured by the Dranetz 658 Powerline Monitor. The total odd harmonic contribution comprises approximately 2.5% (10 times the magnitude of the total even harmonic contribution) of the THD. Table 13 shows THD levels at 2.4% and the total odd harmonic contribution levels at 2.4% although this percentage level is only approximately 8 times the total even harmonic contribution level of 0.3%. Neutral to ground voltage contained much higher levels of harmonic content on a percentage basis. This is attributed to the significantly lower fundamental harmonic voltage magnitude in the neutral to ground voltage compared to the phase voltage. This can be seen in Table 14. (Both Tables are sample data taken within 1 minute and 26 seconds of each other.) Tables 13 and 14 show the following:

Fundamental phase voltage magnitude from Table 13 is 121.31V. The third harmonic is 1.7% of the fundamental. The magnitude of the third harmonic phase voltage is 2.06V. The fundamental neutral to ground voltage magnitude from Table 14 is 0.26V. The third harmonic is 342.9% of the fundamental. The magnitude of the third harmonic neutral to ground voltage is 0.93V.

Table 13: Harmonic spectrum of three computer terminals (phase to neutral voltage)

658 GRAPHICAL & HARMONIC ANALYSIS (c)1988-1992 Dranetz Technologies,Inc.
: Print : eXit :
Event Number 4 Channel A Setup 1 03/07/96 11:55:21.00

Fnd:	121.31V	86 deg	18th:	0.1%	310 deg	35th:	0.1%	308 deg
2nd:	0.1%	352 deg	19th:	0.3%	270 deg	36th:	0.0%	262 deg
3rd:	1.7%	29 deg	20th:	0.0%	278 deg	37th:	0.1%	128 deg
4th:	0.1%	337 deg	21st:	0.2%	179 deg	38th:	0.0%	231 deg
5th:	0.6%	203 deg	22nd:	0.1%	262 deg	39th:	0.1%	40 deg
6th:	0.0%	340 deg	23rd:	0.2%	275 deg	40th:	0.1%	223 deg
7th:	1.2%	25 deg	24th:	0.1%	278 deg	41st:	0.1%	221 deg
8th:	0.1%	336 deg	25th:	0.2%	221 deg	42nd:	0.0%	229 deg
9th:	0.7%	225 deg	26th:	0.1%	286 deg	43rd:	0.0%	129 deg
10th:	0.1%	328 deg	27th:	0.0%	117 deg	44th:	0.0%	195 deg
11th:	0.2%	271 deg	28th:	0.1%	246 deg	45th:	0.0%	260 deg
12th:	0.1%	312 deg	29th:	0.1%	285 deg	46th:	0.1%	209 deg
13th:	0.4%	299 deg	30th:	0.1%	258 deg	47th:	0.1%	166 deg
14th:	0.0%	290 deg	31st:	0.2%	208 deg	48th:	0.0%	162 deg
15th:	0.4%	209 deg	32nd:	0.0%	247 deg	49th:	0.0%	102 deg
16th:	0.1%	318 deg	33rd:	0.1%	66 deg	50th:	0.1%	183 deg
17th:	0.1%	308 deg	34th:	0.0%	208 deg			

T.H.D.: 2.4% ODD CONTRIB.: 2.4% EVEN CONTRIB.: 0.3%
Frequency: 60.0 Hz
Fri 05 Jul 1996 | compcam6 | 15:27:13

Table 14: Harmonic spectrum of three computer terminals (neutral to ground voltage)

658 GRAPHICAL & HARMONIC ANALYSIS (c)1988-1992 Dranetz Technologies,Inc.
: Print : eXit :
Event Number 4 Channel C Setup 1 03/07/96 11:55:21.00

Fnd:	0.27V	262 deg	18th:	19.9%	128 deg	35th:	24.4%	70 deg
2nd:	23.6%	168 deg	19th:	43.0%	123 deg	36th:	22.4%	76 deg
3rd:	342.9%	232 deg	20th:	20.5%	115 deg	37th:	33.4%	56 deg
4th:	19.0%	174 deg	21st:	41.6%	65 deg	38th:	18.4%	72 deg
5th:	83.4%	160 deg	22nd:	21.4%	108 deg	39th:	15.8%	54 deg
6th:	18.4%	163 deg	23rd:	28.7%	100 deg	40th:	20.1%	56 deg
7th:	59.0%	157 deg	24th:	19.4%	110 deg	41st:	20.9%	60 deg
8th:	22.4%	153 deg	25th:	41.6%	99 deg	42nd:	22.5%	59 deg
9th:	105.5%	82 deg	26th:	20.3%	100 deg	43rd:	28.6%	37 deg
10th:	19.9%	149 deg	27th:	21.0%	65 deg	44th:	19.6%	60 deg
11th:	42.1%	136 deg	28th:	21.5%	92 deg	45th:	20.0%	44 deg
12th:	19.0%	149 deg	29th:	22.5%	82 deg	46th:	18.1%	41 deg
13th:	41.7%	141 deg	30th:	20.5%	97 deg	47th:	20.4%	49 deg
14th:	19.4%	134 deg	31st:	39.2%	79 deg	48th:	21.9%	41 deg
15th:	76.8%	73 deg	32nd:	20.9%	82 deg	49th:	23.3%	16 deg
16th:	19.6%	132 deg	33rd:	12.5%	80 deg	50th:	23.1%	52 deg
17th:	32.4%	119 deg	34th:	20.8%	74 deg			

T.H.D.: 416.5% ODD CONTRIB.: 403.6% EVEN CONTRIB.: 102.8%
Frequency: 60.0 Hz
Fri 05 Jul 1996 | compcam6 | 15:28:39

4.5.2 Current Harmonics:

The mean total harmonic distortion for the phase current is approximately 109% of the fundamental current magnitude. Percentages are based on sample waveforms (10% of 5000 waveforms) captured by the Dranetz 658 Powerline Monitor. The total odd harmonic contribution comprises approximately 125% (80 times the magnitude of the total even harmonic contributions) of the THD. Table 15 shows THD levels at 120.4% and the total odd harmonic contribution levels at 120.4% although this percentage level is approximately 86 times the total even harmonic contribution level of 1.4%. Neutral current contained higher levels of harmonic content on a percentage basis. This is attributed to the similarities in the fundamental harmonic current magnitude of the phase and neutral conductors and the increased number of non-linear devices providing harmonic coupling into the power system. This can be seen in Table 16.

The harmonic levels in the current follow patterns similar to the voltage due to the V=IZ relationship (Z is the system impedance). The basic harmonic levels expressed as a current do not change significantly from one conductor to another. As an example, the data seen in Tables 15 and 16 contain fundamental currents for the phase conductor and the neutral conductor which are 2.02A and 1.80A respectively. The third harmonic for each is 87.7% and 145.4% respectively. Translating to third harmonic currents of approximately 1.77A and 2.6A respectively. Neutral conductor current harmonic levels seem significant when seen as a percentage, although an average magnitude of the current harmonic of approximately 1A is not significant. This illustrates the neutral conductors susceptibility to harmonics and the ease with which substantial harmonics could enter a power system.

Table 15: Harmonic spectrum of three computer terminals (phase current)

658 GRAPHICAL & HARMONIC ANALYSIS (c)1988-1992 Dranetz Technologies,Inc.
: Print : eXit :

Event Number 4 Channel B Setup 1 03/07/96 11:55:21.00

Fnd:	2.02A	262 deg	18th:	0.2%	263 deg	35th:	0.6%	10 deg
2nd:	0.3%	177 deg	19th:	2.2%	353 deg	36th:	0.3%	84 deg
3rd:	87.7%	92 deg	20th:	0.2%	112 deg	37th:	0.9%	290 deg
4th:	0.2%	114 deg	21st:	2.3%	269 deg	38th:	0.4%	124 deg
5th:	66.5%	277 deg	22nd:	0.3%	140 deg	39th:	1.0%	131 deg
6th:	0.3%	162 deg	23rd:	3.5%	110 deg	40th:	0.3%	43 deg
7th:	42.3%	102 deg	24th:	0.2%	117 deg	41st:	0.8%	345 deg
8th:	0.3%	185 deg	25th:	2.5%	319 deg	42nd:	0.5%	110 deg
9th:	19.3%	289 deg	26th:	0.2%	73 deg	43rd:	0.5%	211 deg
10th:	0.3%	144 deg	27th:	1.0%	180 deg	44th:	0.2%	62 deg
11th:	3.0%	140 deg	28th:	0.2%	132 deg	45th:	0.7%	89 deg
12th:	0.4%	177 deg	29th:	1.7%	89 deg	46th:	0.4%	58 deg
13th:	7.1%	100 deg	30th:	0.3%	96 deg	47th:	0.7%	315 deg
14th:	0.1%	78 deg	31st:	1.6%	304 deg	48th:	0.3%	113 deg
15th:	8.6%	293 deg	32nd:	0.1%	252 deg	49th:	0.5%	184 deg
16th:	0.4%	167 deg	33rd:	1.6%	141 deg	50th:	0.4%	89 deg
17th:	5.9%	125 deg	34th:	0.2%	12 deg			

T.H.D.: 120.4% ODD CONTRIB.: 120.4% EVEN CONTRIB.: 1.4%
Frequency: 60.0 Hz

Fri 05 Jul 1996 | compcam6 | 15:28:13

Table 16: Harmonic spectrum of three computer terminals (neutral current)

658 GRAPHICAL & HARMONIC ANALYSIS (c)1988-1992 Dranetz Technologies,Inc.
: Print : eXit :

Event Number 4 Channel D Setup 1 03/07/96 11:55:21.00

Fnd:	1.00A	11 deg	18th:	47.5%	278 deg	35th:	32.8%	198 deg
2nd:	54.5%	350 deg	19th:	47.4%	278 deg	36th:	31.7%	195 deg
3rd:	145.4%	66 deg	20th:	46.0%	268 deg	37th:	31.4%	190 deg
4th:	52.3%	342 deg	21st:	46.5%	262 deg	38th:	28.7%	186 deg
5th:	23.1%	15 deg	22nd:	44.9%	259 deg	39th:	27.5%	180 deg
6th:	52.3%	333 deg	23rd:	46.2%	256 deg	40th:	26.4%	176 deg
7th:	38.7%	300 deg	24th:	43.1%	250 deg	41st:	25.5%	170 deg
8th:	52.0%	323 deg	25th:	42.0%	249 deg	42nd:	23.9%	167 deg
9th:	79.8%	297 deg	26th:	41.3%	241 deg	43rd:	24.0%	161 deg
10th:	51.3%	314 deg	27th:	38.4%	234 deg	44th:	21.0%	157 deg
11th:	55.0%	312 deg	28th:	39.7%	232 deg	45th:	20.4%	153 deg
12th:	50.0%	305 deg	29th:	40.1%	226 deg	46th:	18.7%	146 deg
13th:	51.5%	298 deg	30th:	37.4%	223 deg	47th:	17.6%	141 deg
14th:	49.4%	296 deg	31st:	36.5%	219 deg	48th:	15.8%	136 deg
15th:	62.6%	286 deg	32nd:	35.5%	213 deg	49th:	15.8%	130 deg
16th:	48.7%	287 deg	33rd:	32.7%	206 deg	50th:	12.9%	124 deg
17th:	52.0%	286 deg	34th:	33.5%	204 deg			

T.H.D.: 318.3% ODD CONTRIB.: 246.3% EVEN CONTRIB.: 201.7%
Frequency: 60.0 Hz

Fri 05 Jul 1996 | compcam6 | 15:29:08

4.6 Harmonics (Thirty Terminals):

Current and voltage harmonics of thirty computer terminals (also including the computer laser printer) measured at their associated phases of the three phase power supply electrical panel can be seen in Tables 17-24. Neutral current and ground to neutral voltage have also been included because harmonic coupling through a power system can be significant in both the ground and neutral conductors. Emphasis is placed on the neutral conductor as it interconnects with the power system in the same manner as the phase conductors.

