A THEORETICAL STUDY OF THE APPLICATION OF HARTLEY TRANSFORM FOR POWER QUALITY ANALYSES

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PREFACE

The subject related of this thesis is Hartley transform and its usage in the study of power quality. The main purpose of this is to conduct a theoretical study of the application of Hartley Transform in power system analyses and explore its potential in solving power quality problems.

An effort has been made to keep the level of this thesis as simple as possible. There is a wide scope for further studies. Hartley Transform, although mainly used in Communication Engineering, is seldom used to solve power related problems. Literature on this is just becoming available. I wish to express my sincere gratitude to Dr R. Yarlagadda of the School of Electrical and Computer Engineering of Oklahoma State University for his advice in literature search for Hartley Transform. I am also specially grateful to Dr. J . A. Allison for his help in allowing me to use the VMS mainframe computer system for computer programming.

Special Thanks are due to my uncle Dr. N. C. Das of Wilksbarre, Pennsylvania and Mr D. P. Das of Philadelphia for their constant support and understanding. I offer my deepest appreciation to my parents for their moral encouragement.

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LIST OF SYMBOLS

a_n	Fourier coefficient
b_n	Fourier coefficient.
B_n	Hartley coefficient.
Cas	Sum of sine and cosine function (Argument).
C_{SH}	Capacitance of the SH network.
DIN	Distortion index used mostly in Europe.
e	Exponential base (e=2.7183)
E(f)	Even part of a function.
E(v)	Even part of Hartley transformed function.
f(t)	An arbitrary function.
$F(v)_f$	Discrete Fourier transform of function F(t).
F_{imag}	Imaginary part of a complex function F(f).
F_{real}	Real part of a complex function F(f)
$f_{symm}(x, y)$	Symmetrical part of f(x, y).
$f_{antisymm}(x, y)$	Antisymmetrical part of f(x, y).
G_{SH}	Conductance of (SH network.)
H(s) or H(f)	Hartley transformed function.
H(u, v)	Two Dimensional Hartley transform of a function f(x, y).
I_n	Hartley current.
I_n^+	Positive sequence Hartley current.
I_n^-	Negative sequence Hartley current.

$I(\nu)$	Discrete Hartley transformed function ofcurrent function i(t).
$I(k\Omega)$	Discrete Fourier transformed function I(kt).
$I_{SE}(t)$	Current of SE network.
i and j	Complex operator which is equal to $\sqrt{-1}$.
k or K	Any arbitrary integer.
KVT	Expression for Audio weight.
L_{SE}	Inductance of the SE network.
n or N	Any Integer.
N_1 and N_2	Two arbitrary Matrices.
O(f)	Odd part of a function.
$O(\nu)$	Odd part of Hartley transformed function.
p(t)	An arbitrary function of t.
R_{SE}	Resistance of the SE network.
$S(\omega)$	Fourier transform of a function S(t).
THD	Total Harmonic Distortion.
TIF	Telephone influence factor.
V_{rms}	Root Mean Square Voltage.
$V_{SE}(t)$	Bus voltages of SE network.
V(t)	Inverse Hartley Transform of Function $\psi(\omega)$.
V(k)	Discrete functional form of voltage V.
$V(\nu)$	Discrete Hartley transformed function of voltage function V(t).
$Y^i(\omega)$	Admittance of the ith network.
$Y_{SE}(\omega)$	Admittance of the SE network.
$Y_{SH}(\omega)$	Admittance of the SH network.

$Z(\nu)$	Hartley transformed function of impedance function $Z(t)$.
$Z(k\Omega)$	Discrete Fourier transformed function $Z(kt)$.
$Z_{SE}(\omega)$	Impedance of the SE network.
$Z_{SH}(\omega)$	Impedance of the shunt network.
$Z_{HT}(n\omega)$	Hartley impedance.
β	An arbitrary constant.
δ	An arbitrary constant.
ν	Discrete frequency variable.
π	Pi which is equal to 3.1416.
θ	Angle.
τ	Discrete time variable.
ω	Angular frequency.
∞	Infinity.
Σ	Summation Symbol.
$\psi(\omega)$	An arbitrary mathematical function of frequency ω.

CHAPTER I

INTRODUCTION

Background

The study of Power Quality is a relatively new topic in Electrical Engineering. Although it is in a relatively infant stage, more and more people are realizing its effect on power related problems. Previously the problem was not so acute, but with the introduction of various power electronics devices such as SCR (Silicon Controlled Rectifiers), power transistors, various solid state relays and circuit breakers it started to grow in dimension. Furthermore there has been a significant increase in the use of electronic data communication devices, computing devices with the advent of LSI, VLSI and ULSI (Largescale, Very Large and Ultra Large Scale Integrated) circuits in recent years. However most of these equipments are highly sensitive to the problems in power distribution circuits. Although their introduction is essential for progress of science, engineering, the art of computation, safety and control, they are creating a new set of problems in power systems.

Unlike simpler and rugged electrical equipment such as motors, these new electronic equipments require much more stable voltage sources due to their highly sensitive digital circuitry. These equipments are more susceptible to power disturbances that originate on either side of the electric meter. Complicating matters, end-use devices such as adjustable speed motor drives, laser printers and fluorescent lamp ballasts can feedback disturbances (in the form of nonsinusoidal currents) into the power lines that cause problems not only within a building, but in the neighboring buildings as well. The consequences of power disturbances for building owners are significant. Disturbances such as impulses, sags and surges can have negative impacts on electronic equipments.

Scope

Problems due to voltage and current variations range from operational problems such as data errors, program errors or memory loss, to system interruptions or equipment damage. Building owners might be blamed not only for any end-user equipment damage, but also for the loss of productivity due to equipment downtime. Building marketability can also be impaired as a consequence of inadequate electrical supply. Viewing the potentially damaging effects of power disturbances, building owners and tenants cannot disregard power quality issues. Ensuring good power quality requires a well-planned, well-executed power quality survey and upgrading of the existing electrical distribution network.

Such a procedure not only describes the approaches for diagnosing power quality problems in the building power distribution system serving sensitive electronic equipments and systems but also common power disturbances are addressed, as are planning and performance requirements for conducting a power quality survey. Thus the time has come for power engineers to conduct an extensive effort using different mathematical techniques for the analysis of power quality related problems.

Hartley transform is one of the most efficient mathematical tools available for the analysis of power quality. It is closely related to Fourier transform. Hartley transform can change convolution operations into a simple multiplication and hence is used to calculate various transient and nonsinusoidal waveshapes (current or voltage) in power distribution networks generated by power quality problems. The importance of this type of calculation relates to the impact of loads, particularly electronic loads, whose input currents are not sinusoidal in nature. Hartley transform can be used for the analysis of electric power circuits. Because Hartley transform is a real transformation from the mathematical viewpoint, it is found to be computationally more efficient than Laplace or Fourier transform. It is not imperative to think that Hartley transform should replace the classical Laplace or Fourier transform but it has a distinct edge in rapid calculation of wide bandwidth signal propagation phenomena.

The microelectronic revolution is rapidly changing the electrical environments of the world. Emerging electronic technologies that consume less power and utilize faster switching speeds are increasingly being installed to meet cost effectiveness criteria and higher efficiencies. To meet these challenges more and more ideas are required to enhance the application domain of mathematical techniques.

The electrical world and the associated events around us are mostly found to be nonlinear in character. Nonlinear effects are found in conductance, resistance as well as capacitance and inductance. A resistive element which has a range of terminal voltage and current for which $dv/di < 0$ (Here dv and di represent the infinitesimal change of voltage and current) is generally included in a category of elements called nonlinear conductors. Such nonlinear conductors are designed and built into the integrated circuits and microprocessors of today.

To the end-users of electric power, power quality is directly connected to reliable service; service which is dependable with little or no interruption. Also, it is important that the supplied power be maintained within a set of given standards. Although it is seen that utility's reliability has improved over the years, the susceptibility of the customer's equipments to failure and malfunction has increased severalfold.

Purpose

The advanced electronic equipment that has brought efficiencies to our homes, offices and factories has introduced some extra problems as well. Much of these equipments are uncommonly sensitive to routine power line disturbances and some devices even create their own disturbances that feedback to the utility line. It is estimated by EPRI (Electrical Power Research Institute) that industries all over the United States have been hit particularly hard, with momentary outages (a phenomenon of complete loss of power lasting from several milliseconds to several hours) costing some plants as much as $300,000 per incident. Numerous efforts have been made by power engineers and scientists on a continuous basis to maintain perfect sinusoidal current and voltage waves (clean power) free of distortions and harmonics. Now, electronic and solid state devices are creating a power quality problems which feedback into the system. So it is very essential to get rid of this problem with an early warning system in the utility line with round the clock monitoring and effective countermeasure capability to deal with unclean power waves. Emphasis is put on the study of this problem by employing spectral analyses of the power waves and their broadband analyses with all available tools(such as Hartley transform) to understand the nature of these waves. Once the analyses are completed, the facts are uncovered and the problem can be remedied. The band analyses of voltage and current waveforms are very essential to estimate power quality disturbances.

CHAPTER II

POWER QUALITY

Introduction

The term "power quality" has taken on a substantially significant meaning since the introduction of the microprocessor. Previously, the responsibility of the power engineer stopped with the provision of a reliable power supply with voltage control and with minimum or no voltage flicker. Simple guidelines were enough to handle this job. Today, the proliferation of microcomputer and digital communication equipment has forced a new definition of power quality to suit the needs and deeds of these devices. Power quality no longer confines itself to power engineering but encompasses all other branches as well. The phenomena that were of secondary importance such as transient over-voltages, harmonic distortion, and conducted interference have become more significant now. Traditional electro-mechanical equipment will draw sinusoidal current from a sinusoidal voltage. But electronic equipment which converts ac power to dc power does not draw current over the entire period of the voltage waveform.

The resulting current irregularities can cause disturbances such as voltage or current impulses and voltage loss in the power distribution circuits. Efforts are underway to better understand the power quality issue. There is a growing amount of literature covering individual power quality phenomena, such as harmonics and transient overvoltages, while argument continues over measurement equipment, extended version of definitions and possible standards. There are many unpublished spot surveys by users and equipment producers of suspected power quality problems. However, there is less information on general power quality site surveys. Analysis of the results from site surveys is often difficult to generalize because of location-specific qualities. Spot surveys will not expose synergisms among the utility, the facility disturbances at work and at the plant equipments.

A traditional studies and measurements of reliability do not deal with the power quality needs of sensitive electronic equipments. Rather, they deal with permanent or prolonged outages and how to improve upon it. While this is indeed important to sensitive loads (power supplies to computers and other microelectronic devices) also, there is increased concern for short term or momentary disturbances. The American National Standard Institute (ANSI) standard code C84.1, entitled "Voltage Ratings for Electric Power Systems and Equipment (60 Hz)", is the basis for rulings of regulatory commissions as far as voltage requirements are concerned. This standard was derived with the assistance of the utilities and the manufacturers. Basically, the standard separates the voltage requirements into two categories, Range A and Range B [16]. Range A and Range B are parts of a Bell shaped curve with Range A consisting of the middle portion of the curve and Range B making up the extremities of the curve.

Within each range, specifications are given for both service and utilization voltages. The Range A values are defined as the span over which systems shall be designed and operated so that most of the service voltages are within the set limits (i.e., 114-116v for 120v service). Voltage range B levels occur infrequently and are of limited duration (110-127v). The standard requires that the steady state voltage tolerances at the point of utilization or at the point of service be within + or - 5% for nonlighting loads. The standard also specifies the steady state voltage tolerances at the point of utilization. This standard only addresses two types of power disturbances which occur in electric power systems, surges and voltage sags. Present day electronic devices require near "ideal conditions " to function properly. Therefore, the above mentioned standard is no longer sufficient to specify the power requirements at the present time. In fact the end-use equipments often become the source of power quality problems; disturbances introduced into the systems by these nonlinear loads result in harmonic distortions. Utility systems are designed to provide reliable bulk power. However it is not feasible for them to provide continuous power of the quality required for a completely undisturbed computer operation .

Because normal use of electricity generates disturbances and because unexpected power system failures do occur, every site would experience some power disturbances. The nature of these power disturbances, their severity and their incidence rate vary from time to time. All these happen like random processes. To place the problem in perspective, however, one should remember that poor quality power is only one of the many causes of computer downtime. Hardware problems, and operator errors also contribute to computer downtime.

Historically, transient over-voltage effects on novel semiconductor and microelectronic systems were the first concern; by now, the scope of under-voltage or loss of power has also been recognized. Power quality problems (rather disturbances) that affect sensitive electronic loads have a variety of sources such as lightning, utility switching, and utility outages. However, power disturbances are often caused by users themselves by switching of loads, introduction of ground faults or normal but nonlinear operation of equipment. Computer system is one example of many such nonlinear loads that are not only sensitive but also can generate some disturbances by themselves. Their nonlinear load characteristics can cause interactions with the power system such as unusual voltage drops, overloaded neutral conductors, or distortions of the line voltage.

Definition of power quality

Power quality can be defined as the relative absence of utility related voltage variations-- particularly the absence of outages (power blackouts and brownouts), sags, surges and harmonics as measured at the point of service. Obviously this definition is based on the viewpoints of addressing what quality level a utility delivers power to its customers. If someone takes the viewpoint of customer then power quality is simply the relative absence of voltage variations as measured at the point of service. Disturbances caused by other customers or even by that particular customer's own equipment still affect that customer's perception of power quality.

The importance of semiconductor switching devices has penetrated to both the distribution and transmission level. In fact, at the transmission level, there is a program devoted to "Flexible AC Transmission System", FACTS, which proposes the use of semiconductor devices for bulk power control. Semiconductor devices of the power level required for realistic power control are now available; and the capabilities of commercial devices are on a state of steady increase. The MVA switching capabilities

MVA = | Circuit voltage| |Switching current|

(With voltage in kV and current in kA) are increasing with an added decrease in cost per MVA. Although these are not the only source of power quality problems, identifying and technically solving these emerging problems is an engineering challenge that can be met only on a case by case basis. Perhaps a more basic issue however is determining strategies that allow utilities and end-users to find an equitable and effective process to correct these situations. For utilities this may mean occasionally crossing over to the customer's side of the meter and for the end-users it may mean incurring expenses for services such as a conditioned power source or UPS (Uninterruptable Power Supply). Everyone agrees that power quality problems can best be resolved when all the people involved work together towards a common goal, namely quality power provided at a fair price. A consistent definition of terms describing power quality disturbances has not yet been developed. Voltage sag is commonly accepted to mean a brief reduction in voltage, but is not included in the IEEE (Institute of Electrical and Electronics Engineers) standard dictionary of electrical and electronics terms. Voltage and duration limits for the sag vary and the term outage means the complete absence of power at the point of use. Nonetheless, many utilities define an outage to be the absence of power for more than 4-5 minutes. Whereas to industrial plants, any disturbance that disrupts production is a outage. Responsibility for a reliable power source lies first with the utility company that generates and distributes power to the customer service entrance. For example, a power source can be reliable for semiconductor manufacturing at the delivery point if no more than two outages occur per year of less than two seconds duration each.