4.6.1 Voltage Harmonics:

Harmonic levels associated with thirty terminals were higher in magnitude for currents than they were for voltage. The mean total harmonic distortion for the phase voltage is approximately 3% of the fundamental voltage magnitude. Percentages are based on sample waveforms (10% of 5000 waveforms) captured by the Dranetz 658 Powerline Monitor. The total odd harmonics contribution comprises approximately 2.9% of the THD. Tables 17, 18 and 19 show THD levels at 2.5%, 3.4%, and 2.4% respectively and the total odd harmonic contribution levels at 2.5%, 3.3%, and 2.3% respectively although these percentage levels are only approximately 8, 4, and 11 times the total even harmonic contribution level of 0.3%, 0.8%, and 0.2% respectively. Neutral to ground voltage contained much higher levels of harmonic content on a percentage basis. This is attributed to the significantly lower fundamental harmonic voltage magnitude in the neutral to ground voltage compared to the phase voltage. This can be seen in Table 20 (both Tables are sample data taken within 47 seconds of each other). Tables 19 and 20 show the following:

Fundamental phase voltage magnitude from Table 19 is 120.94V. The third harmonic is 1.9% of the fundamental. The magnitude of the third harmonic phase voltage is 2. 29V. The fundamental neutral to ground voltage magnitude from Table 20 is 0.11V. The third harmonic is 800.1% of the fundamental. The magnitude of the third harmonic neutral to ground voltage is 0.88V. Extremely large harmonic levels in the neutral conductor in comparison to its fundamental arise if, as an example, there is a third harmonic in the phase voltage of 10% instead of 1.9%. In this case, the harmonic would couple into the neutral to ground voltage producing a third harmonic voltage level of 4224% that would make the neutral to ground fundamental voltage seem insignificant. These high harmonic levels could reciprocate in other conductors such as communication wires creating a variety of potentially hazardous problems.

Table 17: Harmonic spectrum of thirty computer terminals (phase A to neutral voltage)

658 GRAPHICAL & HARMONIC ANALYSIS (c)1988-1992 Dranetz Technologies,Inc.
: Print : eXit :
Event Number 4 Channel A Setup 1 02/12/96 14:15:47.89

Fnd:	120.85V	89 deg	18th:	0.1%	201 deg	35th:	0.0%	99 deg
2nd:	0.1%	315 deg	19th:	0.3%	312 deg	36th:	0.0%	46 deg
3rd:	1.0%	41 deg	20th:	0.1%	139 deg	37th:	0.1%	213 deg
4th:	0.1%	237 deg	21st:	0.2%	231 deg	38th:	0.0%	341 deg
5th:	0.8%	204 deg	22nd:	0.0%	345 deg	39th:	0.1%	121 deg
6th:	0.0%	118 deg	23rd:	0.1%	340 deg	40th:	0.0%	210 deg
7th:	1.1%	47 deg	24th:	0.0%	261 deg	41st:	0.0%	307 deg
8th:	0.0%	328 deg	25th:	0.2%	303 deg	42nd:	0.0%	177 deg
9th:	0.7%	245 deg	26th:	0.0%	213 deg	43rd:	0.1%	219 deg
10th:	0.1%	232 deg	27th:	0.1%	169 deg	44th:	0.0%	278 deg
11th:	0.2%	298 deg	28th:	0.0%	144 deg	45th:	0.1%	90 deg
12th:	0.1%	166 deg	29th:	0.1%	29 deg	46th:	0.0%	17 deg
13th:	0.4%	323 deg	30th:	0.0%	315 deg	47th:	0.0%	280 deg
14th:	0.0%	99 deg	31st:	0.1%	259 deg	48th:	0.0%	196 deg
15th:	0.5%	241 deg	32nd:	0.1%	248 deg	49th:	0.0%	208 deg
16th:	0.1%	304 deg	33rd:	0.1%	148 deg	50th:	0.0%	317 deg
17th:	0.1%	356 deg	34th:	0.0%	165 deg			

T.H.D.: 2.5% ODD CONTRIB.: 2.5% EVEN CONTRIB.: 0.3%
Frequency: 60.0 Hz
Fri 05 Jul 1996 | compcam1 | 16:01:49

Table 18: Harmonic spectrum of thirty computer terminals (phase B to neutral voltage)

658 GRAPHICAL & HARMONIC ANALYSIS (c)1988-1992 Dranetz Technologies,Inc.
: Print : eXit :
Event Number 4 Channel C Setup 1 02/12/96 14:15:47.89

Fnd:	119.99V	330 deg	18th:	0.2%	228 deg	35th:	0.2%	291 deg
2nd:	0.1%	283 deg	19th:	0.3%	327 deg	36th:	0.1%	83 deg
3rd:	2.4%	51 deg	20th:	0.2%	128 deg	37th:	0.1%	232 deg
4th:	0.2%	193 deg	21st:	0.4%	270 deg	38th:	0.1%	331 deg
5th:	1.3%	328 deg	22nd:	0.1%	34 deg	39th:	0.2%	141 deg
6th:	0.2%	92 deg	23rd:	0.1%	159 deg	40th:	0.2%	242 deg
7th:	1.3%	311 deg	24th:	0.1%	266 deg	41st:	0.1%	352 deg
8th:	0.1%	339 deg	25th:	0.1%	2 deg	42nd:	0.1%	155 deg
9th:	0.6%	257 deg	26th:	0.2%	202 deg	43rd:	0.2%	278 deg
10th:	0.2%	248 deg	27th:	0.2%	304 deg	44th:	0.1%	55 deg
11th:	0.5%	8 deg	28th:	0.1%	114 deg	45th:	0.1%	187 deg
12th:	0.2%	158 deg	29th:	0.2%	233 deg	46th:	0.2%	299 deg
13th:	0.4%	282 deg	30th:	0.1%	17 deg	47th:	0.1%	102 deg
14th:	0.1%	63 deg	31st:	0.0%	350 deg	48th:	0.1%	212 deg
15th:	0.6%	266 deg	32nd:	0.2%	257 deg	49th:	0.1%	341 deg
16th:	0.1%	313 deg	33rd:	0.1%	57 deg	50th:	0.1%	141 deg
17th:	0.2%	68 deg	34th:	0.2%	186 deg			

T.H.D.: 3.4% ODD CONTRIB.: 3.3% EVEN CONTRIB.: 0.8%
Frequency: 60.0 Hz
Fri 05 Jul 1996 | compcam1 | 16:02:49

Table 19: Harmonic spectrum of thirty computer terminals (phase C to neutral voltage)

658 GRAPHICAL & HARMONIC ANALYSIS (c)1988-1992 Dranetz Technologies,Inc.

: Print : eXit :

Event Number 4 Channel A Setup 1 02/15/96 16:11:30.16

Fnd:	120.94V	88 deg	18th:	0.0%	116 deg	35th:	0.0%	75 deg
2nd:	0.2%	69 deg	19th:	0.2%	234 deg	36th:	0.0%	193 deg
3rd:	1.9%	40 deg	20th:	0.0%	120 deg	37th:	0.1%	107 deg
4th:	0.1%	135 deg	21st:	0.1%	201 deg	38th:	0.0%	254 deg
5th:	0.6%	145 deg	22nd:	0.0%	174 deg	39th:	0.0%	49 deg
6th:	0.0%	111 deg	23rd:	0.2%	321 deg	40th:	0.0%	101 deg
7th:	0.7%	47 deg	24th:	0.0%	347 deg	41st:	0.0%	129 deg
8th:	0.1%	75 deg	25th:	0.1%	231 deg	42nd:	0.0%	82 deg
9th:	0.7%	230 deg	26th:	0.0%	205 deg	43rd:	0.1%	78 deg
10th:	0.0%	91 deg	27th:	0.1%	104 deg	44th:	0.0%	264 deg
11th:	0.1%	352 deg	28th:	0.0%	278 deg	45th:	0.0%	69 deg
12th:	0.0%	112 deg	29th:	0.1%	339 deg	46th:	0.0%	33 deg
13th:	0.3%	274 deg	30th:	0.0%	262 deg	47th:	0.0%	135 deg
14th:	0.0%	103 deg	31st:	0.1%	89 deg	48th:	0.0%	68 deg
15th:	0.4%	229 deg	32nd:	0.0%	34 deg	49th:	0.0%	9 deg
16th:	0.0%	159 deg	33rd:	0.1%	46 deg	50th:	0.0%	247 deg
17th:	0.2%	352 deg	34th:	0.0%	356 deg			

T.H.D.: 2.4% ODD CONTRIB.: 2.3% EVEN CONTRIB.: 0.2%

Frequency: 60.0 Hz

Fri 05 Jul 1996 | compcam3 | 16:04:48

Table 20: Harmonic spectrum of thirty computer terminals (neutral to ground voltage)

658 GRAPHICAL & HARMONIC ANALYSIS (c)1988-1992 Dranetz Technologies,Inc.

: Print : eXit :

Event Number 4 Channel C Setup 1 02/15/96 16:11:30.16

Fnd:	0.11V	318 deg	18th:	32.6%	175 deg	35th:	12.5%	305 deg
2nd:	126.8%	85 deg	19th:	29.4%	117 deg	36th:	23.2%	19 deg
3rd:	800.1%	46 deg	20th:	24.7%	220 deg	37th:	19.7%	203 deg
4th:	95.1%	186 deg	21st:	38.6%	158 deg	38th:	11.8%	167 deg
5th:	63.5%	85 deg	22nd:	59.6%	334 deg	39th:	25.7%	246 deg
6th:	39.7%	224 deg	23rd:	35.0%	16 deg	40th:	8.3%	203 deg
7th:	151.1%	207 deg	24th:	29.6%	117 deg	41st:	14.0%	220 deg
8th:	65.8%	277 deg	25th:	29.1%	19 deg	42nd:	22.6%	0 deg
9th:	239.9%	227 deg	26th:	16.7%	166 deg	43rd:	36.9%	163 deg
10th:	51.0%	44 deg	27th:	5.8%	23 deg	44th:	9.6%	162 deg
11th:	44.3%	66 deg	28th:	38.8%	299 deg	45th:	13.0%	241 deg
12th:	29.6%	209 deg	29th:	23.3%	353 deg	46th:	9.5%	138 deg
13th:	68.8%	181 deg	30th:	28.0%	80 deg	47th:	4.4%	127 deg
14th:	51.4%	255 deg	31st:	23.7%	336 deg	48th:	15.5%	1 deg
15th:	132.8%	198 deg	32nd:	18.2%	201 deg	49th:	36.7%	131 deg
16th:	74.7%	8 deg	33rd:	28.2%	285 deg	50th:	16.6%	253 deg
17th:	49.1%	58 deg	34th:	17.7%	248 deg			

T.H.D.: 903.3% ODD CONTRIB.: 872.9% EVEN CONTRIB.: 232.3%

Frequency: 60.0 Hz

Fri 05 Jul 1996 | compcam3 | 16:05:37

4.6.2 Current Harmonics:

The mean total harmonic distortion for the phase current is approximately 124% of the fundamental current magnitude. Percentages are based on sample waveforms (10% of 5000 waveforms) captured by the Dranetz 658 Powerline Monitor. The total odd harmonic contribution comprises approximately 85% (8 times the magnitude of the total even harmonic contributions) of the THD. Tables 21, 22 and 23 show THD levels at 115.6%, 95.9%, and 74.2% respectively and the total odd harmonic contribution levels at 115.5%, 93.6%, and 68.6% respectively although these percentage levels are approximately 35, 4.5, 2.4 times the total even harmonic contribution level of 3.3%, 20.9%, and 28.5% respectively. Neutral current contained higher levels of harmonic content on a percentage basis. This is attributed to the similarities in the fundamental harmonic current magnitude of the phase and neutral conductors and the increased number of non-linear devices providing harmonic coupling into the power system. This can be seen in Table 24.

The harmonic levels in the current follow patterns similar to the voltage due to the V=IZ relationship (Z is the system impedance). The basic harmonic levels expressed as a current do not change significantly from one conductor to another. As an example, the data seen in Tables 23 and 24 contain fundamental currents for the phase conductor and the neutral conductor which are 12.02A and 3.76A respectively. The third harmonic for each is 46.5% and 620.8% respectively. Translating into third harmonic currents of approximately 5.58A and 23.5A respectively. Harmonic coupling into the neutral conductor creates potential problems as the harmonic current levels are much higher than the fundamental harmonic current.

Table 21: Harmonic spectrum of thirty computer terminals (phase A current)

658 GRAPHICAL & HARMONIC ANALYSIS (c)1988-1992 Dranetz Technologies,Inc.

: Print : eXit :

Event Number 4 Channel B Setup 1 02/12/96 14:15:47.89

Fnd:	7.89A 266 deg	18th:	0.1% 292 deg	35th:	0.8% 112 deg
2nd:	1.8% 196 deg	19th:	2.9% 55 deg	36th:	0.1% 233 deg
3rd:	85.8% 100 deg	20th:	0.1% 312 deg	37th:	1.4% 15 deg
4th:	1.7% 39 deg	21st:	2.6% 326 deg	38th:	0.2% 106 deg
5th:	63.3% 290 deg	22nd:	0.2% 244 deg	39th:	1.5% 255 deg
6th:	1.3% 244 deg	23rd:	3.2% 179 deg	40th:	0.2% 40 deg
7th:	38.6% 121 deg	24th:	0.3% 95 deg	41st:	0.7% 108 deg
8th:	1.0% 92 deg	25th:	2.6% 30 deg	42nd:	0.4% 346 deg
9th:	17.0% 319 deg	26th:	0.3% 342 deg	43rd:	0.9% 13 deg
10th:	0.6% 318 deg	27th:	1.1% 257 deg	44th:	0.3% 251 deg
11th:	3.7% 202 deg	28th:	0.4% 274 deg	45th:	0.7% 244 deg
12th:	0.2% 223 deg	29th:	1.4% 175 deg	46th:	0.3% 152 deg
13th:	6.9% 123 deg	30th:	0.4% 133 deg	47th:	0.5% 77 deg
14th:	0.1% 171 deg	31st:	2.0% 24 deg	48th:	0.4% 42 deg
15th:	8.2% 336 deg	32nd:	0.3% 19 deg	49th:	0.6% 326 deg
16th:	0.2% 23 deg	33rd:	1.8% 242 deg	50th:	0.3% 272 deg
17th:	5.7% 181 deg	34th:	0.4% 315 deg		

T.H.D.: 115.6% ODD CONTRIB.: 115.5% EVEN CONTRIB.: 3.3%

Frequency: 60.0 Hz

Fri 05 Jul 1996 | compcam1 | 16:02:14

Table 22: Harmonic spectrum of thirty computer terminals (phase B current)

658 GRAPHICAL & HARMONIC ANALYSIS (c)1988-1992 Dranetz Technologies,Inc.

: Print : eXit :

Event Number 4 Channel D Setup 1 02/12/96 14:15:47.89

Fnd:	17.81A 129 deg	18th:	3.2% 218 deg	35th:	2.1% 228 deg
2nd:	9.9% 330 deg	19th:	3.0% 316 deg	36th:	2.0% 6 deg
3rd:	73.3% 78 deg	20th:	3.0% 120 deg	37th:	2.2% 134 deg
4th:	11.7% 235 deg	21st:	4.5% 237 deg	38th:	1.8% 256 deg
5th:	49.1% 20 deg	22nd:	2.2% 12 deg	39th:	1.8% 28 deg
6th:	7.1% 129 deg	23rd:	3.7% 155 deg	40th:	1.7% 157 deg
7th:	26.3% 320 deg	24th:	2.5% 264 deg	41st:	1.7% 278 deg
8th:	3.7% 16 deg	25th:	2.0% 39 deg	42nd:	1.6% 50 deg
9th:	5.2% 258 deg	26th:	2.8% 164 deg	43rd:	1.8% 176 deg
10th:	3.9% 269 deg	27th:	2.6% 272 deg	44th:	1.5% 302 deg
11th:	5.8% 13 deg	28th:	2.5% 64 deg	45th:	1.6% 74 deg
12th:	4.5% 185 deg	29th:	3.2% 182 deg	46th:	1.6% 200 deg
13th:	8.9% 304 deg	30th:	2.3% 317 deg	47th:	1.5% 315 deg
14th:	3.5% 80 deg	31st:	2.5% 91 deg	48th:	1.5% 92 deg
15th:	6.0% 233 deg	32nd:	2.4% 209 deg	49th:	1.6% 216 deg
16th:	2.5% 309 deg	33rd:	1.9% 336 deg	50th:	1.5% 340 deg
17th:	2.2% 133 deg	34th:	2.2% 109 deg		

T.H.D.: 95.9% ODD CONTRIB.: 93.6% EVEN CONTRIB.: 20.9%

Frequency: 60.0 Hz

Fri 05 Jul 1996 | compcam1 | 16:03:14

Table 23: Harmonic spectrum of thirty computer terminals (phase C current)

658 GRAPHICAL & HARMONIC ANALYSIS (c)1988-1992 Dranetz Technologies,Inc.
: Print : eXit :
Event Number 4 Channel B Setup 1 02/15/96 16:11:30.16

Fnd:	12.02A	68 deg	18th:	0.6%	57 deg	35th:	0.5%	212 deg
2nd:	27.3%	289 deg	19th:	2.3%	192 deg	36th:	0.2%	342 deg
3rd:	46.5%	260 deg	20th:	0.6%	103 deg	37th:	0.7%	81 deg
4th:	5.3%	347 deg	21st:	0.3%	12 deg	38th:	0.3%	144 deg
5th:	40.6%	107 deg	22nd:	0.9%	150 deg	39th:	0.7%	326 deg
6th:	2.5%	11 deg	23rd:	2.0%	312 deg	40th:	0.2%	263 deg
7th:	25.3%	287 deg	24th:	0.2%	202 deg	41st:	0.4%	169 deg
8th:	3.4%	324 deg	25th:	1.2%	165 deg	42nd:	0.3%	252 deg
9th:	13.2%	135 deg	26th:	0.5%	147 deg	43rd:	0.7%	40 deg
10th:	1.1%	68 deg	27th:	1.3%	356 deg	44th:	0.4%	128 deg
11th:	2.6%	303 deg	28th:	0.6%	185 deg	45th:	0.4%	288 deg
12th:	1.2%	19 deg	29th:	0.7%	276 deg	46th:	0.2%	296 deg
13th:	4.7%	275 deg	30th:	0.5%	270 deg	47th:	0.6%	109 deg
14th:	0.7%	4 deg	31st:	1.0%	138 deg	48th:	0.0%	26 deg
15th:	4.3%	151 deg	32nd:	0.2%	183 deg	49th:	0.4%	28 deg
16th:	1.1%	112 deg	33rd:	0.9%	346 deg	50th:	0.4%	136 deg
17th:	4.3%	318 deg	34th:	0.2%	206 deg			

T.H.D.: 74.2% ODD CONTRIB.: 68.6% EVEN CONTRIB.: 28.3%
Frequency: 60.0 Hz
Fri 05 Jul 1996 | compcam3 | 16:05:13

Table 24: Harmonic spectrum of thirty computer terminals (neutral current)

658 GRAPHICAL & HARMONIC ANALYSIS (c)1988-1992 Dranetz Technologies,Inc.
: Print : eXit :
Event Number 4 Channel D Setup 1 02/15/96 16:11:30.16

Fnd:	3.76A	128 deg	18th:	1.1%	345 deg	35th:	2.5%	206 deg
2nd:	80.4%	293 deg	19th:	12.4%	79 deg	36th:	0.4%	147 deg
3rd:	620.8%	272 deg	20th:	1.3%	48 deg	37th:	4.8%	330 deg
4th:	11.7%	3 deg	21st:	11.3%	112 deg	38th:	0.5%	83 deg
5th:	76.1%	3 deg	22nd:	2.0%	95 deg	39th:	2.3%	342 deg
6th:	5.4%	1 deg	23rd:	4.5%	258 deg	40th:	0.3%	210 deg
7th:	47.3%	102 deg	24th:	0.9%	236 deg	41st:	1.3%	209 deg
8th:	10.4%	316 deg	25th:	7.2%	44 deg	42nd:	0.9%	106 deg
9th:	111.1%	128 deg	26th:	0.7%	168 deg	43rd:	3.8%	303 deg
10th:	4.0%	78 deg	27th:	3.8%	39 deg	44th:	0.6%	88 deg
11th:	13.3%	328 deg	28th:	1.6%	139 deg	45th:	1.0%	333 deg
12th:	4.1%	341 deg	29th:	2.3%	202 deg	46th:	0.8%	226 deg
13th:	19.8%	96 deg	30th:	1.2%	230 deg	47th:	0.8%	202 deg
14th:	2.7%	359 deg	31st:	6.1%	4 deg	48th:	0.2%	129 deg
15th:	45.7%	133 deg	32nd:	1.1%	84 deg	49th:	2.6%	272 deg
16th:	3.8%	86 deg	33rd:	3.7%	341 deg	50th:	1.3%	113 deg
17th:	8.1%	296 deg	34th:	0.4%	230 deg			

T.H.D.: 644.8% ODD CONTRIB.: 639.5% EVEN CONTRIB.: 82.5%
Frequency: 60.0 Hz
Fri 05 Jul 1996 | compcam3 | 16:06:00

4.7 Voltage Drop in Supply:

Voltage levels in the supply of power from the University of Alberta power distribution system to the power supply electrical panel are monitored on a regular basis by the electrical utility department at the University of Alberta. Voltage, power factor, and current availability are monitored in order to maintain strict standards in supply quality from the distribution system to all its loads. Maintaining high power factor and stable voltage levels increases power delivery efficiency. Monitoring, corrective action, and preventative maintenance keep voltage levels well within standard specifications [CSA: CAN3-235-83] during normal operating conditions. Voltage levels are consistent to +/- 3% during low demand periods and +/- 5% during peak demand periods. These levels do not include severe operating conditions such as black-outs.

Voltage levels are maintained within the power distribution system at the Cameron Library up to and including the main transformer unit located in the penthouse. From the penthouse, power is transferred to distribution transformers which provide power to cables running to power supply electrical panels including the electrical panel associated with this powerline monitor study. In turn, these electrical panels provide power to all the various loads throughout the building.

4.8 Equivalent Circuit Model of multiple computer terminal power supplies:

Performance modeling of multiple computer terminals requires both the knowledge of voltage and current characteristics as well as internal structuring of computer terminals. An equivalent circuit model for multiple computer terminals requires voltage and current input, components representing the changes performed on the input signal, and voltage and current output. The multiple computer terminal model can be applied to any number of computer terminals for which data is available.

The input is a voltage source equivalent to voltage seen at the phase connection to the power supply electrical panel. Following IEEE Standard 519-1992 Section 8.1, non-linear devices (such as a computer terminal power supply) can be replaced with a current source. IEEE Standard 519 also includes a limitation, as the voltage source must contain harmonic levels less than approximately ten percent. For the purpose of developing this model, these standards are used. The voltage source contains impedance, although in this instance, the impedance is governed by the cable impedance from the power supply panel to the distribution transformer (within Cameron Library) and the distribution transformer itself.

The voltage input signal (and neutral to ground voltage output signal) travels along a cable seen as a series inductance and resistance (Figure 17). The cable is a group of short parallel cables, each providing power to one computer terminal, connected to the phase cable running to the computer laboratory power supply panel. The inductance and resistance is calculated from the voltage drop characteristics seen in section 3.5. An approximation is used when calculating the impedance of the short parallel cables. Each short cable contains power = (total power)/(number of short cables). These cables are combined and treated as one single cable containing the total power. For example, three cables each containing 1/3 of the total power are placed in parallel to reduce the total impedance by three. The total power flowing through the equivalent cable is three times the power each original cable thus equivalently increasing the impedance by a factor of three. The net result using this approximation is no net change to the impedance value of the equivalent cable regardless of the number of cables in parallel. Standard 519 also provides a cable line impedance approximation as an alternate method of determining line inductance when cable data is not available. Per-phase line inductance on a three-phase ac line can be considered to be 1 μH/m.

After traversing the cable, the voltage and current signals then enter the computer power supplies. The group of computer terminal power supplies are in parallel. All of the computer power supplies are similar and are treated as identical. The power supplies are modeled as being one single power supply containing the sum of the total power seen in each parallel power supply. The characteristics of each computer power supply vary depending on the harmonic order in question. The fundamental harmonic is represented as a simple resistance where power, including the full range of harmonics provided from the power supply panel voltage source, is being absorbed by the computer power supplies to operate the computer terminals and their peripheral devices.

The output of the computer power supplies include several different components. The fundamental voltage harmonic of the computer power supplies flows through Z_{CPU1}. The rest of the harmonics are seen individually as current sources providing direct coupling to the power supply electrical panel. For each harmonic order above 1, there is a current source which is directly proportional in magnitude to the percentage harmonic level with respect to the fundamental harmonic magnitude. The model shows only a few current sources, representing the highest percentage harmonic levels with respect to the fundamental harmonic magnitude.

The equivalent circuit model is developed using two sets of equations. Initial calculations are required to determine the impedance of the parallel computer terminals at the fundamental harmonic. Equation (3-1a) can be used to calculate the impedance Z_{CPU1} from the magnitude of the voltage and current. Equation (3-2) may be used to calculate the resistive component of the impedance Z_{CPU1} from the magnitude of current and power. Equation (3-2) is an approximation as it assumes the total watts of power used by the computer terminals fall within the fundamental harmonic. Equation (3-3) is used to calculate the inductive or capacitive portion of the impedance Z_{CPU1}. The imaginary portion of the computer terminals' impedance is a function of harmonic order and can be re-calculated for each harmonic order using the n as a multiplying factor. A second set of equations is necessary for determining overall voltage and current relationships for the circuit model. Equation (3-4) is applied at each harmonic which is relevant to the circuit model. This includes the fundamental harmonic and any subsequent harmonic for which there is an associated current source.