A stable frequency is a must in a semiconductor environment. Domestic U.S power distribution industry is at such a level that frequency variations are rare unless there there are widespread grid blackouts. An uninterrupted power source is paramount to a semiconductor manufacturer's ability to predictably deliver product. Not only will manufacturing time be lost during a momentary power outage, work in progress will be lost since the wafers could be damaged beyond recovery. Additionally many hours and days may be lost in recertification of production equipment. According to ANSI utility power profile, power is considered clean when its steady-state voltage changes between +6 and -13 percent of nominal. In order to achieve this, utilities attempt to hold their steady-state voltage at the level between +10 and -10 percent. ANSI gives wider utility voltage window limits for shorter periods of time. For variations over a period of 20-30 cycles, the ANSI standard says utilities must hold the voltage between +15 and -20 percent. For variations over 1/2 -1/4 cycle, the limit is +20 to -30 percent. The ANSI standard does not deal with transients, noise content, waveshape, or frequency.

The Computer Business Equipment Manufacturer's Association (CBEMA) publishes criteria for computer power systems. The CBEMA curve or envelope nearly matches the ANSI envelope for durations above 30 cycles. Below 30 cycles the CBEMA envelope is tighter. This phenomenon explains why utilities can satisfy ANSI standards and still produce short duration disturbances that are unacceptable to computer business equipment manufacturers. Typical range of input power quality requirements of major computer manufacturers is listed in Table I. The parameters listed in Table II are typical for use as a preparation guide.

Types of power quality disturbances

Despite efforts to improve and standardize power quality, power disturbances still can manifest themselves in the electrical environment. They may be generated from a variety of sources - severe weather, electrical faults, lightning or customer loads. Operational problems are the most visible indication of power disturbances. Typical of these are system crashes and processing errors in computer's data system. Some computer users accept these operational problems because they regard them as unavoidable. Because of increasing reliance on computers in the

TABLE I

TYPICAL RANGE OF INPUT POWER QUALITY AND LOAD PARAMETERS OF MAJOR COMPUTER MANUFACTURERS [14]

Parameters	Range
1) Voltage regulation (steady state).	+5%, -10% to +10% (ANSI), c84.1, 1970 is +6% , -13 %.
2) Voltage disturbances (Momentary Under-voltage).	-25% to -30% for less than 0.5s with -100% acceptable for 4-20ms.
Transient Over-voltages.	+150-200% for less than 0.2 ms.
3) Voltage harmonic distortion.	3-5% with (linear load).
4) Noise.	No standard.
5) Frequency Variation..	60 Hz to (+0.5 Hz to - 0.5Hz). or (+1 to -1 Hz).

TABLE I (Continued)

Parameters	Range
6) Frequency rate of change.	1Hz/s (Slew rate).
7) 3 phase voltage unbalance.	2.5% to 5 %.
8) Three phase load unbalance	5% -20% maximum for any phase.
9) Power factor.	0.8-0.9
10)Load Demand.	0.75-0.85

TABLE II

TYPES OF DISTURBANCES AND OTHER INFORMATION [15]

Types of Disturbances	Range	Duration	Origin	Type of Equipment
Impulses, spikes & noise.	Upto 6Kv.	< 0.5cycles.	Lightning strike, Rectifier, power supply, welding.	spikes can destroy electronic loads.
Short duration voltage variation.	0 to 1.76p.u.	0.5 to 30 cycles.	Lightning strike, Motor starting.	Sags can effect power down-sensing circuit in computer & can cause shutdown.

TABLE II (Continued)

Types of Disturbances	Range of magnitudes	Duration	Origin	Type of equipment
Long duration voltage variations (Over-voltage & Under-voltages).	0.8 to 1.2 p.u.	>30 cycles.	Circuit over-loads, poor voltage regulation.	Over-voltage &Under - Voltage affect all equipments despite ± 10% tolerance.
Harmonic distortion.	Upto 1p.u.	Seconds to steady -state.	Electronic equipments such as rectifiers & inverters, uninterruptable power supplies, electric furnace controllers, welding machines, ac & dc motor drive and computers.	Harmonic distortion causes motor loads such as compress-ors, and disk drives to get over heated.

workplace, however, they require the same amount of attention as demanded by more damaging power disturbances such as lightning-induced high voltage spikes that can cause data loss and hardware damage in the computers or interrupt power to major building systems (such as lighting, HVAC, and security, as well as elevator system).

Power quality disturbances are generally classified into six categories as follows:

(1) Voltage Sags and Swells.

(2) Spikes, Impulses & Surges.

(3) Outages.

(4) Harmonic Distortion

(5) Electrical Noise.

(6) Under-Voltage & Over-Voltage.

(1) <u>Voltage Sags and Swells</u> Voltage sags and swells as shown in Fig.1 are momentary (less than two seconds) decreases and increases in line voltage outside the normal tolerance of the electronic equipment.

<u>Sources of Sags.</u> Sags are typically caused by the starting of heavy loads or when faults occur in a power system. A voltage drop (sag) occurs on the faulted phase during the period.

<u>Impacts of Sags.</u> Sags can cause computers and other microprocessor- based equipments to shut down due to a lack of optimum voltages. Undervoltage (sag) can result in increased currents and overheating of motors (particularly stepped motors

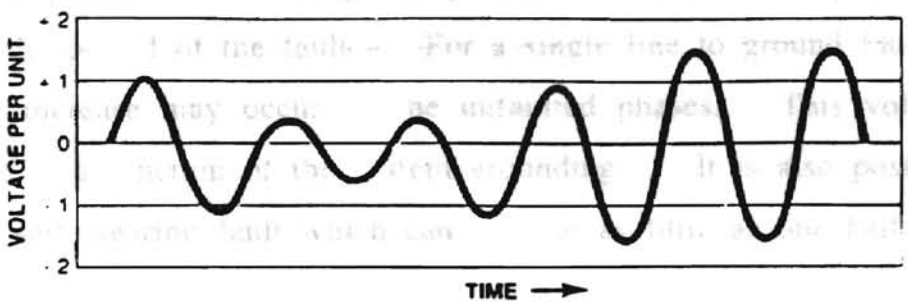

Figure1. Voltage Sag and Swell [15]

used in computer printers), lights dimming and computer malfunctioning.

Sources of Swells. Swells are generated by sudden load decreases, such as de-energizing of heavy equipments (such as demagnetization of large electromagnets in nuclear particle accelerators). Short duration overvoltages can also be associated with ferroresonance in transformer circuits .

Impacts of Swells. Swells can damage equipments having insufficient over-voltage tolerance and protection. Besides, overvoltages can cause increased equipment stress and mid-operation failure. A voltage drop occurs on the faulted phases during the period of the fault. For a single line to ground fault, a voltage increase may occur on the unfaulted phases. This voltage increase is a function of the system grounding. It is also possible to have a self clearing fault which can last for as little as one half of a cycle.

(2) Spikes, Impulses & Surges. Spikes, also known as impulses or switching surges or lightning surges, are high-voltage transients of very short duration (ranges from a fraction of a microsecond to a millisecond) with high amplitudes as shown Fig.2 . These types of disturbances can occur at customer locations due to events on the utility distribution system or to events within the customer's premises. Table III summarizes some of the important events which can cause the aforementioned disturbances .

TABLE III

TYPICAL SOURCES OF SPIKES, IMPULSES & SURGES [17]

Disturbances initiated on the distribution system	Disturbances initiated on the Customer premises
Lightning Impulses.	Lightning Impulses.
Feeder Energizing/Reclosing.	Capacitor Energizing.
Transformer Energizing.	Power Electronics Switching.
Capacitor Energizing.	Motor Interruption.

Sources of Spikes,Impulses & Surges . There are mainly four factors involved in the generation of these kind of disturbances. They are:

(i) Lightning transients

(ii) Capacitor energizing transients.

(iii) Power electronic switching operations.

(iv) Motor interruption.

(i) Lightning Transients. The main cause of this is the result of a direct lightning strike to a conductor or to a ground conductor or pole. The resulting surge on the distribution lines will be of relatively short duration (30-200 micro seconds) with very fast rise times (1-10 microsecond). Due to fast rise times, these surges can be coupled to secondary circuits by the capacitance ratio of step down transformers, rather than turns ratio. In per unit terms, the transient magnitudes on the secondary can be many times higher than the transient magnitude on the transformer primary.

(ii) Capacitor Energizing Transients. Capacitor energizing operations on the utility system are an important source of transient disturbances to the customer since these energizing operations can occur quite frequently (more than once per day). One of the principal source of such problem is the capacitor banks installed by customer to correct power factors. The customer capacitors on the secondary usually have much lower KVAR rating than the utility capacitors on the primary.

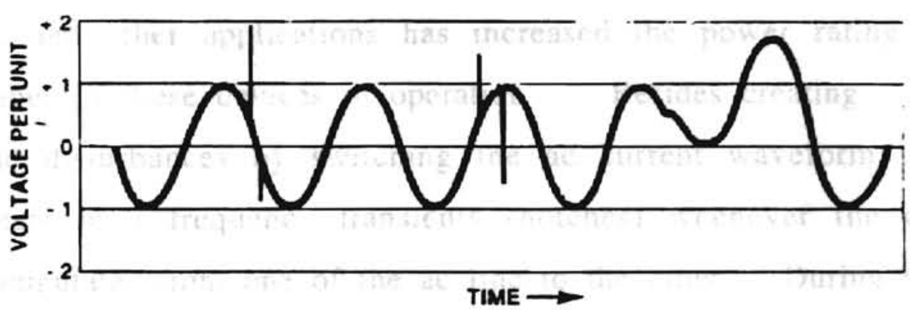

Figure2. Spikes, Impulses, and Surges [15]

The resonant circuit of Fig.3 formed by these capacitors and the step-down transformer reactance can cause significant magnification of transient oscillations associated with capacitor switching on the utility primary.

While the primary oscillation will have a transient magnitude of less than 2.0 pu, the magnified transients on the secondary can have magnitudes in the range of 3-4 p. u with significant energy content. Voltage waveforms illustrating this magnification phenomena of primary and secondary are shown in Fig.4 .

(iii) Power Electronics Switching Operations. The use of power converters for motor speed controls, dc loads, power supplies, UPS systems, and other applications has increased the power rating and the number of these devices in operation. Besides creating harmonic disturbances by switching the ac current waveform, they also create high frequency transients (notches) whenever the current flow commutates from one of the ac line to the other. During this commutation period, there is a short circuit on the system resulting in a notch in the voltage waveform. The notch characteristics are dependent on the magnitude of the current being commutated and the short circuit reactance of the ac supply to the converter.

(iv) Motor Interruption Large motors can cause significant voltage dips on the system when they are started, depending on the motor starting technique employed. A motor will typically draw anywhere from 6 to 10 times its full load current during starting.

Impacts of Spikes, Impulses and Surges. Spikes can cause data alterations, equipment errors or system damage. Impulses and

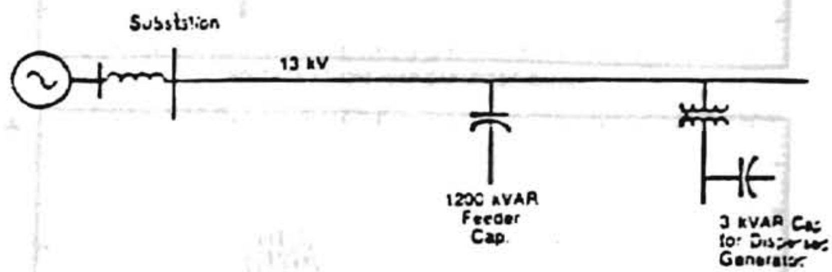

Figure3. Simplified Circuit Illustrating Magnification [17]

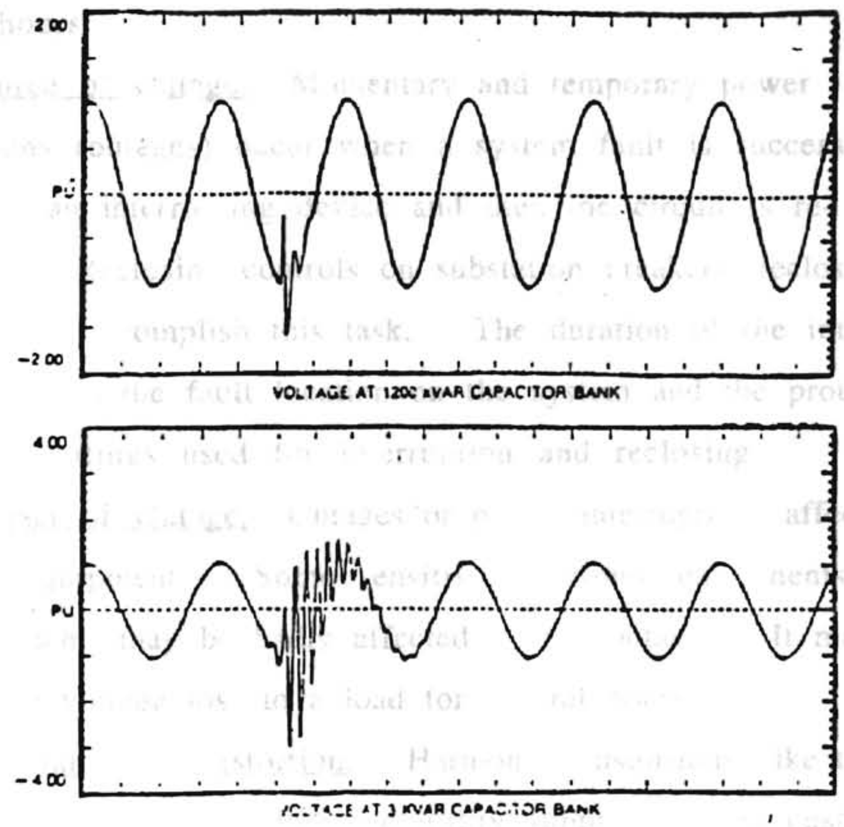

Figure4. Waveforms on Primary and secondary Illustrating Magnification phenomena. [17]

surges can cause failure of the insulation of equipments. Moreover they interfere with communication lines, data acquisition, and control applications.