4.8.1 Three Computer Terminals' Equivalent Circuit Model:

An example of a circuit model for three computer terminals, Figure 19, was developed using data from cable voltage drop (Section 3.5), voltage characteristics from Table 13 as well as current characteristics from Table 15. The voltage source is 121.31V RMS at 86° at the fundamental harmonic (but still contains all input harmonics). The voltage source impedance (in parallel with the voltage source itself) is considered to be large due to the extensive cable length to the distribution transformer and large size of the distribution transformer relative to the small amount of power being used by the computer power supply. The equivalent cable impedance, for the phase and neutral cables(a length of 15 feet), for the fundamental (positive sequence), is 0.0122 + j0.0011n ohms. The computer power supply is represented by a resistive component (to be calculated) and several current sources. For a comprehensive model, a current source should be included for each harmonic being considered. To illustrate the application of the model, current sources are shown for harmonics containing at least 10% of the magnitude of the fundamental harmonic current. These values are:

3rd Harmonic:	1.77A at 92°
5th Harmonic:	1.34A at 277°
7th Harmonic:	0.85A at 102°
9th Harmonic:	0.39A at 289°

Application of equation (3-1) yields $Z_{CPU1} = 121.31V\angle 86/2.02A\angle 262 = 60.05$ ohms.

Equation (3-2), given that real power (from computer specifications) is 68 Watts, $R_{CPU1} = 68x3/((2.02)^2) = 50.0$ ohms and $X_{CPU1} = (Z_{CPU1}^2 - R_{CPU1}^2)^{1/2} = 33.26$ ohms.

The resulting impedance (equation (3-3))is $Z_{CPU1} = 50.0 + j33.26$ ohms.

The magnitude of Z_{CPUn} (n>1) = (nth voltage across Z_{CPUn}) / (nth harmonic current)

The equivalent circuit model impedance $Z_{equivalent}(n>1) = Z_{neutralcable} // (Z_{CPUn} + Z_{phasecable})$

$Z_{CPUn} >> Z_{phasecable}$ therefore Z_{CPUn} is approximately negligible.

The application of equation (3-4) for the fundamental harmonic includes cable impedance as well as the computer terminal impedance. The resulting equations are:

$V_1 = I_1 \times (Z_{CPU1} + Z_{phasecable} + Z_{neutralcable})$

$V_3 = (I_3)(Z_{equivalent})$, where $Z_{equivalent} = Z_{neutralcable} // (Z_{CPU3} + Z_{phasecable})$

$V_5 = (I_5)(Z_{equivalent})$, where $Z_{equivalent} = Z_{neutralcable} // (Z_{CPU5} + Z_{phasecable})$

$V_n = (I_n)(Z_{equivalent})$, where $Z_{equivalent} = Z_{neutralcable} // (Z_{CPUn} + Z_{phasecable})$

Where $_n$ is the harmonic order.

4.8.2 Application of Three Computer Terminals' Equivalent Circuit Model:

Fundamental voltage and current levels can be calculated to demonstrate the application of the three computer terminal equivalent circuit model. Voltage levels are calculated across the branches corresponding to the nodes, A, B, C, and D seen in Figure 19. Current levels are calculated along the branches in-between the nodes in the direction of first to second node. For example, current I_{AB} is the current along the branch from node A to node B.

$V_{AB} = \sim 121.31V \angle 86°$ (same as input)

$I_{AB} = \sim 0A$ (large impedance)

$I_{AC} = I_{CD} = I_{DB} = I_{SOURCE} = 2.02A \angle 262°$

$V_{AC} = I_{AC} \times 0.0122{+}j0.0011\Omega = 2.02A \angle 262° \times 0.0122{+}j0.0011\Omega = 0.025V \angle -92.8°$

$V_{AC} = V_{DB} = \sim$ negligible with respect to voltage levels across other segments in the circuit model.

$V_{CD} = Z_{CPU1} \times I_{CD} = 50.0{+}j33.26\Omega \times 2.02A \angle 262° = -121.30V \angle -64.4°$

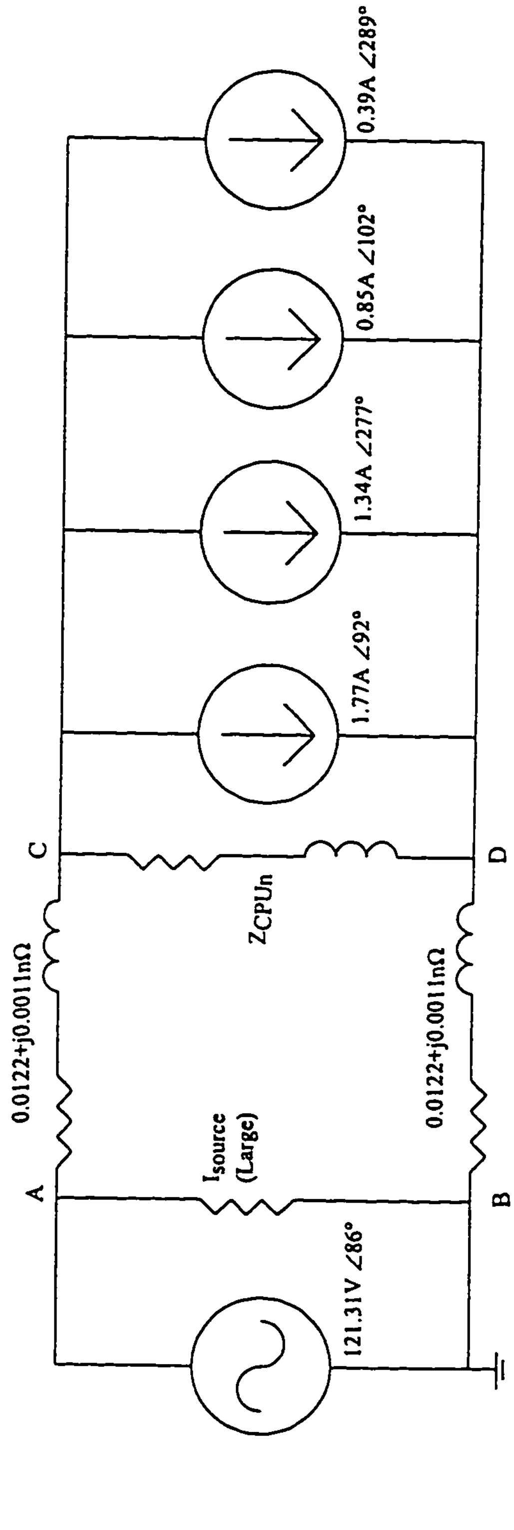


Figure 19: Circuit model (three computer terminals)

4.8.3 Thirty Computer Terminals' Equivalent Circuit Model:

An example of a circuit model for thirty computer terminals, Figure 20, was developed using data from cable voltage drop (Section 3.5), voltage characteristics from Tables 17, 18, and 19 as well as current characteristics from Tables 21, 22, and 23. The values used in Tables 17, 18, and 19 as well as 21, 22, and 23 are averaged to obtain values used within the model. The voltage source is 120.59V RMS at 169° at the fundamental harmonic (but still contains all input harmonics). The voltage source impedance (in parallel with the voltage source itself) is considered to be large due to the extensive cable length to the distribution transformer and large size of the distribution transformer relative to the small amount of power being used by the computer power supply. The equivalent cable impedance, for the phase and neutral cables (a length of 15 feet), for the fundamental (positive sequence), is 0.0122 + j0.0011n ohms. The computer power supply is represented by a resistive component (to be calculated) and several current sources. For a comprehensive model, a current source should be included for each harmonic being considered. To illustrate the application of the model, current sources are shown for harmonics containing at least 10% of the magnitude of the fundamental harmonic current. These values are:

3rd Harmonic:	11.55A at 146°
5th Harmonic:	9.48A at 139°
7th Harmonic:	5.59A at 243°
9th Harmonic:	2.19A at 319°

Application of equation (3-1) yields $Z_{CPU1} = 120.59V\angle169/18.59A\angle138 = 6.49$ ohms.

Equation (3-2), given that real power (from computer specifications) is 68 Watts, $R_{CPU1} = 68x30/((18.59)^2) = 5.903$ ohms and $X_{CPU1} = (Z_{CPU1}^2 - R_{CPU1}^2)^{1/2} = 2.697$ ohms.

The resulting impedance (equation (3-3)) is $Z_{CPU1} = 5.903 + j2.697$ ohms.

The application of equation (3-4) for the fundamental harmonic includes cable impedance as well as the computer terminal impedance. The resulting equations are:

$V_1 = I_1 \times (Z_{CPU1} + Z_{phasecable} + Z_{neutralcable})$

$V_3 = (I_3)(Z_{equivalent})$, where $Z_{equivalent} = Z_{neutralcable} // (Z_{CPU3} + Z_{phasecable})$

$V_5 = (I_5)(Z_{equivalent})$, where $Z_{equivalent} = Z_{neutralcable} // (Z_{CPU5} + Z_{phasecable})$

$V_n = (I_n)(Z_{equivalent})$, where $Z_{equivalent} = Z_{neutralcable} // (Z_{CPUn} + Z_{phasecable})$

Where **n** is the harmonic order.

4.8.4 Application of Thirty Computer Terminals' Equivalent Circuit Model:

Fundamental voltage and current levels can be calculated to demonstrate the application of the thirty computer terminal equivalent circuit model. Voltage levels are calculated across the branches corresponding to the nodes, A, B, C, and D seen in Figure 20. Current levels are calculated along the branches in-between the nodes in the direction of first to second node. For example, current I_{AB} is the current along the branch from node A to node B.

$V_{AB} = \sim 120.59V \angle 169°$ (same as input)

$I_{AB} = \sim 0A$ (large impedance)

$I_{AC} = I_{CD} = I_{DB} = I_{SOURCE} = 18.6A \angle 113°$

$V_{AC} = I_{AC} \times 0.0122{+}j0.0011\Omega = 18.6A\angle 113° \times 0.0122{+}j0.0011\Omega = 0.234V \angle 117.3°$

$V_{AC} = V_{DB} = \sim$ negligible with respect to voltage levels across other segments in the circuit model.

$V_{CD} = Z_{CPU1} \times I_{CD} = 5.903{+}j2.697\Omega \times 18.6A \angle 113° = 120.65V \angle -137.53°$

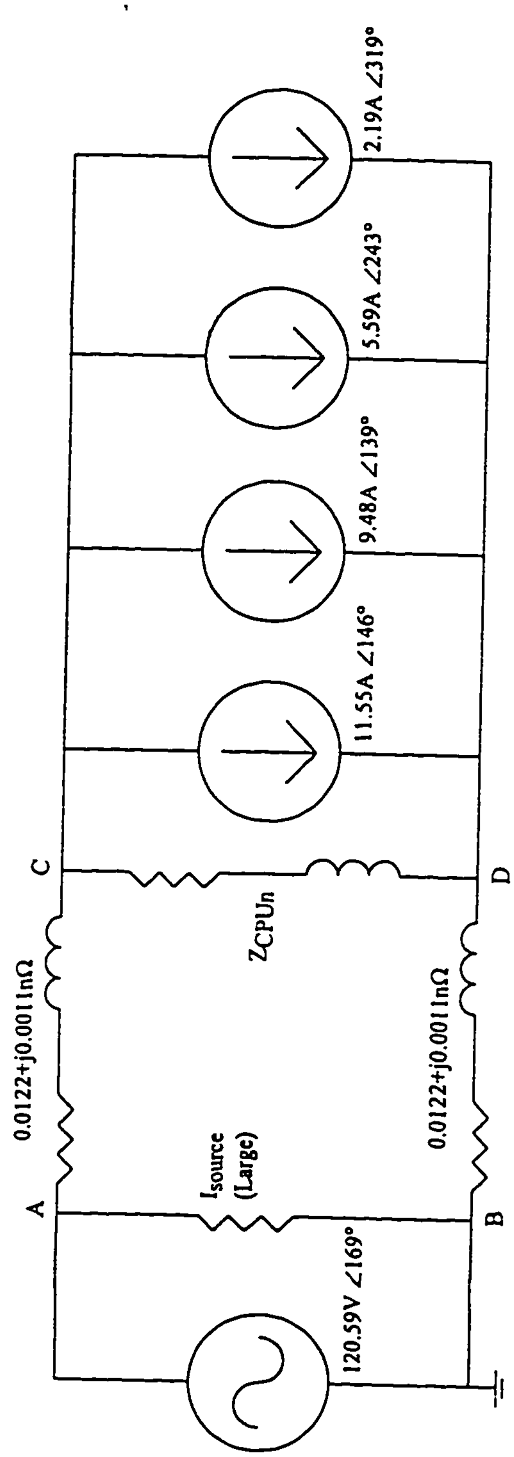


Figure 20: Circuit model (thirty computer terminals)

Chapter 5

Integrated Computer Laboratory Results

5.1 Distortion of the University of Alberta Power Supply:

The definition of distortions is not as simple as voltage or current because distortions are deviations from the expected or normal operating conditions and do not exist without the presence of a secondary symbiotic electrical property such as a voltage or current sinusoidal waveform. These distortions can be momentary or long term and can vary in magnitude, type, and number. Waveform distortions are given categories to simplify the knowledge of their existence. Some examples of this are voltage sags, swells, spikes (see Figure 23), brown-outs, and black-outs. These waveform distortions can be harmonic or transient. Harmonic distortions are usually long term and repetitive, while transients are usually short term and non-repetitive.

Waveform distortion of the University of Alberta power supply is dependent upon time of day and specific location at which distortions are being measured. Each load being fed by the power supply is creating harmonics and feeding them back through the power supply system. As the harmonics venture further from the origin, they decrease in magnitude. As well, transformers and power supply conditioners further reduce harmonics. As every load creates these harmonics, it is evident that elimination of all harmonics is not possible. Rather, management of harmonic levels is required. Some of this management is done naturally from power supply system components like transformers, while the rest must be accomplished by preventative maintenance harmonic analysis surveys at key locations throughout the power supply system.

The Cameron Library received a harmonic analysis survey after some anomalies were reported in the lighting system. Such checks provide valuable information regarding the possibility of harmonic problems throughout the power supply system. Distortions noted throughout the Cameron Library gave rise to the production of this thesis. Although these harmonic levels are seen as acceptable in most areas by IEEE 519 standards, the computer laboratory harmonic levels are marginally higher than the minimum acceptable standards.

5.2 Measured THD of Voltage Supply:

The measured THD of the voltage supply observed in the power supply electrical panel for the computer laboratory in Cameron Library was collected as part of the harmonic analysis survey. Sample THD calculations and formulae are seen in section 2.5. The data taken from the Dranetz 658 Powerline Monitor was verified in section 3.4. The THD is specified as a percentage of the fundamental harmonic voltage magnitude. The fundamental voltage level remained constant to within +\- 5% in most cases, providing relatively simple comparisons of the THD levels. In total, approximately five thousand screen captures were taken encompassing 1, 2, 3, and 30 computer terminals as well as laser printer data. The THD's for each computer terminal category were averaged to illustrate the overall harmonic distortion levels based on the number of terminals connected. The average voltage THD for a single computer terminal is 2.1%. This level is within IEEE 519 Standards shown in Table 4. Two computer terminals produced an average voltage THD of 2.3% while three computer terminals averaged 2.5%. This steady increase in THD is observed due to the increase in loading produced by utilizing more computer terminals and their peripheral devices. Thirty computer terminals produced average voltage THD levels of 2.9%. The increase in voltage THD slows as the number of computer terminals increase. The increase in voltage THD is not linear, as seen in Figure 21.

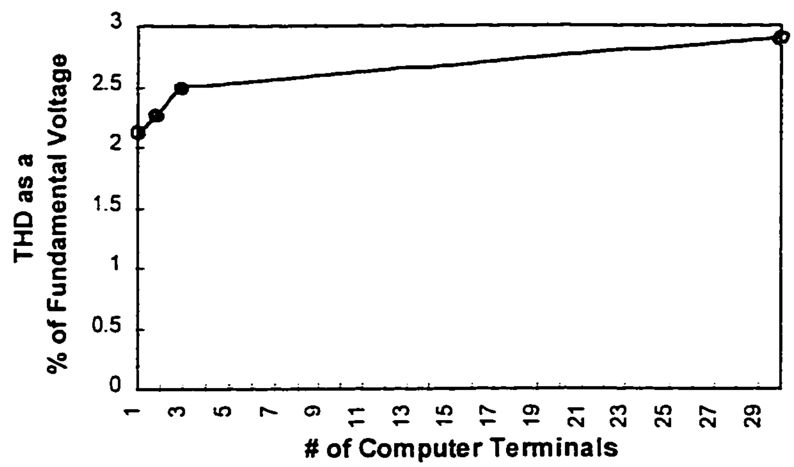


Figure 21: Phase to neutral voltage THD

5.3 Measured THD of Current Supply:

The measured THD of the current supply observed in the power supply electrical panel for the computer laboratory in Cameron Library was collected as part of the harmonic analysis survey. Sample THD calculations and equations are shown in section 2.5. The data taken from the Dranetz 658 Powerline Monitor is verified and available in section 3.4. The THD is specified as a percentage of the fundamental harmonic current magnitude. Current fundamental harmonic levels fluctuated depending upon the number of terminals and the number of peripheral devices being used by the computers. Due to the random nature of computer users using peripheral devices, at least one twenty-four hour time period is included for each set of data taken to provide a plausible method for averaging data. In total, approximately five thousand screen captures are taken encompassing 1, 2, 3, and 30 computer terminals as well as laser printer data. The THD's for each computer terminal category are averaged to illustrate the overall harmonic distortion levels based on the number of terminals connected. The average current THD for a single computer terminal is 91%. This level is acceptable using IEEE 519 Standards seen in Table 4. As the number of computer terminals increases, so does the THD. Two computer terminals produced an average current THD of 98% while three computer terminals averaged 109%. This non-linear increase in THD is observed due to the increase in loading produced by utilizing more computer terminals and their peripheral devices. Thirty computer terminals produced average current THD levels of 124%. This shows another increase in THD due to increased loads. The relationship of current THD to number of computer terminals is not linear as seen in Figure 22. The increase in current THD at the computer power supply panel slows as additional computer terminals are connected. The reduction in harmonics on a 'per terminal' basis is due to harmonic interaction between computer terminals due to phase variations [19].

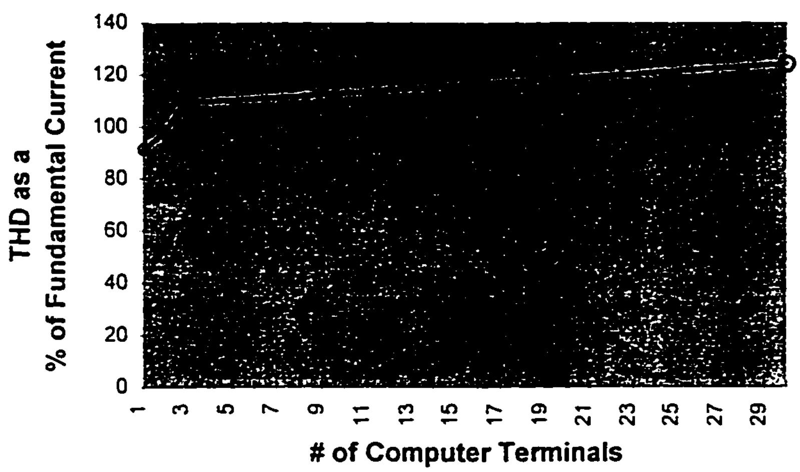


Figure 22: Phase current THD

5.4 Design parameters of computer manufacturers:

Computer manufacturers design computers based on many standards. These standards may come from organizations such as Underwriters Laboratories, Canadian Standards Association, or Institute of Electronic and Electrical Engineers. IEEE Standard 493-1990 published a table of standards for typical ranges of input power quality and load parameters of major computer manufacturers in its orange book. Table 25 includes a section from the standard for voltage harmonic distortion [4]. In

Table 25, the voltage harmonic distortion is remain at 3-5% or less. The standard illustrates the industries need to perform powerline surveys to be certain unreasonable harmonic voltage levels do not create problems within their computer power supplies. Another guide used by industry's leading computer manufacturers is the CBEMA curve (Figure 24) [4]. It provides a visual method of describing computer power supply tolerance zones. Included within the voltage tolerance envelope is voltage harmonics. As voltage harmonics increase, the computer power supply voltage is pushed further toward the voltage breakdown zone. The voltage waveform becomes distorted from the harmonics sometimes causing increased voltage peaking. An example of this is shown in Figure 23. Figure 23 is the waveform representation of the neutral voltage seen from a power supply panel with a single computer terminal load. The voltage spike seen in the waveform represents a momentary severe increase in voltage. Due to the lower magnitude of voltage seen at the neutral conductor, this spike would not likely have any significant impact on the lifetime of the computer power supply. However, if this type of spiking occurs on the phase conductor associated with the same computer terminal setup, it could cause the power supply to fail prematurely due to the increased voltage. This illustrates again why it is important to monitor harmonics and manage the harmonics which may create problems for nearby loads.

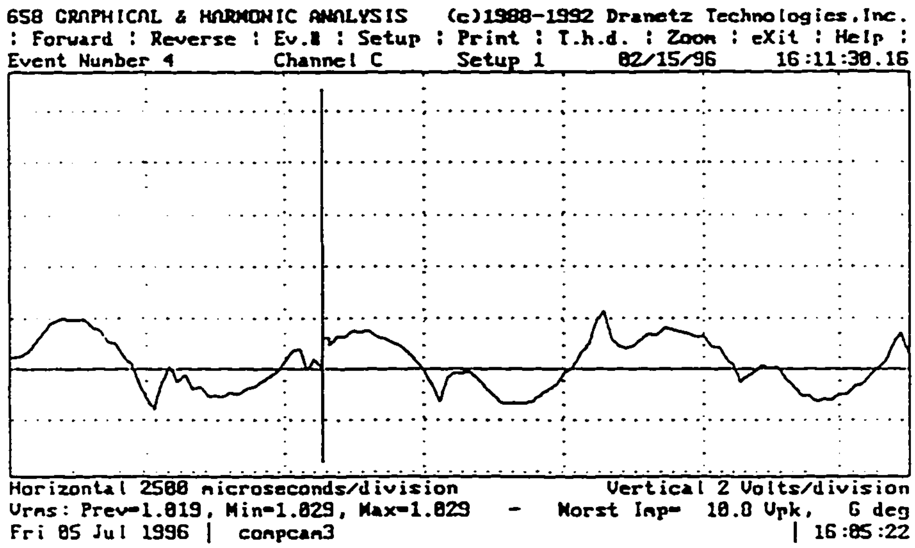


Figure 23: Distorted voltage waveform

Table 25: Input power quality and load parameters of major computer manufacturers

PARAMETERS*	RANGE OR MAXIMUM
1) Voltage regulation, steady state	+5%, -10% to + 10%, -15% (ANSI C84.1 -1970) is: +6%, -13%
2) Voltage disturbances Momentary undervoltage Transient overvoltage	- 25% to - 30% for less than 0.5 ms with -100% acceptable for 4 ms to 20 ms +150% to 200% for less than 0.2 ms
3) Voltage harmonic distortion (1)	3 - 5 % (with linear load)
4) Noise	No standard
5) Frequency variation	60 Hz ± 0.5 Hz o ± 1 Hz
6) Frequency rate of change	1 Hz / s (slew rate)
7) 3-phase, Phase voltage unbalance (2)	2.5 to 5 %
8) 3-phase, Load unbalance (3)	5 to 20 % maximum for any one phase
9) Power factoer	0.8 to 0.9
10) Load demand	0.75 to 0.85 of connected load