(3) Outage or Power Interruption. An outage as shown in Fig.5 is a complete loss of power lasting from several milliseconds to several hours.

Source of Outage. Momentary and temporary power interruptions (outages) occur when a system fault is successfully cleared by an interrupting device and then the circuit is re-energized. Reclosing controls on substation breakers, reclosers, and sectionalizers accomplish this task. The duration of the interruption will depend on the fault location on the system and the protection equipment settings used for interruption and reclosing.

Impact of Outage. Outages or power interruptions affect all electrical equipment. Some sensitive electronic equipments (without backup system) may be badly affected by the outage. It may lead to complete voltage loss to a load for several hours.

(4) Harmonic Distortion. Harmonic distortions, like transient surges, can come from either the utility supply or from customer's own equipment. Harmonic disturbances such as the ones shown in Fig.6 refer to power system frequencies that are multiples of the fundamental (60 Hz) frequency.

Source of Harmonic Disturbances. Harmonic disturbances are mainly caused by three major categories of devices.

(i) Power Electronics. This category of harmonic sources is one of the main reasons for the increasing concern over harmonic

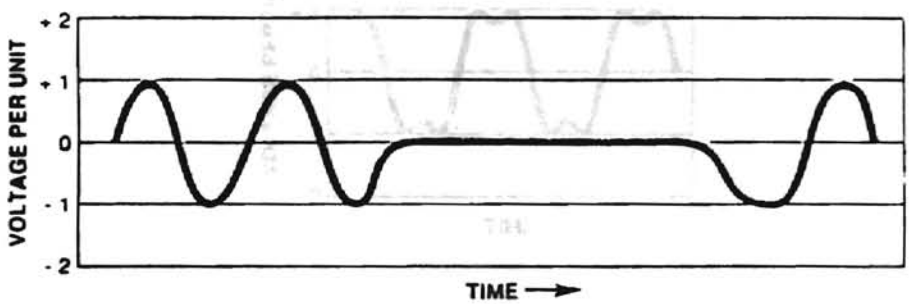

Figure5. Outage [15]

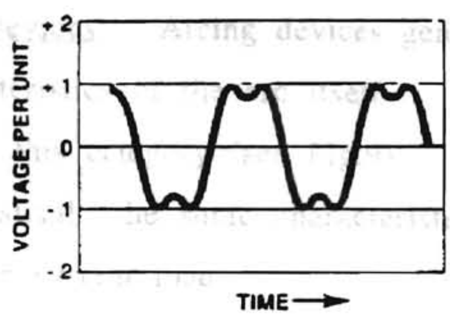

Figure6. Harmonic Distortion [15]

problems in power systems. The applications for power electronic devices (rectifiers, variable speed drives, UPS systems, cycloconverters and inverters) are continually growing. In Fig.7 the nonsinusoidal characteristic of some typical waveforms are shown.

(ii) Ferromagnetic Devices. Transformers are the most important devices in this category. Transformers generate harmonics as a result of their nonlinear magnetizing characteristics as given in Fig.8 . The level of harmonic voltage increases substantially as the applied voltage increases above the transformer rating.

(iii) Arcing Devices. Arcing devices generate harmonics due to the nonlinear characteristics of the arc itself. Arc furnaces are large harmonic sources in this category (see Fig.9). However, fluorescent lighting has also basically the same characteristics and is much more prevalent as a power system load .

Impact of Harmonic Distortion. This type of disturbance may cause overheating and high currents in conductors (specially neutral conductors), transformers, capacitors, motors and other equipment.

(5) Electrical Noise. Electrical noise is a distortion of the normal sine wave. This is illustrated in Fig.10 .

Source of Electrical Noise. It is generated by radio or television (Audio or Video) transmitters, power electronic circuits, Arcing loads, and switching power supplies used in computers.

Impact of Electrical Noise. It can affect the operation of microprocessor based equipments.

(6) Undervoltage and Over-Voltage. Undervoltage and Overvoltage

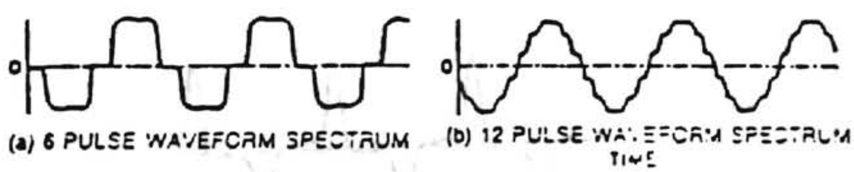

Figure7. Current Waveform Typical of most
Single phase Electronic Loads [17]

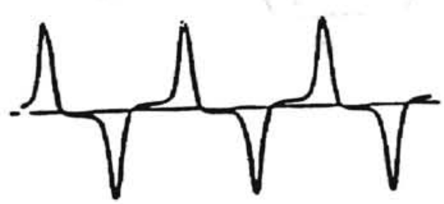

Figure8. Typical Transformer Magnetizing Current [17]

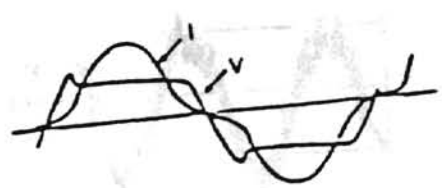

Figure9. Arc Furnace Voltage and Current [17]

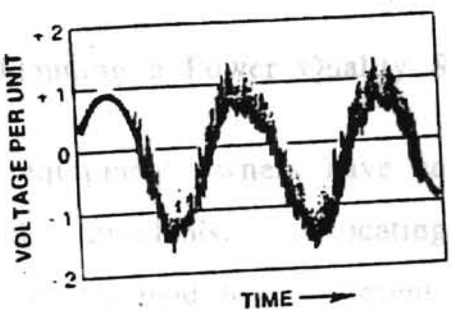

Figure10. Electrical Noise [15]

of Fig.11 are abnormally high or low voltage conditions lasting for more than a few seconds.

Sources of Undervoltage and Over-Voltage. The most important cause of this voltage variation (Under or Over) is a fault condition on the utility system. It happens due to circuit overloads, poor voltage regulation, and intentional reduction in voltage by the utility.

Impact of Over and Under Voltage Condition. The problem caused by Under or Over-Voltage effects performance of all type of equipments.

Planning a Power Quality Survey

Building and equipment owners have several options for resolving power quality problems. Relocating the source of interference or the critical load to a different receptacle or power distribution circuit is possible, but it may not be a solution. Before expensive power conditioning equipment is installed, a well-planned and well executed survey procedure can be used to solve most power quality problems that affect equipment operation. The first and most important step is planning. Important planning requirements are discussed below.

(1) Assemble a professional team. Assembling a team of professionals who are experts in power quality is very critical when planning a survey. A survey team may consist of individuals who understand equipment operation and the building's electrical powersystem (such as building owners, managers, operators etc) and

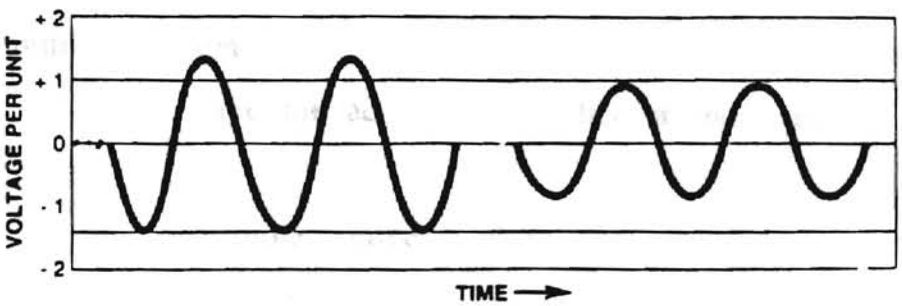

Figure11. Undervoltage and Overvoltage [15]

electrical contractors, electrical engineers, etc) who can make measurements on live electrical circuits and analyze power related problems.

(2) Develop a comprehensive plan. Performing a power quality survey requires a comprehensive plan. The plan should include general and specific survey objectives. Correcting equipment performance problem and neutralizing the problems created by the faults are the general objectives. The specific objectives are as follows:

(i) determine the condition and adequacy of the wiring and grounding system.

(ii) determine the ac voltage quality at the point of use.

(iii) determine sources and impacts of power disturbances on equipment performance.

(iv) analyze findings to identify immediate and near-term cost- effective solutions

(3) Collect and document data. Collecting data and proper documentation are necessary to obtain information about the equipment or the facility that is experiencing power quality related problems. Efforts should be made to obtain the site history. It includes typically the following informations :

(i) normal time for recurrent system problems.

(ii) symptoms of hardware failures.

(iii) recent equipment changes.

(iv) renovations of the facility.

(v) operating cycles for major electrical equipment of the facility.

(vi) verifying the logbooks of equipments to study the history of trouble shooting.

(4) Assemblage of necessary instruments. Certain instruments are necessary to monitor and record the power quality of a facility. The instruments typically needed are used to measure some or all of the electrical parameters such as voltage deviation, voltage loss, frequency, voltage transients, sags or surges, frequency, electrical noise and harmonics. The instruments most commonly required for a power quality survey are enumerated next.

(i) True rms multimeter. A multimeter is a versatile tool that measures voltage, current and resistance. However a true rms multimeter is almost immune from measurement error induced by nonlinear electronic loads. Some true rms multimeters permit the attachment of accessories for reading ac amps, watts, kVA, power factor and ac line frequency, conducting insulation resistance tests, testing of capacitors and diodes and reading temperature using contact (thermocouple) or infrared probes .

Multimeters used for current measurement that are average-responding but rms calibrated may read 20 to 30 percent lower than actual levels.

(ii) True rms Ammeter. An ammeter is used to measure current and analyze current waveforms, particularly when a nonlinear waveform is involved. Among all the ammeters, Hall effect current probe is the most popular. The Hall effect current probe measures dc, ac or dc & ac composite currents. Available in sizes up to 2,000 A, the current probe must have true rms circuitry to avoid measurement error. Hall effect probes are available as stand-alone devices or as a probe accessory for a multimeter.

(iii) Circuit and Impedance Tester. A circuit tester is an useful tool in determining the wiring polarity of receptacles. It checks for open conductors and line-neutral line-ground reversals. Some circuit testers also measure circuit impedances. The greatest benefit of the circuit tester is that it examines the physical condition of the receptacle and outlet assembly for loose and broken mounting. Generally, a high percentage of common wiring errors are detected at this stage.

(iv) Ground Impedance Tester. It is a multifunctional instrument designed to detect wiring and grounding problems in low-voltage power distribution systems. These problems are as follows: wiring errors, neutral to ground shorts and reversals, isolated ground shorts, and neutral impedance shorts.

(v) .Power Monitor. The power monitor [14] is the most important and useful tool in a power survey. It is designed to identify and record events that exceed preset limits, permitting the user to collect data for later review and analysis. Some common power monitor features are summarized in Table IV. Power quality monitors are available in a broad choice of recording capabilities and sophistication. They are classified as follows:

(a) Threshold counter: Applied to a calibrated voltage divide, this device triggers a counter each time a preset voltage is exceeded. Early threshold counters were analog but recent ones are digital.

(b) Oscilloscope with camera: Surges that trigger a single sweep on the CRT (Cathode Ray Tube) of the Oscilloscope are recorded by a shutterless camera as they occur.

(c) Digital storage oscilloscope:

Within this device, the surge is digitized and stored in a shift register for subsequent playback and display whenever a preset threshold is exceeded. This type of oscilloscope has the capability of displaying events

prior to the beginning of the surge.

(d) Screen storage oscilloscope: This device stores and displays the surge on a cathode ray tube.

(e) Digital peak recorder This type of electrical equipment registers the peak value and it can also calculate the duration of the surge.

(f) Digital waveform recorder This device [13] digitizes and stores the surge in a manner similar to the digital storage oscilloscope. Because of the data processing functions which are incorporated in the instrument, the recorder allows reports of many different parameters of the disturbance, relating voltage to time.

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TABLE IV

COMMON POWER MONITORING FEATURES [15]

Features	Description
Harmonic Analysis	Increases the power and flexibility of the power monitor. Harmonic analysis of voltage and current pinpoints loads which cause harmonic currents.
Voltage and current measurements	Analyzes and identifies the source of power problems.
Continuous Monitoring.	Provides unrestricted Monitoring.
Multiple Channels	Enables the use of several channels to observe events in phase, neutral and ground.

TABLE IV (Continued)

Features	Description
Waveform Display	Waveforms are recorded and displayed. Some event waveforms are very characteristics of particular load. Recognizing these waveforms helps to point immediately to the cause.
Waveform Manipulation	Allows quick waveform measurement using zoom, frequency markers and Amplitude markers.
Scopemode (real time monitoring)	Enables quick view of voltage and current magnitudes and waveforms because only the data of interest is stored.
Data storage	Stores event data on disk.

TABLE IV (Continued)

Feature	Description
Broad Frequency response	Captures high speed current and voltage impulses.
Simultaneous Display	Saves waveforms from all channels, even if a disturbance occurs on only one channel. It guarantees a complete picture of the disturbance recorded.
Event Summaries	Provides a graphical plot of rms and high frequency events over user selectable period.

(vi) Infrared scanner Infrared scanners measure infrared emissions from a surface. Typically they are used for monitoring of survey are very important overheating of electrical switchgear , transformers, circuit breakers and other electrical equipment. They convert emissions into a proportional voltage that drives a display (digital or analog scale). Some infrared scanners use video displays for easy location of a scanned item and storage of data.

Performing the Survey

A power quality survey is a necessary step in diagnosing the problem and finding a solution. The survey may include a basic and a comprehensive one. Basic inspection is necessary before the comprehensive one is undertaken. Both types of survey are very important to pinpoint the problem area and search for answers to the complex problem of power quality.

(1) Basic Inspection. The basic inspection is designed to familiarize site examiners with the building. It is important to the survey team members to visually inspect the electrical layout, electrical hardware and the construction techniques used throughout the building.

When inspecting the outside of the building the surveyor should be aware of the following points :

(i) Search for the type of electrical service (underground or aerial) used.

(ii) Determine if there are any utility power factor correction capacitor installations. Neighboring facilities can feed interference back onto a shared utility feeder.