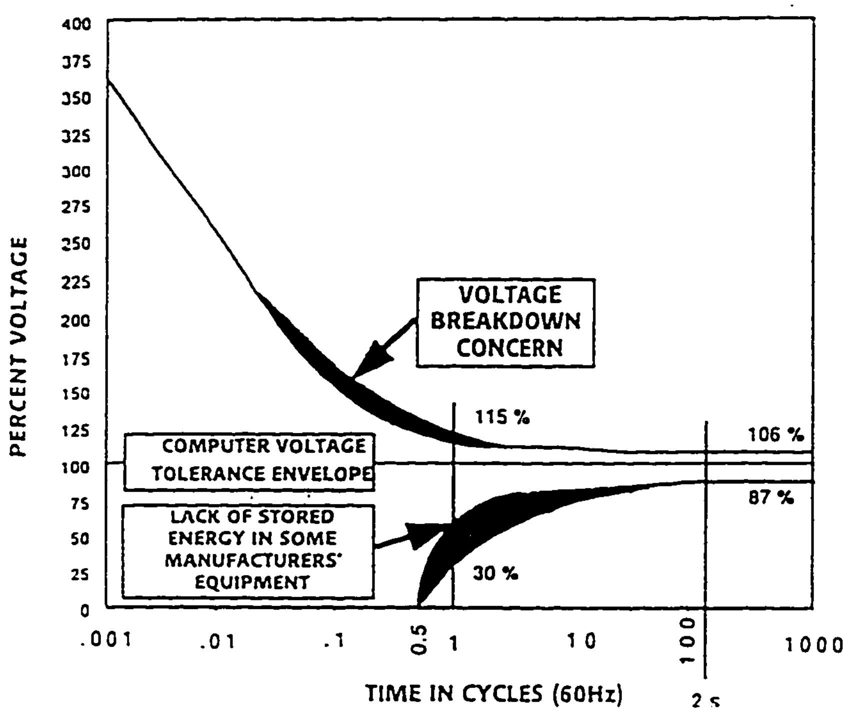


Figure 24: Computer power supply tolerance zones

5.5 Circuit Model Comparison:

Circuit models for one, two, three and thirty terminals share many of the same characteristics. The model for two computer terminals is not presented due to its similarity to three computer terminals. The voltage input signal for each computer terminal is the input voltage from the computer power supply panel. One, two and three computer terminal circuit models use one of the three phases of the power supply system. The thirty computer terminal circuit model input voltage is an average of the input voltages from each phase of the power supply system feeding the associated computer terminals. Source Impedance for each model is considered to be large due to the power supply panel connection with a distribution transformer. Cable impedance (phase and neutral) for one, two and three computer terminal circuit models is calculated for a single cable based upon the cables' characteristics and length. Cable impedance (phase and neutral) for the thirty computer terminal circuit model follows the assumption of parallel identical cables routed for each set of three computer terminals seen in Figure 2. The per cable impedance is the same as the impedance for a single cable in the one, two and three computer terminal circuit models.

The computer terminal equivalent input impedance at the fundamental harmonic (Z_{CPU}) varies with the number of computer terminals. Current (I_1) from the equation V=IZ, must also vary with the number of computer terminals because input voltage (V_1) remains consistent at approximately 120 volts.

Z_{CPU} -1 terminal = 188.89+j67.04 Ω

Z_{CPU} -3 terminals = 50.00+j33.26 Ω

Z_{CPU} -30 terminals = 5.903+j2.697 Ω

I_{SOURCE} - 1 terminal = 0.60A ∠ 84°

I_{SOURCE} - 3 terminals = 2.02A ∠ 262°

I_{SOURCE} - 30 terminals = 18.6A ∠ 113°

5.6 Computer Terminal Conformity to Industry Standards:

Computer Terminal voltage characteristics can be compared to Table 25 and Figure 21 standards. Table 25 is concerned with voltage regulation and voltage harmonic distortion. Steady state voltage levels should remain within +10% (132V) and -15% (102V) of expected voltage steady state levels. Total harmonic distortion should remain less than 5%. Computer terminal input power levels remained between 122V and 116 V during steady state conditions. These levels are within the voltage steady state standards seen in Table 25. Computer terminal total voltage harmonic distortion remained within 3.4%, within the 5% voltage standard (see Table 25). Voltage regulation is also of concern as can be seen in Figure 23. Steady state voltage levels should remain within +6% (127.2V) to -13% (104.4V) of expected voltage steady state levels. Computer terminal input power levels remained between 122V and 116 V during steady state conditions. These levels are within the voltage steady state standards seen in Figure 24.

Chapter 6
Conclusions

6.1 Conclusions:

A comprehensive and controlled set of data was collected from a computer laboratory on the first floor of Cameron Library at the University of Alberta. This data includes powerline monitoring of one computer terminal. Data collection involving an individual computer terminal requires a single connection of one computer terminal to one phase of the three phase power supply electrical panel. The terminal is also connected in parallel with twenty-nine other terminals to a central modem hub via modem lines. Powerline monitoring consisted of voltage and current connections to the associated phase of the power supply electrical panel as well as ground to neutral voltage measurement and neutral current measurement also located within the power supply electrical panel. The ground connection is made of electro-metallic tubing. Powerline monitoring included collecting data for two, three, and thirty computer terminals as well as a computer laser printer. Each device is connected to the power supply panel in a similar fashion as the single computer terminal. To better illustrate the data, several categories are used in the analysis. The data was then used to develop a model of computer power supplies as seen by the computer laboratory power supply electrical panel.

6.2 Total Harmonic Distortion of Phase Voltage:

Voltage total harmonic distortion (THD) is the industry standard parameter for determining the effect of harmonics on a power system. Table 25 (Chapter 5) lists voltage harmonic distortion as a parameter measured when determining the power quality of a power system. Voltage THD within the Cameron Library computer laboratory is analyzed and discussed in Chapters 3 and 4. The results show that the voltage THD increases as the number of computer terminals increases. This can be appreciated by observing the trend of the curve plotted in Figure 21. The voltage THD, on average, did not exceed the 3-5% voltage harmonic distortion level seen as the maximum acceptable level for input power quality by IEEE standard 493-1990 in Table 25.

6.3 Total Harmonic Distortion of Phase Current:

Current total harmonic distortion (THD) responds in a similar fashion to the voltage harmonics for each of the monitoring configurations. Current THD within the Cameron Library computer laboratory is analyzed and discussed in Chapters 3 and 4. A summary of the results, shown in Figure 22, includes a current THD increase as the number of computer terminals increases. Current THD, seen as a percentage of the fundamental current magnitude, is much higher than the voltage THD.

6.4 Computer Terminal Power Supply Modeling Parameters:

The models seen as Figures 18, 19 and 20 illustrate the interaction between a power system and the power supplies of computer terminals. The model itself varies from most other power supply models as it illustrates the computer power supply's ability to generate harmonics and couple them into the power system. Most power supply models deal with the computer power supply as a simple user of power, and do not consider the computers as a generator of voltage and current harmonics. This model type helps to understand harmonics and how they are created. It can be used as a tool to determine if and when quantities of computer terminals begin to create harmonics that exceed minimum standards (as seen in Table 25). Data from the Cameron Library for one, two, three, and thirty computer terminals (Figures 21 and 22) provides trends that help to develop power system modeling of a computer system. Visual relationships such as curves may help to estimate values used in models for situations that need data extrapolation such as a computer laboratory with more than 30 computer terminals. Other data used such as cable voltage drop can either be calculated or approximated using standards including IEEE standard 519-1992. The model can be used as a simple method of expressing the overall power quality of the power system with respect to the location the model is being used.

6.5 Overall Conclusions:

Understanding power quality conditions within a power system requires the use of various tools for power system analysis. Many tools exist for power system analysis including powerline monitors, standardized tables of acceptable power system characteristics and documented examples of various power system configurations. Another tool can be the use of device models to determine the effects of certain devices energized by a power system. An increasingly common device utilizing power systems is a computer terminal. A computer terminal not only uses power. but alters it, causing a coupling of distorted voltage and current waveforms with the original power system supply.

Computer terminals are a leading cause of industrial harmonic pollution in the office environment. These, along with other devices such as laser printers and photocopiers, can create potentially hazardous power system problems including device overheating or device failure. Being able to predict harmonics is a key requirement for locating and resolving these potentially hazardous problems. A comprehensive circuit model of computer terminal power supplies as seen in Chapters 3 and 4 can aid in predicting harmonic pollution associated with a power system before a complete powerline analysis is performed. This may help to pinpoint possible power system problems and reduce the overall time required to complete a power system study.

The circuit model presented in this thesis contains two distinct characteristics. The distortion of the supply current waveform is non-linear. As the number of computer terminals increase, the total distortion in the supply current waveform tends to saturate. This can be seen in Figure 22, where the total distorted current as a percentage of fundamental current approaches a finite level as the number of computer terminals connected to the power system becomes large. Similarly, as seen in Figure 21, the distortion of the supply voltage waveform tends to saturate as the number of computer terminals increase.

6.6 Suggestions for Future Work:

Continuation of the work produced by this thesis may be extended. Some ideas for additional work are:

- Vary the magnitude of the supply voltage while monitoring the computer laboratory. Determine the impact of increased current and change in harmonics.
- Monitor different configurations of computers such as 4 terminals or more than 30 terminals.
- Monitor more than 1 computer terminal simultaneously to determine the degree of variance between computers.
- Develop a SPICE simulation of the power supply models.

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Appendix A

Matlab code written to produce waveforms

Appendix A1: Figures 6 and 7, Page 18
Appendix A2: Figures 8 - 11, Pages 20 and 21
Appendix A3: Figure 16 Page 37

```
x=[0:pi/511:2*pi];
A=(1/2)*sin(2*x);
y=sin(x);
q=y+A;
axis([0 6.28 -2 2])
hold on
figure(2)
subplot(2,2,1), plot (x,A);grid on
hold on
subplot(2,2,1), plot (x,y);grid on
subplot(2,2,1), plot (x,q);grid on
title('Summation of 1/2sin2x and sinx')
ylabel('Voltage/Current')
xlabel('2.5 Milliseconds/Division')

clear
x=[0:pi/511:2*pi];
A=(1/4)*sin(4*x);
y=sin(x);
q=y+A;
axis([0 6.28 -2 2])
hold on
figure(2)
subplot(2,2,2), plot (x,A);grid on
hold on
subplot(2,2,2), plot (x,y);grid on
subplot(2,2,2), plot (x,q);grid on
title('Summation of 1/4sin4x and sinx')
ylabel('Voltage/Current')
xlabel('2.5 Milliseconds/Division')
print sub2
```

```
x=[0:pi/511:2*pi];
A=(1/3)*sin(3*x);
y=sin(x);
q=y+A;
axis([0 6.28 -2 2])
hold on
subplot(2,2,1),plot (x,A);grid on
hold on
subplot(2,2,1),plot (x,y);grid on
subplot(2,2,1),plot (x,q);grid on
title('1/3sin3x and sinx -In Phase-')
ylabel('Voltage/Current')
xlabel('2.5 Milliseconds/Division')

clear
x=[0:pi/511:2*pi];
A=(-1/3)*sin(3*x);
y=sin(x);
q=y+A;
axis([0 6.28 -2 2])
hold on
subplot(2,2,2),plot (x,A);grid on
hold on
subplot(2,2,2),plot (x,y);grid on
subplot(2,2,2),plot (x,q);grid on
title('1/3sin3x and sinx -Out of Phase-')
ylabel('Voltage/Current')
xlabel('2.5 Milliseconds/Division')

clear
x=[0:pi/511:2*pi];
A=(1/5)*sin(5*x);
y=sin(x);
q=y+A;
axis([0 6.28 -2 2])
hold on
subplot(2,2,3),plot (x,A);grid on
hold on
subplot(2,2,3),plot (x,y);grid on
subplot(2,2,3),plot (x,q);grid on
title('1/5sin5x and sinx -In Phase-')
ylabel('Voltage/Current')
xlabel('2.5 Milliseconds/Division')

clear
x=[0:pi/511:2*pi];
A=(-1/5)*sin(5*x);
y=sin(x);
q=y+A;
axis([0 6.28 -2 2])
hold on
subplot(2,2,4),plot (x,A);grid on
hold on
subplot(2,2,4),plot (x,y);grid on
hold on
subplot(2,2,4),plot (x,q);grid on
title('1/5sin5x and sinx -Out of Phase-')
ylabel('Voltage/Current')
xlabel('2.5 Milliseconds/Division)')
print sub
```

```
% Each angle given from the Dranetz is negative
% Therefore 360 degrees minus the angle will
% shift the angle to a positive starting position.

x=[0:pi/511:2*pi];
A=.22*cos(x+4.8694);
B=.22*(2.4/100)*cos((2*x)+3.2114);
C=.22*(98.8/100)*cos((3*x)+1.4660);
D=.22*(3.9/100)*cos((4*x)+.2967);
E=.22*(92.5/100)*cos((5*x)+4.4855);
F=.22*(3.2/100)*cos((6*x)+3.4208);
G=.22*(84.2/100)*cos((7*x)+1.2043);
H=.22*(2.8/100)*cos((8*x)+.6632);
I=.22*(72.6/100)*cos((9*x)+4.2586);
J=.22*(2.6/100)*cos((10*x)+3.5256);
K=.22*(61.0/100)*cos((11*x)+.9948);
L=.22*(2.7/100)*cos((12*x)+6.1261);
M=.22*(50.7/100)*cos((13*x)+3.9968);
N=.22*(2.5/100)*cos((14*x)+3.3510);
O=.22*(36.8/100)*cos((15*x)+.7156);
P=.22*(3.1/100)*cos((16*x)+1.0647);
Q=.22*(25.9/100)*cos((17*x)+3.7350);
R=.22*(1.6/100)*cos((18*x)+4.3459);
S=.22*(15.2/100)*cos((19*x)+.3142);

q=A+B+C+D+E+F+G+H+I+J+K+L+M+N+O+P+Q+R+S;
figure(1)
axis([0 6.28 -6 6])
hold on
plot (x,q);grid on
hold on
title('Illustration of harmonics for verification')
ylabel('Instantaneous Voltage')
xlabel('2.5 Milliseconds/Division')
print negcos
```

Appendix B

Specifications for computer terminals, computer monitors, laser printers, and cables.