(iii) Locate any utility substations in the immediate vicinity.

During the internal inspection of the building, the surveyor should note the following important points :

(iv) Notice any large electrical loads (adjustable speed drives, elevators, welders etc.) in the facility.

(v) Checkup on any equipment which has a history of problems .

(vi) Arrange a tour of the important sites inside the building and collect as much data as possible from consultation with different people who are knowledgeable of the building and its electrical machineries.

(2) Comprehensive Inspection. A comprehensive inspection involves physical verification of site and monitoring procedures. The electrical distribution system and grounding must be physically inspected to identify problems with electrical system equipment and grounding. Table V summarizes some important measurements and considerations in identifying problems with various electrical distribution systems.

(i) Inspection.Procedures The best place to start a physical inspection is the supply transformer. From this point, each additional panel for the distribution system should be checked for rms voltage levels and current levels. All these tests should include voltage, current, phase sequence, ground impedance and neutral impedance, proper conductor termination, absence of neutral ground and isolated ground shorts.

(ii) Monitoring procedures.

Power monitoring with the help of cathode ray screen is very important to locate various types of voltage disturbances. In the following a few of the important points would be highlighted.

(a) Hookup.

Use of twisted pair of cables for monitor inputs reduces the possibility of picking up radiated RFI/EMI (radio frequency and electromagnetic interference) fields. Other hookup procedures are as follows:

(I) Whenever possible, the monitor should be connected to record both voltage and current at a load.

(II) When a power monitor is installed at a load, the channel connections for the monitor should match the wiring connection for the power supply of the load.

(III) Current transformers (probes) should be added to vacant channels to record phase, and neutral or ground current.

(IV) Monitoring phase current is essential to determine the source of a power disturbance.

(V) Monitoring neutral or ground current is essential to determine the source of neutral-to-ground faults/disturbances and to identify the sources of current flowing in the grounding conductor.

(b) Grounding The grounding of the power monitor should be performed with caution. Since a chassis ground is provided through

TABLE V

ELECTRICAL DISTRIBUTION SYSTEM AND GROUNDING MEASUREMENTS AND CONSIDERATION [15]

Equipment or Grounding	Measurements and considerations
Wiring	Ensure compliance with NEC (National Electrical Code). Make a detailed inspection for broken or corroded conduits. Immediately replace the defective wires.
Grounding	Compliance is maintained with the NEC. It is made sure that any electrical distribution devices, receptacles, power panels, conduits etc - are bonded to ground structures. No independent ground systems should be established.

TABLE V (Continued)

Equipment or Grounding	Measurements and considerations
Electrical panelboards	Inspect loose electrical connections, excessive hardware temperature and improper neutral to ground bonds. Special attention should be paid to bus-bar assemblies. Measurement of all phase to phase, phase to ground and phase to neutral voltages are made and these values are recorded. All currents in feeder conductors branch circuits and grounding conductors are measured. Circuit breakers are checked for hot spots.
Electrical conduits	Electrical conduits are checked for mechanical connection and excessive warmth. A hot and vibratory conduits should be replaced immediately.

TABLE V (Continued)

Equipment or grounding	Measurements and considerations
Electrical service entrance	Grounding of switch gear is checked for compliance with the NEC regulation. Wiring connection is checked for looseness and special attention is given toward neutral and grounding.
Transformers	They should be checked for excessive heat, vibration or audible noise. All phase voltages are measured and a detailed inspection is maintained for transformer output neutral and safety ground.
Receptacles	Inspect grounding connections, cracked faceplates, or visible sign of arcing. Load is removed from the receptacle and checked for proper polarity and ground resistance.

TABLE V (Continued)

Equipment or grounding	Measurements and considerations
Undercarpet Wiring	Checking is conducted for excessive warmth around the carpet. Excessive weight if present is removed from wiring.
Equipment power cords & plugs.	Inspection is done for wear and tear of patches of Insulation and warm spots.

the ac input power cord, any chassis ground connections to the circuit being monitored can cause ground loops that result in additional noise being injected into the sensitive equipment feeder. To avoid this problem one should not make chassis ground connection to the circuit being monitored.

(c) Location. The general priorities for positioning of the power monitor are :

(I) To place it as close as to the load.

(II) At the service entrance to determine the power quality of the site.

(III) Locate the important regions as determined by the previous survey. Some limitations may affect the ability of power monitoring

equipment to predict power supply disturbances at a specific locations. Also, monitoring over a period of less than one year may produce an inaccurate power disturbance profile.

(d) Duration. Monitoring should be performed for at least one full weekly cycle which comprises 7-8 days.

(e) Threshold. Power monitoring equipments require selection of threshold at which disturbances are to be measured. Some of those techniques are grouped as follows:

(I) The sensitive level captures almost every important event and shows the constant power quality problem on the line.

(II) The normal level captures events that are more severe.

(III) The tolerant level captures very severe power problems in the line (distribution network). The tolerant level may also be used for regular monitoring.

The usual procedure for setting power monitor thresholds are :

(A) The monitor is set in oscilloscope mode & the power is observed for any voltage or current waveform distortion. If there arises any abnormality then that event should be recorded.

(B) The monitor is next adjusted to sensitive level and is left for 10-15 minutes. The subsequent event summaries are plotted for analysis. The information is stored in a floppy disk for evaluation at a later time.

(C) The monitor is reset for normal thresholds. If the scopemode or sensitive level monitoring record events which exceed the normal thresholds, then the threshold setting is readjusted.

(f) <u>Monitoring.</u> The monitor is checked and readjusted regularly to capture any events. Periodic inspections may indicate the need to modify the monitor installation. The changes may be classified as follows:

(I) Threshold setting may have to be altered to increase or decrease sensitivity.

(II) Current probe is added to determine the direction or to monitor the phase of neutral or ground current.

(III) Environmental, temperature and chromatographic sensors are installed to measure the change in humidity, temperature and any change in air composition.

(IV) Sensors to measure radio frequency and microwave interference are installed.

Analyzing the survey data

Once the power quality survey has been performed, the next step is the analysis of all collected information and data. In the analysis a detailed inspection is maintained for unusual voltage and current waveforms. The data provided by the power monitor should be carefully analyzed to determine sources of disturbances, as well as cost effective methods for elimination of disturbances.

Although relatively simple analysis can be helpful, the key to identifying power-related equipment problems is to conduct a thorough scan which involves the following steps:

(1) Examination of pre and post survey data. It is essential to examine all information prior to survey. Any specific power events that may cause equipment symptoms is documented in the site history and equipment logs. Also it is imperative to go through the post survey events such as the power monitor event data. As an example, a hard disk crash (loss of information) on a computer may be due to an impulse, outage or over-voltage in the power distribution network. The procedures of correct wiring and grounding of the equipments are verified.

(2) Comparison and plotting of power monitor output. It is essential to plot power monitoring event summaries which can help to identify the main cause of power problems. At a minimum level at least there are three different event summaries as ---- 24-hour, seven day and total. Fig.12 shows a typical seven-day event summary.

The power events and equipment event logs are compared. By arranging all equipment log entries into a format similar to the power monitor event summaries, trend analysis and event correlation become easier. It is important to note the time, frequency, amplitude and event number of all events which correspond with the recorded equipment problems. Comparison of power events to equipment performance specifications is necessary to determine if recorded events exceed limits.

Main equipment specifications include voltage limit, frequency tolerance, and impulse withstand capability. The listings of several equipment specifications and their normal and critical tolerances are tabulated in Table VI.

(3) Determination and classification of key power events. Power events that correspond to or exceed limits would be apparent . Grouping key events into general categories improves event analysis. Some events reflect problems within a building while other events are clearly power source-related.

The general categories of events are :

(i) High frequency events such as unidirectional impulse, oscillatory impulse, repetitive events and common and normal mode noise.

(ii) Voltage events (such as sags, surges, under-voltage, over-voltage, outages and line interruptions etc.).

(iii) Distortion.

(4) Confirmation of Power Monitoring Correlation. It is very essential to confirm that the correlation of power events and equipment

symptoms is valid. The general guidelines to be followed are listed below.

TABLE VI

EQUIPMENT SPECIFICATIONS AND TOLERANCE [15]

Specifications	Normal Tolerance	Critical Tolerance
Frequency Deviation	47 to 63 Hz	59.5 to 60.5 Hz
Harmonic Distortion	10 to 20% Maximum of Total Harmonic Distortion	3 to10% Maximum of Total Harmonic Distortion.
Impulses	100 to 300 Volt (1X to 3X Nominal)	50 to 100 Volt (0.5X to 1X Nominal)
Neutral to Ground Voltage	3 to 5 Volt	1 Volt
Voltage Dropouts.	20 milliseconds	4 Milliseconds
Voltage Fluctuation	114 to 126 Volt ac	105 to 132 Volt ac

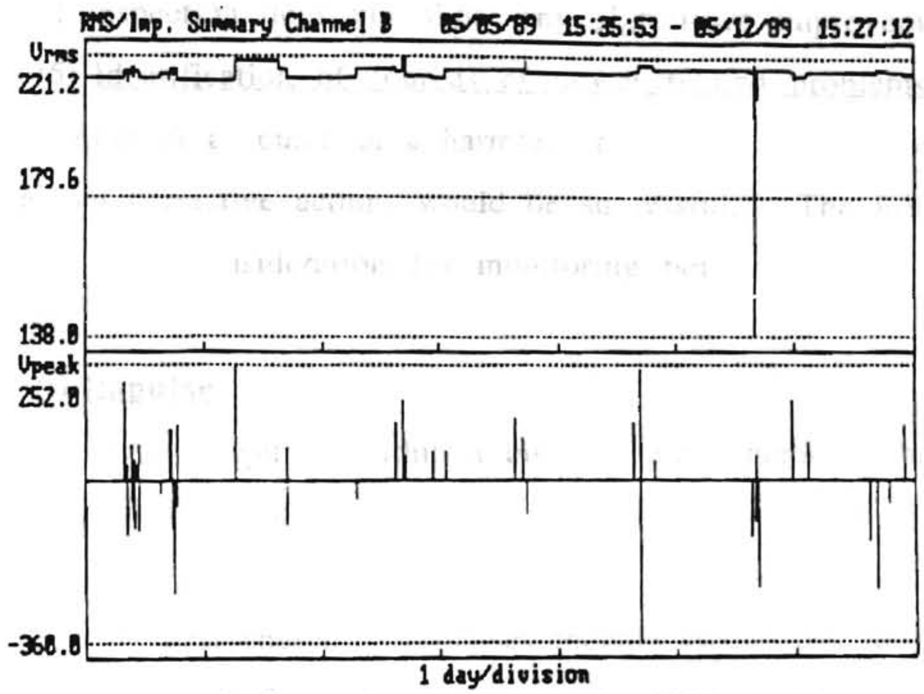


Figure12. Seven-Day Event Summary [15]

(i) Sufficient analysis is done to see whether the recorded power event could have been the cause of the equipment problem. Attention is paid to note that a correlation can indicate the absence of sufficient monitor data.(ii) Physical inspection data is rechecked to determine the necessity of correction of the problem.

(iii) Further continuous monitoring is maintained if the physical inspection does not show any significant improvements.

(5) Identification of sources of power related problems.

Identification of a source of a harmful power event is important to ensure that corrective actions would be successful. The following points provide consideration for monitoring both voltage and current events:

(i) Impulse

(a) Most impulses within a building are generated when load cycles come on and off.

(b) Typical causes of impulses include switch contacts and sharp current transitions interfacing with source impedance.

(c) The direction of the origin of an impulse can be determined by reviewing the polarity of the leading edges of the simultaneous voltage and current waveforms.

(d) If the voltage is "+" and current is "+" or voltage is "-" and current is "-" the origin is source related. If the voltage is "+" and the current. is "-" or voltage is "-" and current is "+", the origin is load related.

(e) Fig.13 shows a voltage source supplying power to an SCR controlled load. Each cycle of the voltage waveform has an Impulse which coincides with the current drawn by the load.

(ii) Voltage Sag.

(a) Voltage sags are sometimes caused by utility power supply variations.

(b) Another major factor is the load interaction with wiring.

(c) If the current on the circuit increases or decreases or goes to zero then the origin of the sag is termed as source oriented.

(iii) Voltage Distortion.

(a) Voltage distortion is caused by large amounts of harmonic currents from nonlinear loads and power sources with nonsinusodal voltage characteristics.

(b) Loads that do not contribute to distortion have a small amount of harmonic current. Loads which cause distortion have high levels of harmonic currents.

(iv) Ground and neutral events.

(a) There are several causes which result in neutral-to-ground voltages and they include return current flowing in the neutral conductor impedance, ground current and too much ground resistance.

(b) Where neutral-to-ground voltage results from neutral current, the neutral current increases and varies along with neutral-to-ground voltage levels.