SPECIFICATIONS

COMPUTER TERMINAL DATA:

Pro-Spec 486 PC
AC 100-240 V, 68W
50/60 Hz
Implemented September 1994.
Assembled in Canada

MONITOR DATA:

Samtron SC-428 TX
AC 100-240 V
50/60 Hz
1 A - 0.5 A
Implemented September 1994
Assembled in Korea

PRINTER DATA:

Hewlett Packard LaserJet III
Resolution Enhancement PCL5
100-115 V
50/60 Hz
7.6 A
Implemented September 1994
Assembled in Japan

WIRING DATA:

Single Phase Voltage Wire:
RW90
XLPE
(-40°C)
600 V
12 AWG

Single Phase Neutral Wire:
RW90
XLPE
(-40°C)
600 V
12 AWG

Feeder Voltage Wire:

RW90
XLPE
(-40°C)
1000 V
6 AWG

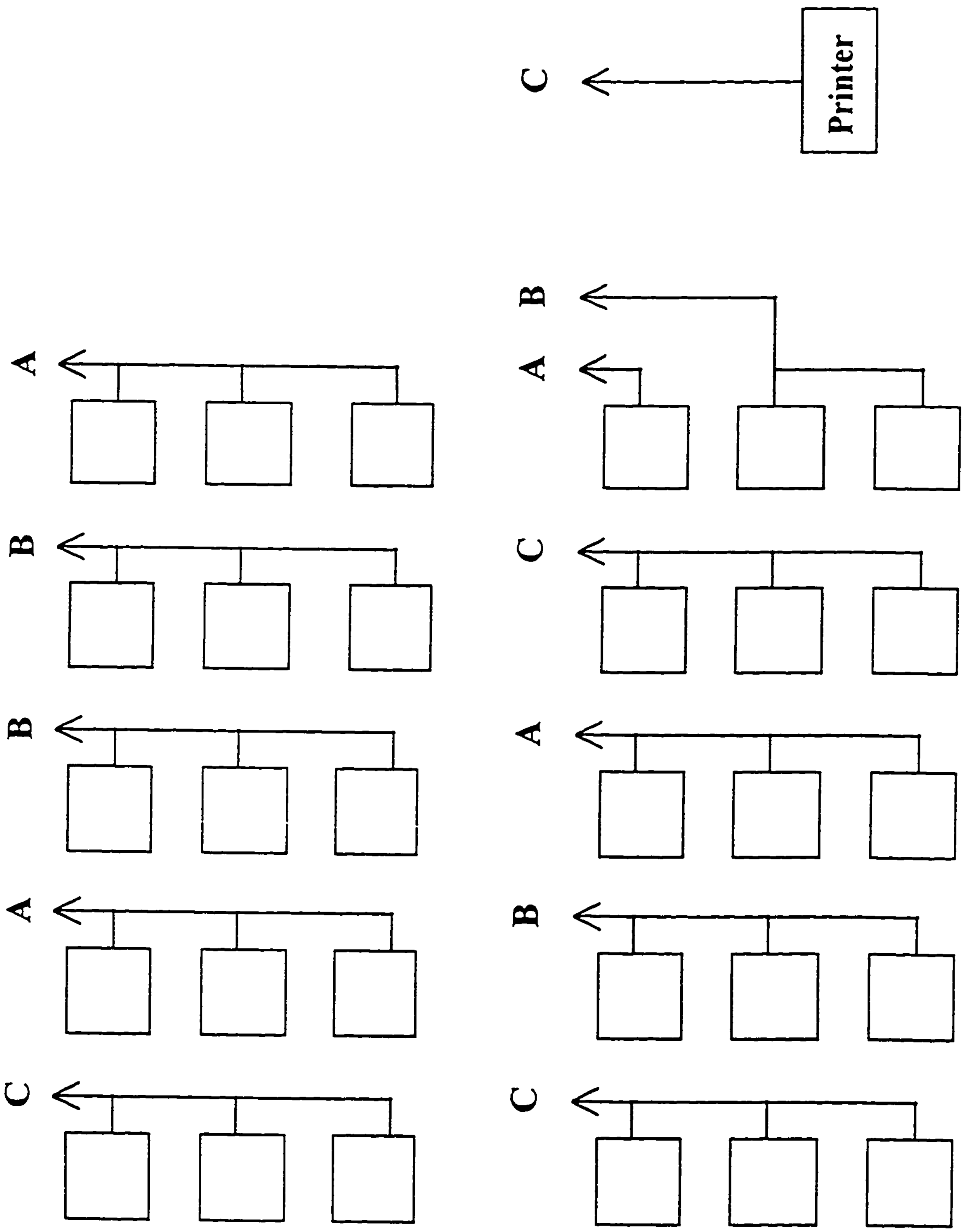
Feeder Neutral Wire:
RW90
XLPE
(-40°C)
1000 V
6 AWG

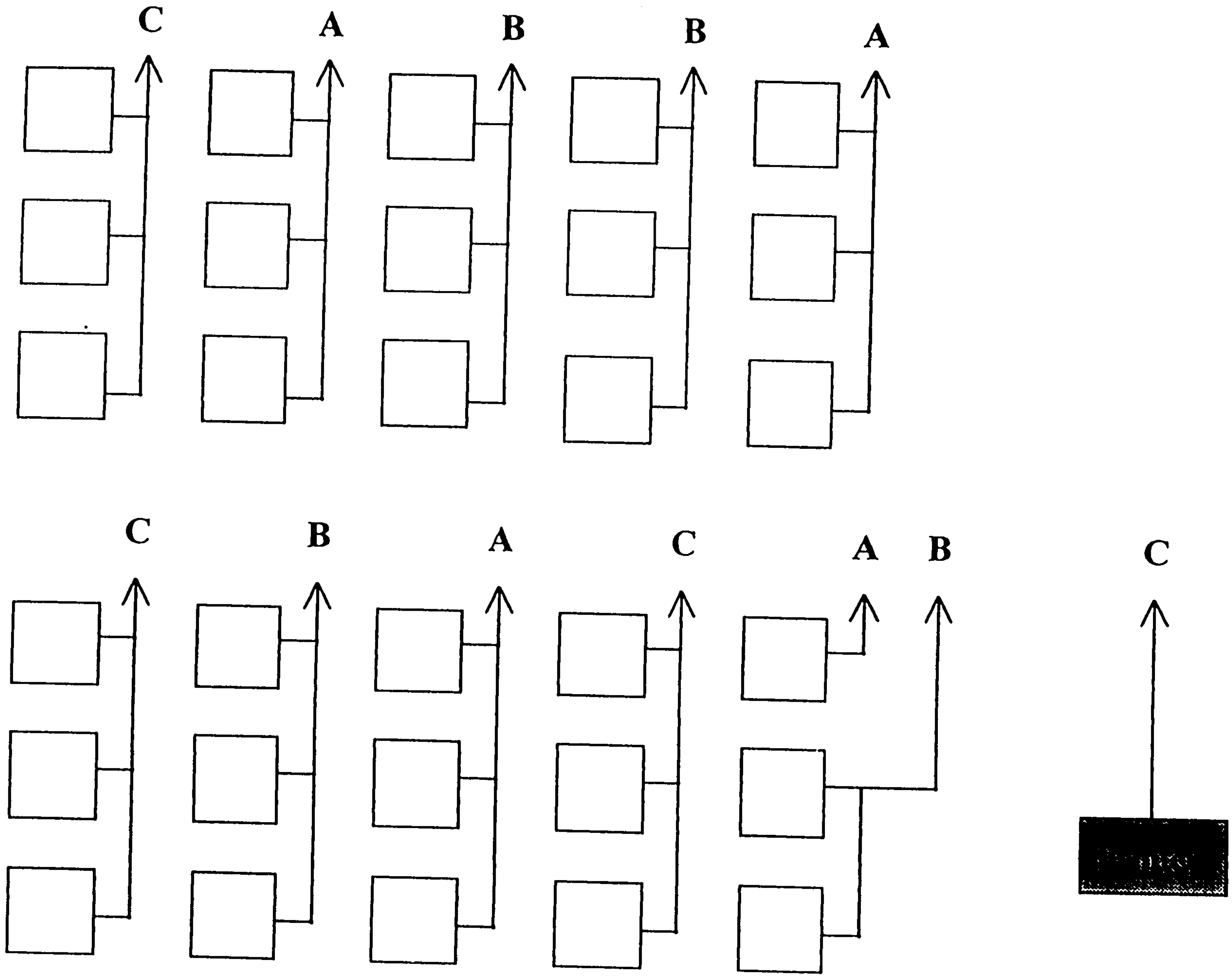
Panel Ground
Electro-Metalic Tubing (EMT)

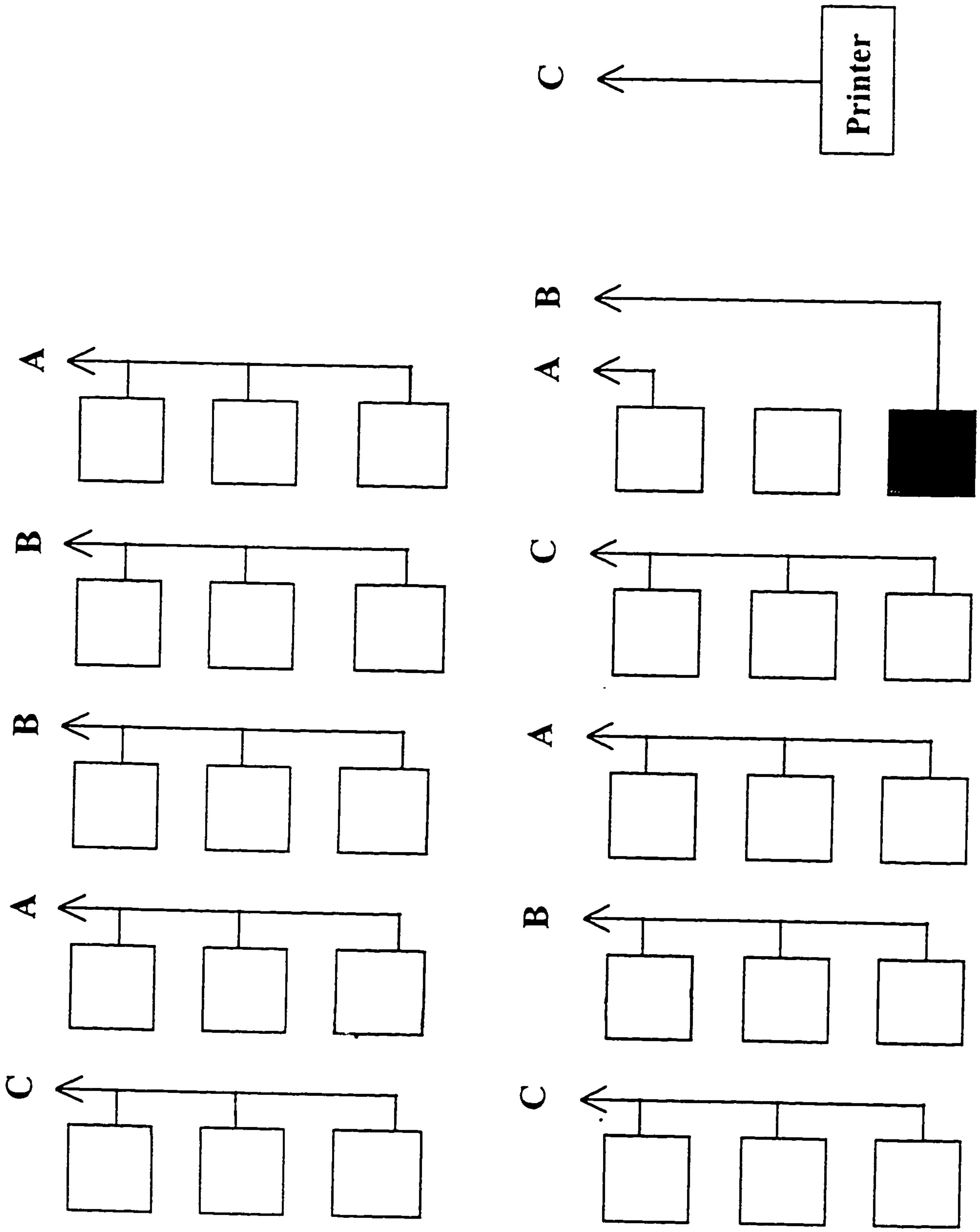
Appendix C

Schematics for monitoring combinations of computer terminals.