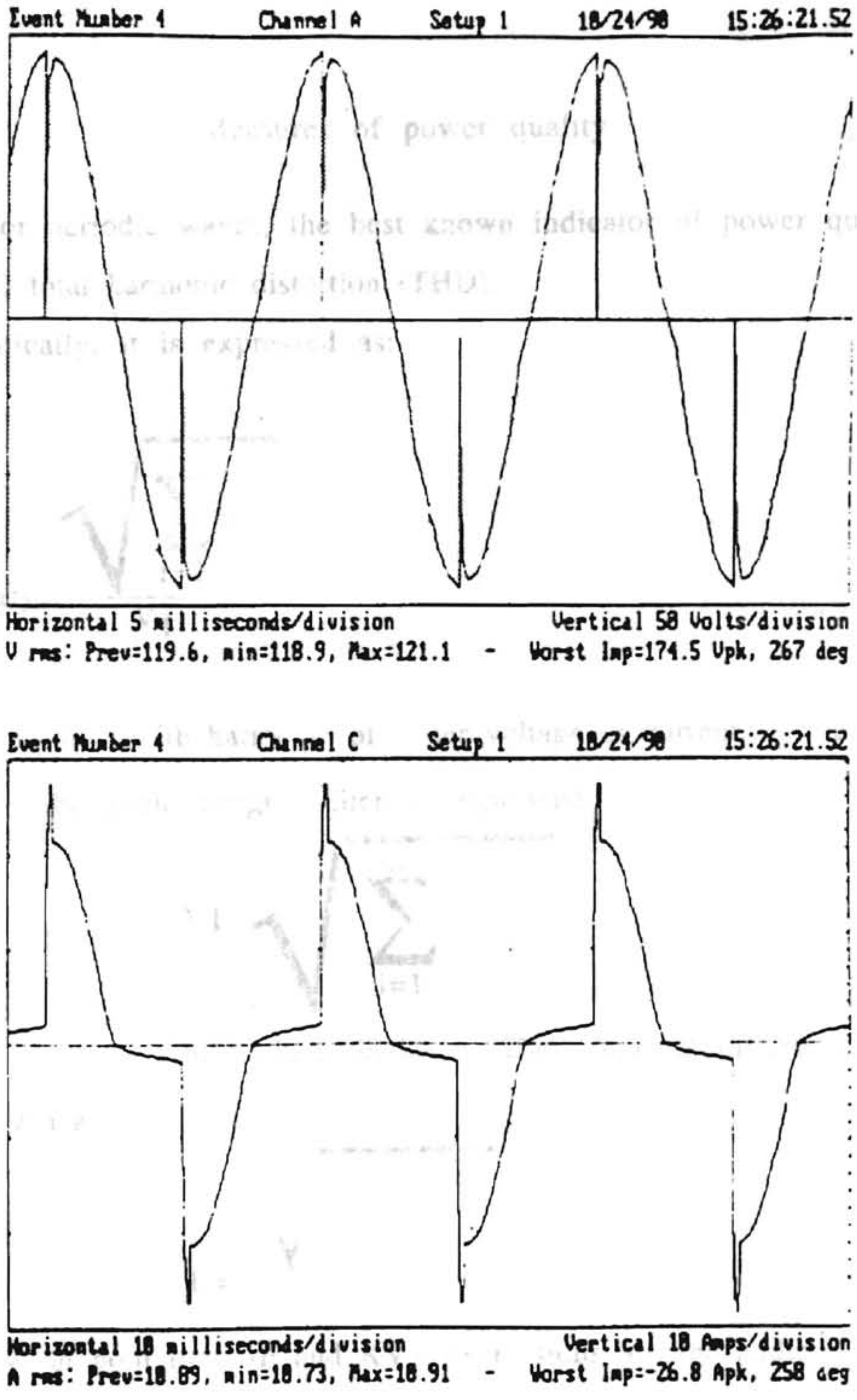


Figure13. Waveform of SCR-Controlled Load [15]

Measures of power quality

For periodic waves, the best known indicator of power quality is the [7] total harmonic distortion (THD).
Mathematically, it is expressed as:

$$THD=\frac{\sqrt{\sum_{i=2}^{\infty} V_i^2}}{V_1} \tag{1}$$

Where V_i is the ith harmonic of either voltage or current. The KVT product is the audio weight which is expressed as:

$$KVT=\sqrt{\sum_{i=1}^{\infty} V_i^2 w_i^2} \tag{2}$$

with V_i in line-to-line voltage in kV. The telephone influence factor TIF is given as:

$$TIF=\frac{\sqrt{\sum_{i=1}^{\infty} (w_i V_i)^2}}{V_1} \tag{3}$$

Where w_i in both the TIF and KVT expressions are the audio weights which reflect the response of the human ear. The European Distortion Index (DIN) is given as:

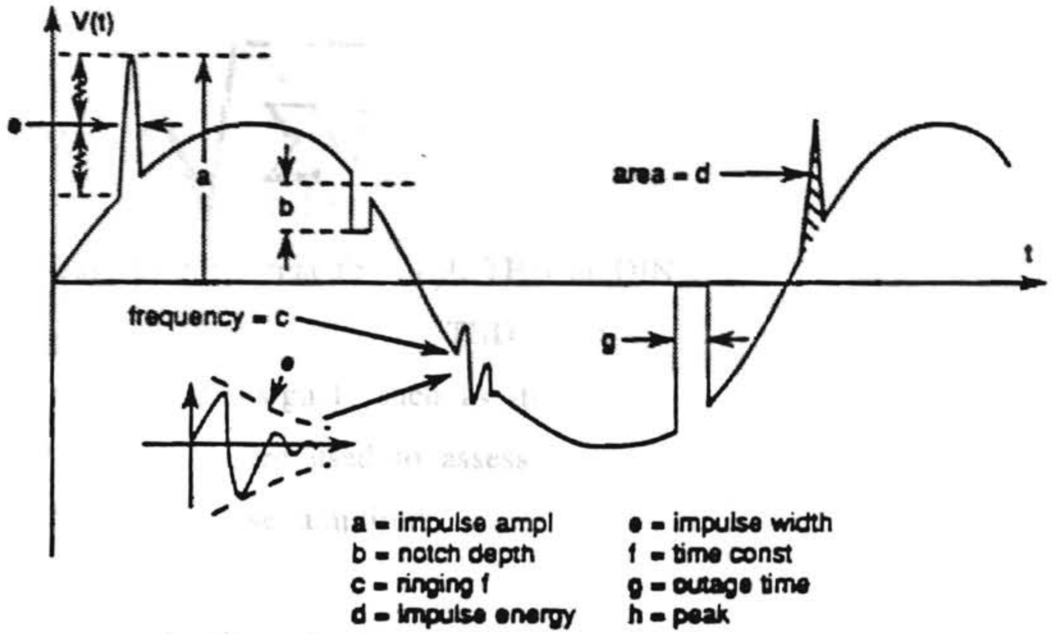


Figure14. Power quality indices for non-periodic phenomena [11]

$$\text{DIN}=\frac{\sqrt{\sum_{i=2}^{\infty} V_i^2}}{V_{rms}} \tag{4}$$

Where V_{rms} is the rms voltage

$$V_{rms}=\sqrt{\sum_{i=1}^{\infty} V_i^2} \tag{5}$$

It is easy to show that for small THD or DIN,

THD = DIN

For non-periodic signals such as the one illustrated in Figure.14, the following indices are used to assess power quality:

(1) Impulse amplitude

(2) Notch Depth.

(3) Ringing frequency.

(4) Impulse energy

(5) Impulse width.

(6) Damping time constant associated with ringing pulses.

(7) Waveform peak.

Discussion of various methods to improve Power Quality

There are two parts to the solution to improve the quality of power that is distributed to a large number of customers. The first part is known as customer site corrections and the second part is the solution of utility's voltage variation problem. These are briefly discussed next.

(1) Customer Site Corrections. A variety of voltage regulation equipment is available to provide a constant voltage magnitude at critical loads during short or momentary voltage variations in the supply voltage. A few of these type of devices are listed below.

(i) Equipment power supplies. With advanced and improved equipments, it is possible to get a certain degree of clean power (by providing the capability to ride) through the under voltage conditions of short duration. Larger capacitors in the output circuit can ride through 1/4 cycle to approximately two cycles (longer for low power devices) of the period of voltage loss.

(ii) Voltage regulators. Fast responding voltage regulators can typically control the output voltage to within ±2% when the input voltage varies within ±15%. Often the output voltage can be controlled to within 10% of nominal for input swings as large as 65%.

(iii) Line Conditioners. By using this type of devices (linear amplifier type line conditioners) very accurate voltage regulation can be obtained. Slightly less accurate regulation at a lower cost is obtained by using ferroresonant type of conditioners.

(iv) Motor generator set . Motor generator sets are generally employed to provide complete isolation between systems or as frequency changers. They can also be provided with the capability to ride through a complete loss of voltage for 0.3 to 0.5 seconds.

(v) Uninterruptible Power Supplies (UPS). These systems are designed to provide uninterruptible power for much longer durations. With battery backup they can easily ride through short duration under-voltages or outages.

(2) Solution of utility sides voltage variation. The most important cause of short duration disturbances is the occurrence of system faults. Therefore the utility can take the following steps to eliminate disturbances to the customer.

(i) Install underground systems instead of overhead systems.

(ii) Follow proper tree trimming policies and provide animal guards.

(iii) Minimize system ground impedances.

(iv) Employ appropriate coordination practices and switching procedures.

(3) Long duration voltage variations Voltage variations longer than 30 cycles (1/2 second) are generally classified as long . These variations are generally in the range of -20% to +10% and they are not the result of system faults. They are caused by system switching operations and some of the specific causes are discussed below.

(i) Motor starting. Large motors can cause significant voltage dips on the system when they are started. The resulting voltage during the motor starting period will depend on the ratio of the motor size to the system short circuit capacity where it is connected.

(ii) Switching system loads and capacitor banks. Energizing a load on the system will result in a sustained voltage drop on the system until voltage regulation or other devices compensate for the change. Similarly, de-energizing a load will result in a sustained over-voltage on the system. If the capacitor bank or load is large enough relative to the system capacity, distribution system voltage regulators or transformer load tap changers would respond in tens of seconds.to bring back the voltage to within allowable tolerance limits.

(iii) Voltage Flicker. Loads which can exhibit continuous, rapid variations in the load current magnitude can cause voltage variations referred to as flicker. Flicker normally refers to voltage variations which exhibit frequencies in the range of 1/2 to 30 Hz.

(4) Intentional voltage reductions. Many utilities follow voltage reduction procedures to help in reducing the load during severe peak load conditions. The system voltage may be reduced from 3% to 8% in steps depending on the severity of the load.

Solution of voltage variation problem. In particular, various types of tapchangers, ferroresonant regulators, line power conditioners, motor generator sets, and uninterruptible power supplies can be used to maintain a constant voltage.

(5) Power interruptions. power interruptions involve the complete loss of voltage to the load for at least 0.5 seconds. The interruptions can be classified as momentary interruptions (less than 2 seconds), temporary interruptions (2 seconds to 2 minutes), or outages (longer than 2 minutes)

Solution to interruption problems. Backup supplies for outage contingencies take the form of UPS system or backup generators.

UPS systems generally provide uninterrupted supply for at least 15 to 30 minutes. The utility determines the duration of interruption through protective devices coordination practices on circuits supplying the customers. Fuses, sectionalizes, reclosers and relays are coordinated when there is a permanent fault so that minimum number of customers suffer outage.

Solution Of harmonic distortion. The problem of harmonic distortion can also be mitigated by the following techniques :

(i) Phase multiplication. The essence of phase multiplication methodologies is the translation of harmonics to a higher frequency and the concomitant reduction of the amplitudes of those harmonics.

(ii) Passive and active filters. This method offers an array of power factor correction and control side benefits.

(iii) Harmonic injection. This scheme needs a triple harmonic current generator, and nullification of more than one harmonic order at any one operating point.

(iv) Pulse width modulation. This method shows great promise, and quite capable of obtaining harmonic suppression to less than 1% of the fundamental.

CHAPTER III

HARTLEY TRANSFORM

Introduction

Complex number theory greatly facilitated the handling of oscillating quantities. To analyze alternating current without the complex phasor $e^{i\omega t}$ is unthinkable. Consequently the theory of Fourier series took advantage of the theory of complex numbers and it came to seem natural that a periodic function p(t) of unit period can be analyzed into complex components $a_n e^{i2\pi nt}$, where the coefficients a_n, are now complex. Thus

$$p(t)= \sum_{n=-\infty}^{\infty} a_n . e^{i2pnt} \tag{6}$$

and in the limit, for a function f(t) that is not periodic,

$$f(t)= \int_{-\infty}^{\infty} f(n) . e^{i2\pi nt} . dn \tag{7}$$

At the same time, p(t) can be expressed in terms of real functions as

$$p(t)=a_0 + \sum_{n=1}^{\infty} (a_n \cos 2\pi nt + b_n \sin 2\pi nt) \tag{8}$$

as shown by Fourier. As a result of which, one can understand that the use of complex exponential is convenient rather than fundamental. Hartley's (in 1942) formulation of a real integral transform made it possible to dispense with complex representation. Although his new discovery was published in the Proceedings of the Institute of Radio Engineers, and mentioned in text books such as Frequency Analysis, Modulation and Noise by S. Goldman, and R. N. Bracewell, Fourier Transform and it's Application (McGraw-Hill,1965), the classical method prevailed. Hartley's famous "Cas" function transform s=iω is related to the Fourier Transform by the following expression as:

$$H(s)= \int_{-\infty}^{\infty} f(x).Cas2\pi sx.dx \qquad (9)$$

where $Cas2\pi sx = Cos2\pi sx + Sin2\pi sx$,

and H(s) is known as the Hartley Transform (HT). The advent of images produced or processed by computer and displayed on cathode ray screen has greatly extended the application of two dimensional analysis and it is very interesting to find that the idea of a real transform generalizes readily. It is obvious that a power spectrum, such as an optical spectrum, is described by a real function of a real frequency variable f.

Definitions of Hartley Transform.

In his original paper in the Proceedings of the Institute of Radio Engineers in 1942, R.V.L. Hartley (1890-1970) laid emphasis on the strictly reciprocal character of a pair of integral formulae that he introduced and in the following section his notation will be followed so that the full symmetry can be appreciated.

Consider a time dependent signal v(t) which may be thought of as a voltage waveform of the kind that might be applied to the terminals of a telephone line. This waveform possesses a frequency spectrum which can be expressed through the Fourier Transform. Let S(ω) be the Fourier transform of the voltage waveform v(t) which can be written mathematically as :

$$s(\omega)=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} v(t).e^{-i\omega t}.dt \qquad (10)$$

The quantity S(ω) is a complex function of the angular frequency variable which itself assumes only real values. Thus, for any given waveform v(t), a Fourier Transform S(ω) can be calculated which is unique for that waveform. Next a question quickly comes to the mind -- can the original function v(t) be recovered?, The answer is definitely affirmative.

In Hartley's definition of the transform Ψ (ω), the factors $1/\sqrt{2\pi}$ were explicitly included in order to achieve a symmetrical appearance. Thus,

$$\psi(\omega)=\frac{1}{(\sqrt{2\pi})}\int_{-\infty}^{\infty} v(t).\text{Cas}\,\omega t.dt \qquad (11)$$

$$v(t)=\frac{1}{(\sqrt{2\pi})}\int_{-\infty}^{\infty} \psi(\omega).\text{Cas}\,\omega t.d\omega \qquad (12)$$

In these relations the Cas function is, as mentioned in the original paper, simply the sum of Cos and Sin functions, as given by

$$\text{Cas}\omega t = \text{Cos}\omega t + \text{Sin}\omega t$$

$$= \sqrt{2}\ \text{Sin}(\omega t + \frac{\pi}{4})$$

Continuous Hartley Transform

Although there is not much apparent difference between the familiar Fourier Transform integral and the new pair of integrals given by Equations (11) and (12), in practice the difference is profound. The main thing to note in this case is that the transform $\psi(t)$ is real, not complex as is the case with $S(\omega)$. In Hartley's definition of the transform $\psi(\omega)$, the factors $1/\sqrt{2\pi}$ were explicitly included in order to achieve a symmetrical appearance. The factor $\frac{1}{2\pi}$ exists because the integration variable is ω . Since $\omega = 2\pi f$, it is a general practice is to place 2π symmetrically in the exponential part of both integrals. This happens automatically when frequency f is taken as a variable in place of angular frequency ω. This leads to the following two transform equations:

$$H(f) = \int_{-\infty}^{\infty} v(t).\text{Cas}2\pi ft.dt \tag{13}$$

$$v(t) = \int_{-\infty}^{\infty} H(f).\text{Cas}2\pi ft.df \tag{14}$$

The function H(f) is called the Hartley Transform of v(t) in honor of Hartley, and v(t) would be the inverse Hartley Transform of H(f).

For comparison, the Fourier Transform relations written according to the same convention are given below:

$$F(f)= \int_{-\infty}^{\infty} v(t).e^{-i2\pi ft}.dt \tag{15}$$

$$v(t)= \int_{-\infty}^{\infty} F(f).e^{i2\pi ft}.df \tag{16}$$

Even and Odd Part. The relationship between Fourier and Hartley Transforms rests upon symmetry condition. H(f) can be split into two parts, namely even part and odd part.

The even part of a function is what we get when the function is reversed (changing t to -t), and then added to the original function and subsequently dividing the sum by two. Naturally, the even part is its own mirror image, having symmetry property E(-f)=E(f). The odd part is formed by subtracting the reversed function from the original and dividing by two; it has the antisymmetrical property, O(-f)=-O(f). Any function can be split uniquely into even and odd parts, and if they are known, the original function can be reconstructed.

Mathematically H(f)=E(f)+O(f) , Where E(f) and O(f) are the even and Odd parts of H(f) respectively,

then
$$E(f)= \frac{H(f)+H(-f)}{2} = \int_{-\infty}^{\infty} v(t).Cos2\pi ft.dt \tag{17}$$

$$O(f)= \frac{H(f)-H(-f)}{2} = \int_{-\infty}^{\infty} v(t).Sin2\pi ft.dt \tag{18}$$

Connecting relation between Fourier and HartleyTransforms.

Given H(f), it is possible to calculate the sum [E(f)- i O(f)] to obtain the Fourier Transform F(f) :

$$E(f)-iO(f)= \int_{-\infty}^{\infty} v(t)[Cos2\pi ft-iSin2\pi ft]dt = \int_{-\infty}^{\infty} v(t).e^{-i2\pi ft}.dt \qquad (19)$$

$$E(f)+iO(f)= \int_{-\infty}^{\infty} v(t)[Cos2\pi ft+iSin2\pi ft]dt= \int_{-\infty}^{\infty} v(t).e^{i2\pi ft}.dt \qquad (20)$$

Thus it is seen that from H(f) the Fourier transform of v(t) can be calculated by simple addition and subtraction. The Fourier Transform F(f) has a real part which is the same as E(f) and an imaginary part whose negative is O(f) . Mathematically it follows as:

$$F_{real}(f)=ReF(f)=E(f) \qquad (21)$$

$$F_{imag}(f)=ImF(f)=-O(f) \qquad (22)$$

Conversely, given the Fourier transform F(f), H(f) can be calculated by the expression given below as:

$$H(f)=F_{real}(f)- iF_{imag}(f) \qquad (23)$$

From F(f), H(f) can be calculated as the sum of real and sign inverse imaginary part of the Fourier transform. Applying the theory that imaginary part of a complex number is real, it can be verified that F(f) is real as it should be, given that the original waveform v(t) was

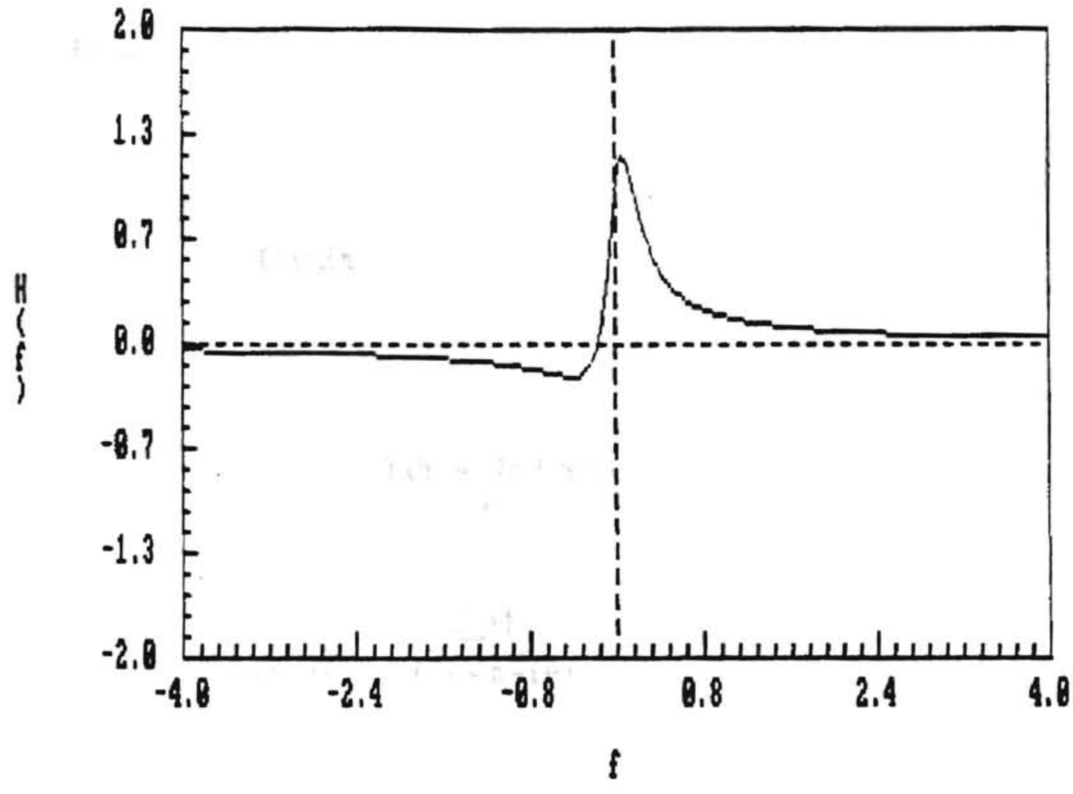


Figure15. Plot of continuous Hartley transform function H(f) [2]

real. Briefly it can be concluded that the Hartley transform is the real-part of the Fourier transform minus the imaginary part of the transform.

A particular example of the continuous Hartley transform is calculated below. Let $f(t)= e^{-t}$, $t>0$

$$H(f)= \int_{-\infty}^{\infty} e^{-t}.Cas2\pi ft.dt$$

$$= \int_{0}^{\infty} e^{-t}.Cas2\pi ft.dt$$

$$= \int_{0}^{\infty} e^{-t}.Cos2\pi ft.dt + \int_{0}^{\infty} e^{-t}.Sin2\pi ft.dt$$

$$H(f) = \frac{1}{(1+4\pi^2f^2)} + \frac{2pf}{(1+4\pi^2f^2)}$$

By inspection it is clear that the even and odd parts are

$$E(f)= \frac{1}{(1+4\pi^2f^2)}$$

and

$$O(f)=\frac{2\pi f}{(1+4\pi^2f^2)}$$

In Fig.15 the plot of the function is shown.

Discrete Hartley Transform

Although it is assumed that time is a continuous variable it is important and necessary in practice to use a discrete variable to describe a time series. This situation arises in case of storage of data in a computer at regular intervals. For computational advantage a discrete variable τ is introduced ranging from 0 to (N-1).

The discrete Hartley Transform (DHT) of a real function $f(\tau)$ is , with its inverse, given by equations (24) and (25) respectively as follows:

$$H(\nu\ )=(\frac{1}{N})\sum_{\tau=0}^{N-1} f(t).Cas(2\pi\nu t/N) \qquad (24)$$

$$f(t)=\sum_{\tau=0}^{N-1} H(\nu).Cas(2\pi\nu t/N) \qquad (25)$$

As before the abbreviation $Cas\theta = Cos\theta + Sin\theta$ is used. To derive the Inverse Discrete Hartley Transform integral, the orthogonality relation

$$\sum_{\tau=0}^{N-1} Cas(2\pi\nu\tau/N).Cas(2\pi\nu\tau'/N)=\left\{\begin{matrix} N \text{ for } \tau=0 \\ 0 \text{ for } \tau\neq\tau' \end{matrix}\right\} \qquad (26)$$

Substituting, $(\frac{1}{N})\sum_{\tau'=0}^{N-1} f(\tau').Cas(2p\nu\tau'/N)$

for $H(\nu)$ in the expression $\sum_{\nu=0}^{N-1} H(\nu).Cas(2p\nu t/N)$, we have

$$\sum_{\nu=0}^{N-1} H(\nu)Cas(2\pi\nu\tau/N)$$

$$= \sum_{\nu=0}^{N-1} (\frac{1}{N}) \sum_{\tau'=0}^{N-1} f(\tau').Cas(2\pi\nu\tau'/N).Cas(2\pi\nu\tau/N)$$

$$= (\frac{1}{N}) \sum_{\tau'=0}^{N-1} f(\tau') \sum_{\nu=0}^{N-1} Cas(2\pi\nu\tau'/N).Cas(2\pi\nu\tau/N)$$

$$=(\frac{1}{N}) \sum_{\tau'=0}^{N-1} f(\tau') \times \left\{ \begin{matrix} N \text{ for } \tau=\tau' \\ 0 \text{ for } t\neq t' \end{matrix} \right\}$$

$$=f(\tau) \tag{27}$$

which verifies the inversion integral.

Meaning of τ and ν. As τ corresponds to time in the similar way discrete variable ν represents the frequency. If the unit of t is seconds, that is if the time interval between successive elements of time series $f(\tau)$ is one second, the frequency increment is $\frac{\nu}{N}$ Hertz. Then the frequency interval between successive elements of the sequence $H(\nu)$ is N^{-1} Hz. As ν increases the corresponding frequency increases, but only up to $\nu=\frac{N}{2}$, beyond that the frequency assumes the expression $(N-\nu)/N$. So the frequency becomes zero at ν.

Even and Odd Parts. As in the continuous case, the Discrete Hartley transform (DHT) possesses even and odd parts.

$$H(\nu) = E(\nu) + O(\nu) \tag{28}$$

But a careful attention is required in this regard because of the convention that ν should cover the range of values form 0 to N-1. The general procedure to handle this type of situation is to assign function values outside the basic range so as to generate a cyclic function with period N. So that at $\nu = -1$ a value can be assigned to H(N-1) due to the fact that $\nu = -1$ and $\nu = N-1$ are separated by one period of length N. In general the value $H(N-\nu)$ is assigned in place of $H(-\nu)$ where $-N \leq \nu \leq -1$ for which the independent variable is in the basic range of ν. By this way a simple relationship can be achieved between ν and frequency. And now it can be interpreted that $\frac{\nu}{N}$ is the same as frequency in Hz, over the range $-\frac{N}{2} < \nu < \frac{N}{2}$. Thus

$$E(\nu) = \frac{H(\nu)+H(N-\nu)}{2} \tag{29}$$

$$O(\nu) = \frac{H(\nu)-H(N-\nu)}{2} \tag{30}$$

From the definition of the Discrete Fourier transform (DFT), $F(\nu)_f$ it is apparent that it can be formed from the even and odd part of discrete Hartley transform (DHT) by as follows:

$$F(\nu)_f = E(\nu) - iO(\nu) \tag{31}$$

Conversely, $H(\nu)$ can be constructed using the discrete Fourier transform $F(\nu)_f$ as follows:

$$H(\nu) = \mathrm{Re}F(\nu)_f - \mathrm{Im}F(\nu)_f \tag{32}$$

The standard form of the Discrete Fourier transform and its Inverse are given by the equations (33) and (34) respectively.

$$F(\nu)_f = \left(\frac{1}{N}\right) \sum_{\tau=0}^{N-1} f(\tau).e^{-i2\pi\nu\tau/N} \tag{33}$$

$$f(\tau) = \sum_{\nu=0}^{N-1} F(\nu)._f e^{i2\pi\nu\tau/N} \tag{34}$$

These relations are strictly analogous to those obtained previously for the continuous variable case. In the following an example is analyzed to consider the characteristics of the Hartley Transform. Let a function $F(\tau)$ be defined as:

$$F(\tau)=\{\begin{matrix}(0.5,\ \tau=o)\\(e^{-\tau/2},\ \tau=1,2,\dots 15)\end{matrix}$$

It represents the continuous function $e^{-\tau}$ that was used before, except that it is sampled. The value at $\tau=0$, since it falls on the discontinuity of V(t), is assigned the value $[V(0+)+V(0-)]/2=0.5$. The results for $H(\nu)$, which are shown in Fig.16, closely resemble samples of a continuous function taken at intervals $\Delta\omega/2\pi=1/16$. The discrepancies, which are small in this example, are due partly to the truncation of the exponential waveform and partly due to aliasing, exactly as with the DFT. Aliasing is caused due to the overlapping of higher frequency portion of a spectrum with the lower frequency part. The values given by this function due to DHT are arranged in the Table VII.