Appendix C1: Undisturbed Computer Laboratory Layout
Appendix C2: Laser Printer Monitoring
Appendix C3: Single Computer Terminal Monitoring
Appendix C4: Two Computer Terminals' Monitoring
Appendix C5: Three Computer Terminals' Monitoring
Appendix C6: Thirty Computer Terminals' Monitoring


C
A
B
B
A
C
B
A
C
A
B
C
Printer


C
A
B
B
A
C
B
A
C
A
B
C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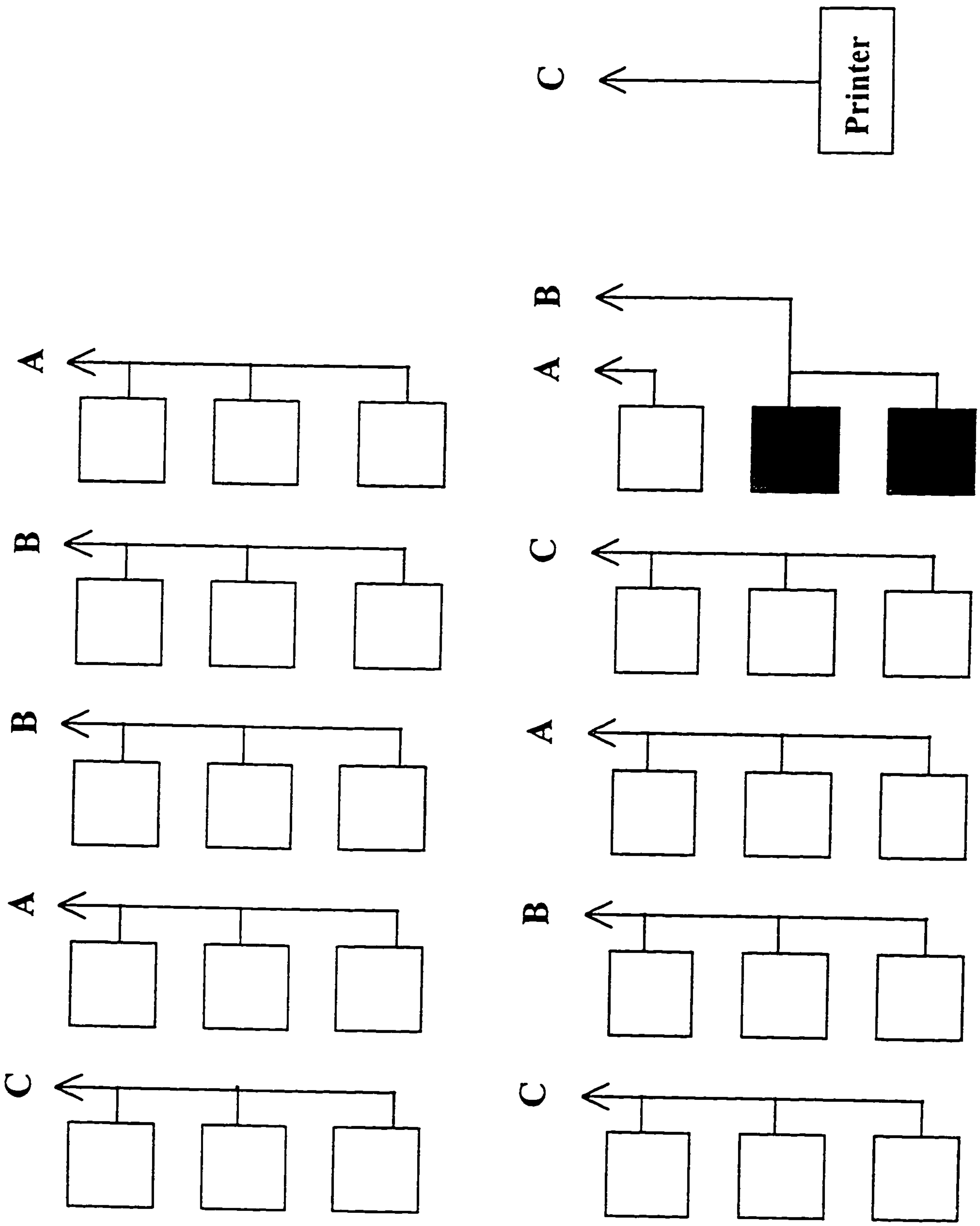

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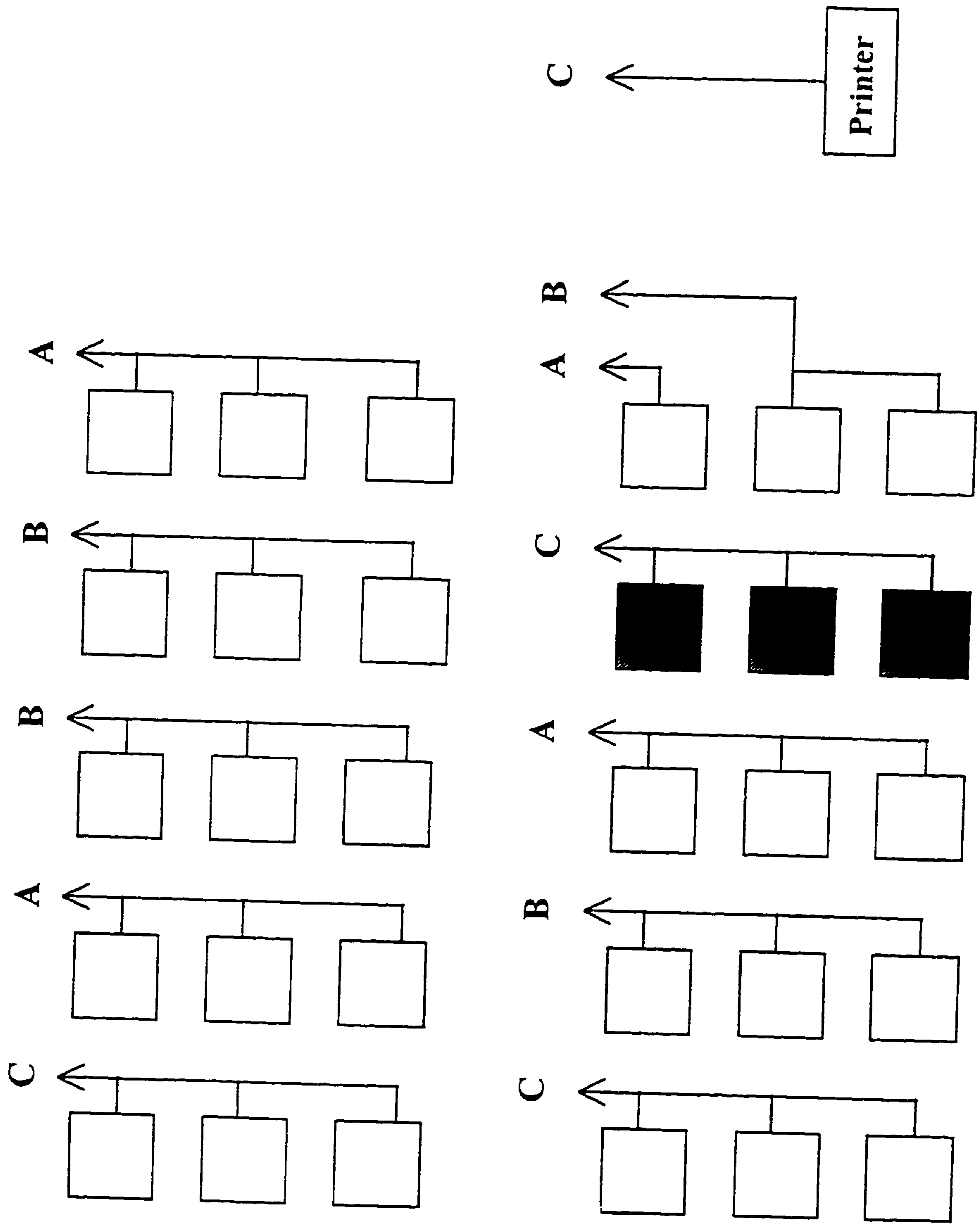
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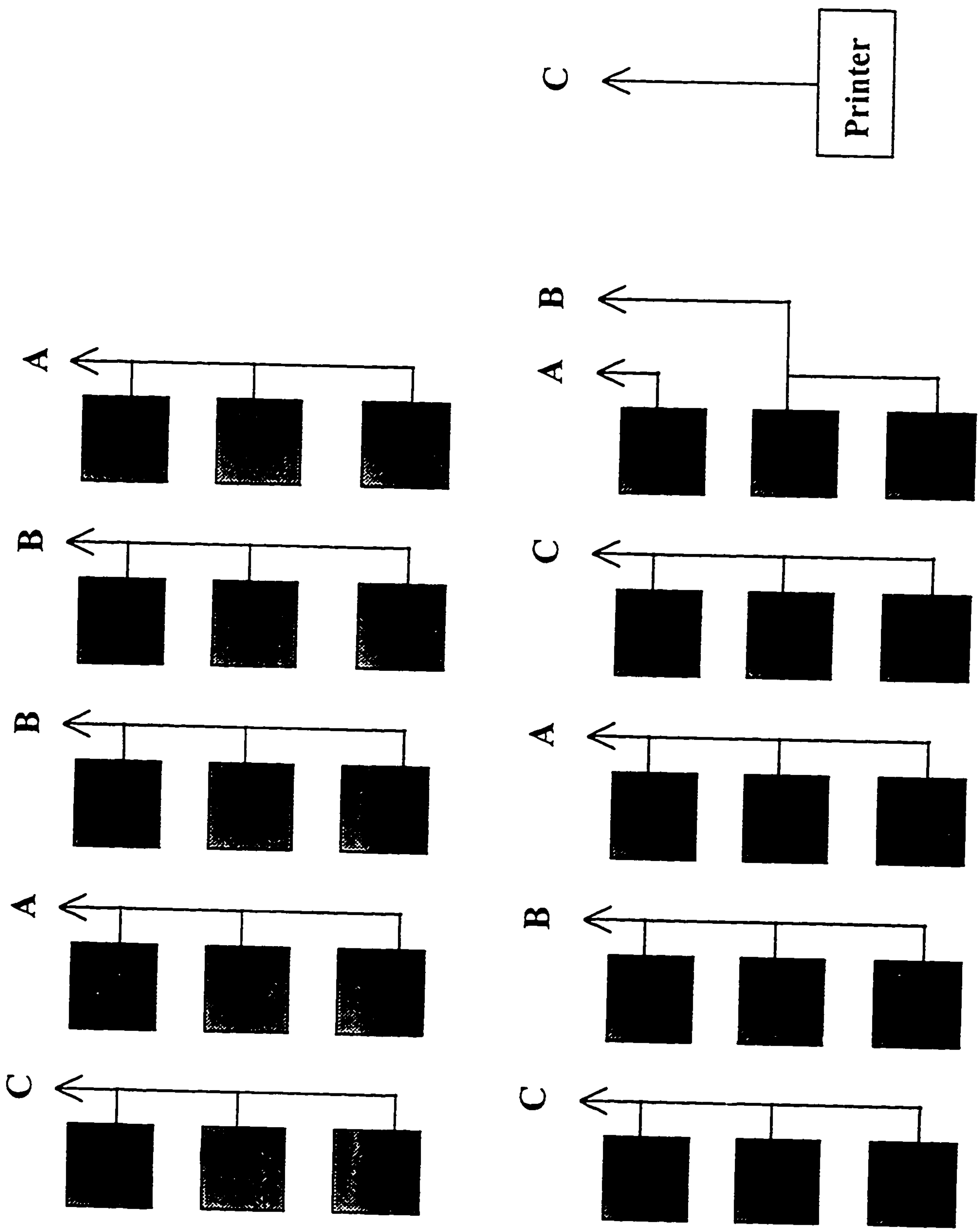
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