<u>Convolution property in Discrete Hartley Case.</u> In general, the transform of the convolution $f_1(t)\otimes f_2(t)$ contains four terms. The fundamental quantities to be computed are the direct products $P_a(\nu)=H_1(\nu)H_2(\nu)$ and the retrograde products $P_b(\nu)=H_1(\nu)H_2(-\nu)$ in these terms

$$H(\nu)=\frac{1}{2}[P_a(\nu)-P_a(-\nu)+P_b(\nu)+P_b(-\nu)] \qquad (35)$$

Thus only two multiplications instead of four are involved. Now if $H_2(\nu)$ is even then

$$H(\nu)=H_1(\nu)H_2(\nu) \qquad (36)$$

TABLE VII

VALUES OF DISCRETE HARTLEY TRANSFORM [2]

τ, ν	=0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15
f(τ)	=20, 15, 6, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 6, 15
H(ν)	=4, 3.56, 2.49, 1.32, 0.5, 0.12, 0.01, 0, 0, 0.01, 0.12, 0.5, 1.32, 2.49, 3.56

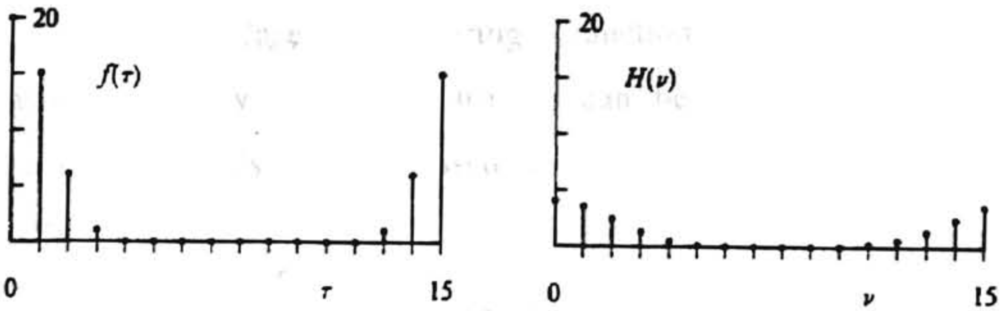


Figure16. A 16-point representation of the the truncated exponential waveform (left) used for illustrating the continuous transform and its DHT (right) [2]

And a similarly simple form results if $H_2(\nu)$ is odd; in this case

$$H(\nu)=H_1(-\nu)H_2(\nu) \tag{37}$$

Because of commutativity, $H(\nu)=H_1(\nu)H_2(\nu)$ is even if either $H_1(\nu)$ or $H_2(\nu)$ is even. Because of it 's importance, the application of this property would be shown in the next chapter in the analysis of power quality in electric networks. These interesting properties of the Hartley transform can be applied in branches of electrical engineering other than communication and signal processing.

Two Dimensional Hartley Transform

Continuous Case. Considering a function f(x, y), it 's two dimensional Hartley transform H(u, v) can be defined and the inverse of it can also be expressed as in the following Equations (38) and (39). Thus,

$$H(u, v)= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y).Cas[2\pi(ux+vy)]dxdy \tag{38}$$

$$f(x, y)== \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} H(u, v).Cas[2\pi(ux+vy)]dudv \tag{39}$$

In terms of Fourier transforms, F(u, v)=R(u, v)+i I(u, v) it follows that

$$H(u, v)=R(u, v)-I(u, v) \tag{40}$$

as may be verified from the Fourier Transforms and the Inverse Fourier Transform takes over the two variables as given by equations (40) and (41).

$$F(u, v)= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y).e^{-2\pi i(ux+vy)}.dxdy \tag{41}$$

$$f(x, y)= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F(u, v).e^{2\pi i(ux+vy)}.dudv \quad (42)$$

Two dimensional Hartley transforms have some advantages in image processing and in measurements. It is well known that the one dimensional Hartley Transform is real, and it is so in two dimensions also. Because the Fourier Transform is complex, half the transform plane is sufficient to determine the Fourier transform. The rest of the plane is occupied by the conjugate values that bear no additional information because points that are diametrically opposite are labelled with conjugate coefficients. In the Hartley plane on the other hand there is no such symmetry and redundancy. The information is spread half as thick over the whole area.

Symmetry and antisymmetry. A given function f(x, y) maybe decomposed into symmetrical and antisymmetrical parts such that

$$f(x, y)=f_{symm}(x, y) + f_{antisymm}(x, y) \quad (43)$$

where

$$f_{symm}(x, y)=\frac{1}{2}[f(x, y) + f(-x, -y)] \quad (44)$$

and

$$f_{antisymm}(x, y)=\frac{1}{2}[f(x, y)-f(-x, -y)] \quad (45)$$

This resolution into parts is the two dimensional generalization of splitting functions of one variable into even and odd parts. Just as the real part of the Fourier transform is even and the imaginary part is odd, the real part of the two dimensional Fourier transform is symmetrical and the imaginary part is antisymmetrical. It follows that the real two dimensional Hartley transform expressed as [R(u, v)- I(u, v)] is already presented in terms of its symmetrical and antisymmetrical parts. To establish the inverse transform as mentioned above taking the two dimensional Hartley transform of the transform H(u,v) it follows as:

$$f'(x, y) = \text{HT of } H(u, v) = \text{HT of } R(u, v) - \text{HT of } I(u, v) \tag{46}$$

$$\text{Now HT of } R(u, v) = f_{symm}(x, y) \tag{47}$$

because R(u, v) is symmetrical. Similarly

$$\text{HT of } I(u, v) = -f_{antisymm}(x, y) \tag{48}$$

$$\text{so } f'(x, y) = f_{symm}(x, y) - [-f_{antisymm}(x, y)] = f(x, y) \tag{49}$$

<u>Two dimensional Discrete Hartley Transform.</u> Manipulation of two dimensional digital images is also enhanced than loose to the existence of a real transform. An image $f(\tau_1, \tau_2)$ represented by an $N_1 \times N_2$ matrix possesses a two dimensional Hartley transform which is itself an $N_1 \times N_2$ matrix $H(\nu_1, \nu_2)$ of real numbers. The two dimensional Hartley transform and its inverse are expressed by the following Eq.50 and Eq.51 as:

$$H(n_1, n_2) = \frac{1}{N_1 N_2} \sum_{t_1=0}^{N_1-1} \sum_{t_2=0}^{N_2-1} f(t_1, t_2) \text{Cas}(2pn_1t_1/N_1 + 2pn_2t_2/N_2) \tag{50}$$

$$f(t_1, t_2) = \sum_{n_1=0}^{N_1-1} \sum_{n_2=0}^{N_2-1} H(n_1, n_2) \text{Cas}(2pn_1t_1/N_1 + 2pn_2t_2/N_2) \tag{51}$$

A two dimensional spatial frequency (ν_1, ν_2) describes an obliquely oriented Cas function which has $\frac{\nu_1}{N_1}$ cycles per unit of τ_1, in for example the east-west direction, and $\frac{\nu_2}{N_2}$ cycles per unit of τ_2 in the north-south direction.

General Discussion

Hartley Transforms plays a very important role in signal processing and communication engineering as well as in nonlinear optics in Physics. Images on surfaces have always been of importance and are becoming more obvious as technical means for creating, modifying and presenting such images are developed. Digital Telemetry of planetary images from spacecraft , and digital processing of these images have become familiar as a result of space exploration and the design of analogue optical imaging systems have made remarkable advances.

Analogue optical image processing is a reality and optical digital processing of two dimensional digital data is in view. In all these fields spectral analysis is a customary tool; Consequently there are corresponding applications of the Hartley Transform in electric power systems.

CHAPTER IV

APPLICATION OF HARTLEY TRANSFORM FOR POWER QUALITY ANALYSES

Introduction

Techniques for electric power quality analyses and assessment have taken on a renewed importance in recent years. This is due to two main factors as given below:

(1) The appearance of high power switching devices and switched loads which can cause power quality problems at the distribution level.

(2) The need for maintaining power quality at all power levels to avoid interference, excessive losses, and misoperation of loads. There are numerous fundamental issues to be resolved relating to quantifying power quality problems, instrumentation and monitoring. The methodology used for the calculation of bus voltage and the line current waveforms is also of salient importance. Electric power quality assessment often involves the calculation of a bus voltage or line current. Hartley transform is applicable and useful for this purpose due to the following criteria:

(i) Limited bandwidth of most electric distribution system makes truncation of Hartley transform practical at a reasonably low frequency (e.g, $v = \pm 9425$ rad/sec in a 60 Hz system or ± 7854 rad/sec in a 50 Hz system corresponding to the 25th harmonic).

(ii) Since only real calculations are needed, use of microprocessors using elementary codes is possible.

(iii) Symmetries of the impedance function $Z(\omega)$ or $Z(\Omega)$ of electrical systems enable further reduction of the computational burden. The calculation of several bus voltages can be done using Hartley Transforms. Before proceeding to examine the use of DHT in electric power system problems, it is helpful to discuss the use of DFT (Discrete Fourier Transform) in the solution of electric power system problems. This problem is represented by the time domain equation

$$v(t)=z(t).i(t) \quad (51)$$

In effect, given i(t) and the impulse or the impedance function z(t) we want to calculate v(t). This is accomplished by evaluating the DFT of i(t) with k as an integer by sampling the current as given by

$$I(k\omega) \Leftrightarrow i(t) \quad (52)$$

Next the DFT of z(t) is calculated as:

$$Z(k\omega) \Leftrightarrow z(t) \quad (53)$$

Subsequently these two transform quantities are multiplied and then the inverse Fast Fourier Transform is taken. The DFT of z(t) deserves special attention since it is not available generally. Instead, samples of the band limited $Z(\omega)$ or $Z(\Omega)$ are used. These are found by the following translational techniques :

$$Z'(k\Omega) = \begin{cases} Z(k\Omega) \text{ for } k<N/2 \\ Z((k-N)\Omega). \text{for } k>N/2 \end{cases} \quad (54)$$

On the right hand side of Eq.54 Z refers to sampled values of $Z(\Omega)$. On the left hand side, Z' refers to the DFT which is used. At k=N/2 in Eq.54 it is to be remembered that a real value is required in order to comply with the properties of the DFT. A convenient selection is made on the basis that there happens to be negligible signal energy at $\Omega_{max}=\pi/T_S$. Thus,

$$Z'(N/2)=0 \tag{55}$$

Then this discrete Fourier sampled function $Z'(k\Omega)$ can be transformed back to the Hartley domain by the following transform formula as :

$$Z(k\nu)= [Re\{Z(k\Omega)\} - Im\{Z(k\Omega)\}] \tag{56}$$

A salient property of the Hartley Transform for the application of power engineering problem which would be discussed next is that the convolution in time domain equation

$$V(t)= Z \otimes i(t) \tag{57}$$

becomes a sum of products in the following Hartley transformed frequency domain equation as:

$$V(\nu)=\frac{1}{2} [Z(\nu)I(\nu) + Z(-\nu)I(\nu) + Z(\nu)I(-\nu) - Z(-\nu)I(-\nu)] \quad (58\text{-}1)$$

Thus it is possible to solve a certain class of electric circuit problems using Hartley transforms by converting the convolution operation to simple real products, just as Ohm's law provides the solution in the frequency domain.

A zero padding technique can be used in this type of situation. A simple explanation is given to illustrate the point. Suppose M samples of a continuous signal is given and it is required to find an approximation of the Fourier Transform (same is true for the

Hartley Transform) at N frequency points, where N > M. It is assumed that the parameters M and T satisfy the constrains in Eq.(58-2) and Eq.(58-3)

$$T \leq \frac{1}{2f_h} \tag{58-2}$$

$$N \leq \frac{2f_h}{\Delta f} \tag{58-3}$$

(where f_h is the highest frequency content in the signal in hertz, Δf is the spacing between the frequency samples, and T is the sampling time), so that the N point DFT (or DHT) is still meaningful. But we have got fewer samples than required by DFT. In this case N-M zeroes are appended to the end of the sample sequence to get an N-point sequence. Then the N-point DFT (true for DHT as well) of the new sequence will yield the desired N frequency samples of the signal. To show that this result is correct , forming the N-point DFT of the spectrum sequence x_k [12] as,

$$F(f)_f = \sum_{k=0}^{N-1} x_k e^{-i2pnk/N}$$

$$= \sum_{k=0}^{M-1} x_k e^{-i2pnk/N} + \sum_{k=M}^{N-1} x_k e^{-i2pnk/N}$$

$$= \sum_{k=0}^{M-1} x_k e^{-i2pnk/N} \quad n=0,1,2,\ldots\ldots\ldots\ldots N-1 \tag{58-4}$$

And here $x_k=0$, for k=M, M+1.........N-1. The above criteria is true for Hartley Transform too. Thus this zero padding technique can be used to improve the frequency resolution of the discrete Hartley Transformed spectrum.

Analyses

It is assumed that due to the presence of a power electronic load such as a solid state rectifier at a certain bus l a nonsinusoidal current $I_l(\nu)$ is injected. Now it is desired to realize the voltage generated by this current at a connected bus k. Using the Hartley transform, the bus voltage $V_k(\nu)$ can be calculated. $I_l(\nu)$ and $V_k(\nu)$ are Hartley transformed current and voltage. To calculate the Bus voltage, the Hartley transformed impedance is needed and that is readily found [3] as

$$Z(\nu)=[Re\{Z(\omega)\} - Im\{Z(\omega)\}]_{\omega=\nu} \quad (59)$$

$Z(\omega)$ is easily found for the buses k and l from using

$$Z(\omega)=[U-j\omega Z_{SE}(\omega)]C_{SH}(\omega) \quad (60)$$

Where U is the identity matrix and C_{SH} is a constant matrix representing the capacitance of the SH network and

$$Z_{SH}(\omega)=\frac{1}{j\omega C_{SH}} \quad (61)$$

To use this approximation given by Eq.60 the network can be decomposed into series network labelled SE (consists of resistive and inductive element) and a shunt network labelled SH (consists of capacitative element) as shown in Fig.17. The SE network consists entirely of R-L circuits joining the system busses and the SH network is the shunt capacitive portion of the network. Together, the SE and SH networks comprise the entire system and the two subnetworks, SE and SH which are in parallel.

In the following, a brief account is discussed for the property of two parallel n-port networks. And further is given to the network

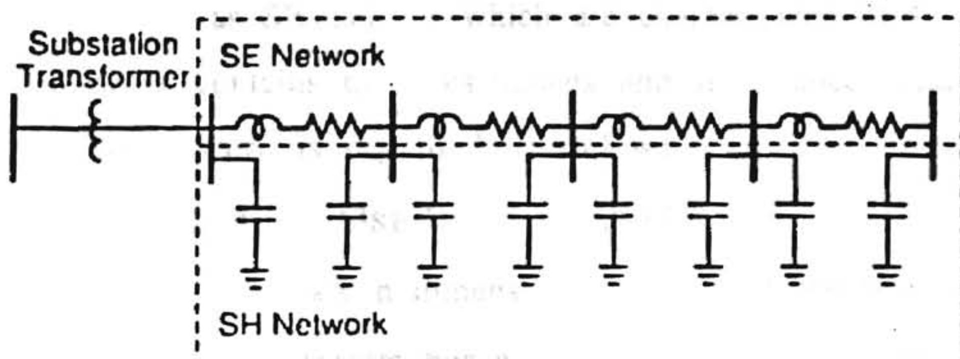


Figure17. Distribution network decomposed into SE and SH networks. [5]

consisting of n+1 buses with voltage measured at each bus from a given reference bus as $v_1(t)$, $v_2(t)$, ...$v_n(t)$. Also consider the injection currents at these buses with return path through the reference bus as $i_1(t)$, $i_2(t)$,... $i_n(t)$. Under most practical circumstances, these voltages and currents can be subjected to two sided Fourier transforms as shown by Eq.62 :

$$v_i(\omega) = \int_{-\infty}^{\infty} v_i(t).e^{-j\omega t}.dt \tag{62}$$

Again considering the electrical network to be decomposed into two networks labelled as SE and SH which are characterized as follows: the SE network contains only resistances and inductances and therefore this network is modelled as follows:

$$v_{SE}(t)=R_{SE}i_{SE}(t) + L_{SE}\frac{d}{dt}i_{SE}(t) \tag{63}$$

where $v_{SE}(t)$ and $i_{SE}(t)$ are n dimensional vectors of the bus voltages and currents using one system bus as reference. Similarly, let the SH network contain only capacitances. The SH network is modelled as given by Eq.64 as follows:

$$i_{SH}(t)=G_{SH}.v_{SH}(t)+ C_{SH}\frac{d}{dt}v_{SH}(t) \tag{64}$$

The terms R_{SE}, L_{SE}, G_{SH}, C_{SH} are n by n matrices. Taking Fourier transforms on Eq.63 and Eq.64, we obtain

$$v_{SE}(\omega) = R_{SE}\, i_{SE}(\omega) + j\omega L_{SE}i_{SE}(\omega) \tag{65}$$

$$i_{SH}(\omega) = G_{SH}v_{SH}(\omega) +j\omega\, C_{SH}v_{SH}(\omega) \tag{66}$$

By further manipulation, the Fourier transforms of (65) and (66) are obtained as

$$Z_{SE}(\omega)=\frac{v_{SE}(\omega)}{I_{SE}(\omega)}=R_{SE}+j\omega L_{SE} \tag{67}$$

and
$$Z_{SH}(\omega)=\frac{v_{SH}(\omega)}{I_{SH}(\omega)}=\frac{1}{(G_{SH}+j\omega C_{SH})} \tag{68}$$

In most cases G_{SH} is nearly equal to zero. therefore for most practical cases we have

$$Z_{SH}(\omega)=\frac{1}{j\omega C_{SH}} \tag{69}$$

Fig.18 shows several parallel n port circuits. Labelling the circuits as 1, 2, 3,...., the n-dimensional vectors $v^k(t)$, $I^k(t)$ denote the time function voltages and currents with a common reference bus for circuit k for k=1,2,3....... In this context the term parallel means

$$V^1(t)=V^2(t)=V^3(t)=\dots\dots\dots \tag{70}$$

and the total supply current I(t) in Fig.18 is the sum of all currents,

$$I(t)=\sum_{k=1}^{n} I^k(t) \tag{71}$$

I(t) is an n dimensional vector. It is assumed that both the bus impedance and admittance matrices [1] are known for each n-port. Then the Fourier transform of Ohm's law applied to the i^{th} circuit at each circuit is of the form

$$I^i(\omega)=Y^i(\omega)\,V^i(\omega) \tag{72}$$

where $Y^i(\omega)$ is the admittance matrix of the ith n-port and the two sided Fourier transform is used. Substitution of $I^i(\omega)$ in Eq.71 gives

$$I(\omega)=\sum_{k=1}^{n} Y^k(\omega)V^k(\omega) \tag{73}$$

All circuits are parallel and $V(\omega)$ is used to denote the transform of the voltage vector at any point of these circuits. Thus

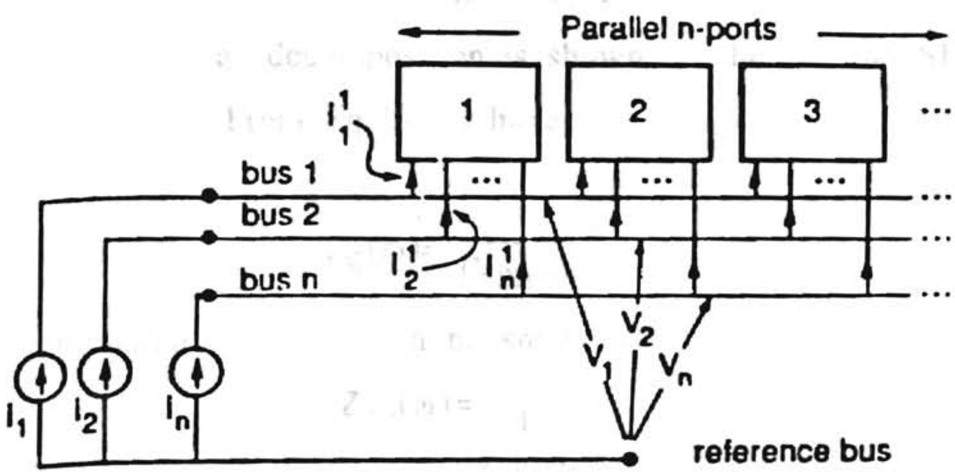


Figure18. Parallel n-port circuits [5]

$$\frac{1}{Z_{eq}(\omega)} = \frac{I(\omega)}{V^{k}(\omega)} = [\sum_{k=1}^{n} Y^{k}(\omega)] \quad (74)$$

and it is convenient to define as:

$$Z_{eq}(\omega) = \sum_{k=1}^{n} [Y^{k}(\omega)]^{-1} \quad (75)$$

It is considered now the case of two n-ports labelled SE and SH. The SE circuit is characterized by the resistive and inductive branches of an electric power network, and SH circuit is characterized by the shunt capacitive branches (either charging capacitances or shunt capacitors). In Fig.19 the diagram of a typical example of such a decomposition is shown. The SE and SH networks are in parallel. From Eq.75 we have

$$Z_{eq}(\omega) = \frac{1}{[Y_{SE}(\omega) + Y_{SH}(\omega)]} \quad (76)$$

By manipulating Eq.75, it can be shown as:

$$Z_{eq}(\omega) = \frac{1}{\frac{1}{Z_{SE}(\omega)} + \frac{1}{Z_{SH}(\omega)}}$$

$$= \frac{Z_{SE}(\omega) Z_{SH}(\omega)}{Z_{SE}(\omega) + Z_{SH}(\omega)} \quad (77)$$

By substituting (60) into (59) it is found that

$$Z(\nu) = [Re\{Z_{SE}(\omega)\} - Re\{j\omega Z_{SE} C_{SH} Z_{SE}(\omega)\} - Im\{Z_{SE}(\omega) + Im\{j\omega\, Z_{SE}(\omega)\, C_{SH} Z_{SE}(\omega)\}]_{\omega=\nu} \quad (78)$$

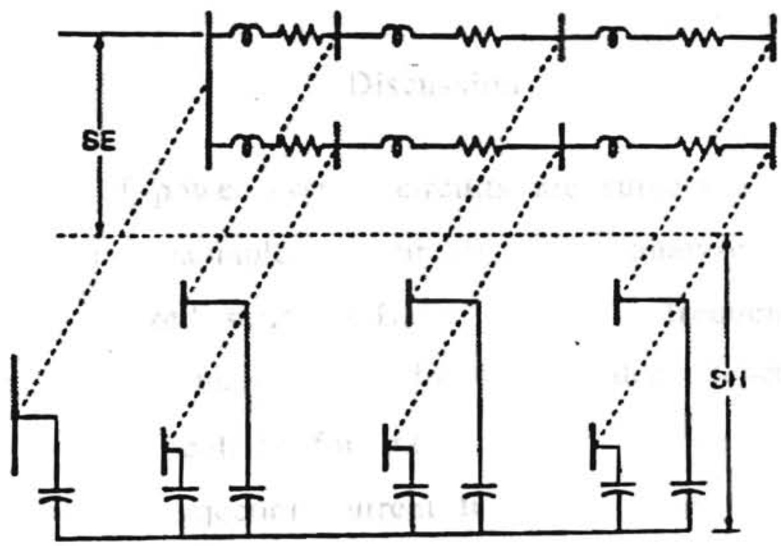


Figure19. Decomposition of a power network into SH and SE network [5]

Further manipulation [10] leads to the expression given by the Eq.78 as

$$Z(\nu)= R_{SE} + [- X_{SE}(\omega) +\omega(Re\{Z_{SE}(\omega)C_{SH}Z_{SE}(\omega)\} + Im\{Z_{SE}(\omega)C_{SH}Z_{SE}(\omega)\}]_{\omega=\nu} \quad (79)$$

The element $Z(\omega)$ is the Fourier transform of $z(t)$ and the element $Z_{kl}(\nu)$ is used in Eq.58-1 to calculate $V_k(\nu)$ given $I_l(\nu)$. To sample $I_l(\nu)$ on the lth bus the Fast or Discrete Hartley Transform is used.

Discussion

Analysis of power system circuits are subject to several restrictions. For example, the circuits under analyses are all three phase balanced fixed series R-L branches and frequency independent ($R \neq R(\omega)$). The importance of frequency independence should not be underestimated particularly for the cases in which significant energy components of the injection current lie above 17th Harmonic of 60 Hz. Distributed parameter models are readily substituted by lumped parameter models for the convenience of analyses. The injected current at the particular bus is assumed to be in phase with the line to neutral voltage. And the nonlinearity was assumed to be in a source.

CHAPTER V

COMPUTER SOLUTION

Introduction

The application of Hartley transforms for analyzing non-sinusoidal situations in power systems is illustrated by means of a three-bus network. Electrical power quality assessment often involves calculation of bus voltage or line current . This work is based on several assumptions as listed below:

(1) Only one phase (such as phase A) is involved in calculation.

(2) The injected non sinusoidal current as shown in Fig.20 has a stepped wave form. Because of symmetry conditions, this waveform has only odd harmonics. The source of this load current is a six pulse rectifier which is commonly used in power systems.

(3) Importance is directed only on the non sinusoidal current drawn by the rectifier and the voltage generated by it on a particular bus of interest. The equivalent delta network as shown in Figure.21 for the convenience of analysis. The resistance R_{SE} and inductor $L_{SE}(\omega)$ together comprises the series impedance $Z_{SE}(\omega)=\frac{R_{SE}+j\omega L_{SE}(\omega)}{3}$ and the capacitor $C_{SH}(\omega)$ forms the shunt inductance $Z_{SH}(\omega)=\frac{1}{(j\omega C_{SH})}$.

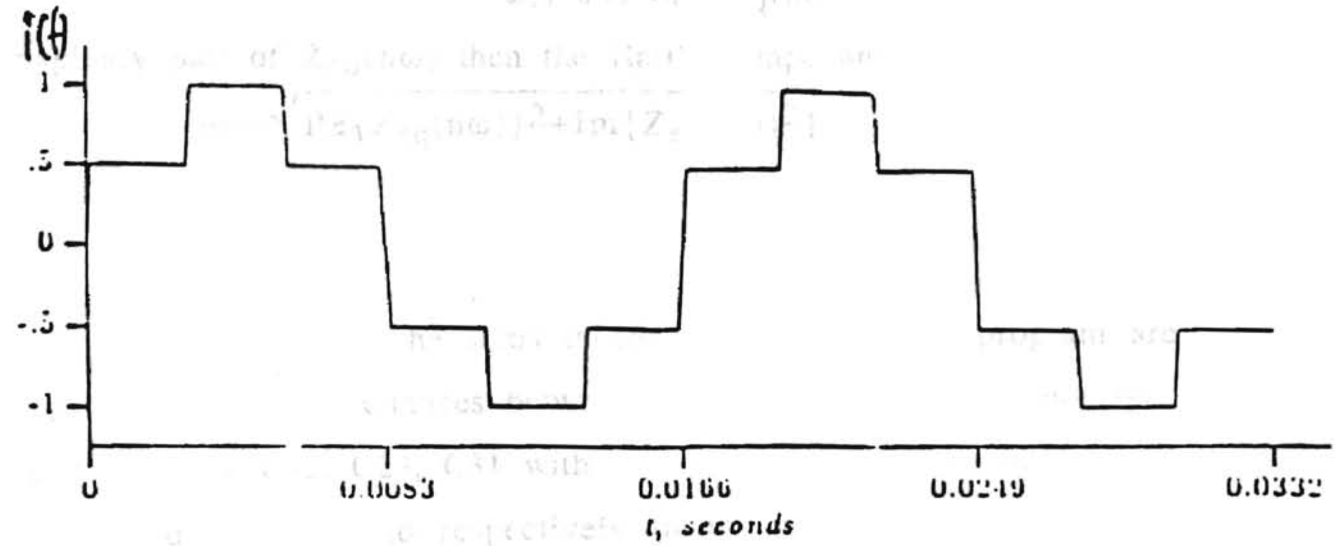


Figure20. Non sinusoidal rectifier injected current waveform [9]

The parallel combination of $Z_{SE}(\omega)$ and $Z_{SH}(\omega)$ is the equivalent impedance $Z_{eq}(\omega)$. Mathematically, $Z_{eq}(\omega)=\frac{Z_{SE}(\omega)Z_{SH}(\omega)}{(Z_{SE}(\omega)+Z_{SH}(\omega))}$, which can be written for n harmonics as,

$$Z_{eq}(n\omega)=\frac{Z_{SE}(n\omega)Z_{SH}(n\omega)}{(Z_{SE}(n\omega)+Z_{SH}(n\omega))} \tag{83}$$

n is also an index number which can assume values from 1 to 64 in the following analysis and ω being the angular frequency ($\omega = 2\pi f$ and $f=60$ Hz).

Furthermore if $Re\{Z_{eq}(n\omega)\}$ and $Im\{Z_{eq}(n\omega)\}$ are the real and imaginary part of $Z_{eq}(n\omega)$ then the Hartley impedance is given by

$$Z_{HT}(n\omega)=\sqrt{Re\{Z_{eq}(n\omega)\}^2+Im\{Z_{eq}(n\omega)^2\}} \tag{84}$$

Procedure

In the following, the steps taken to implement the program are discussed . The capacitances between bus 1-2, bus 2-3 and bus 3-1 are denoted by C12, C23, C31 with numerical values of 0.0026, 0.0026 and 0.0026 farad respectively in the computer program. Similarly the resistances (R) and inductances (X) for the lines connecting buses 1-2, 2-3 and 3-1 are 0.196 ohms and 0.00052 henry respectively. The network is a delta one and it is broken up into equivalent star one, as shown in Fig. 22 for convenience of analyses. The nonsinusoidal current waveform is made up of a Hartley series and a short description of its derivation is discussed in the following. As the six pulse waveform passes through the origin so it is an odd one in characteristics and the Hartley coefficient is evaluated in the following .

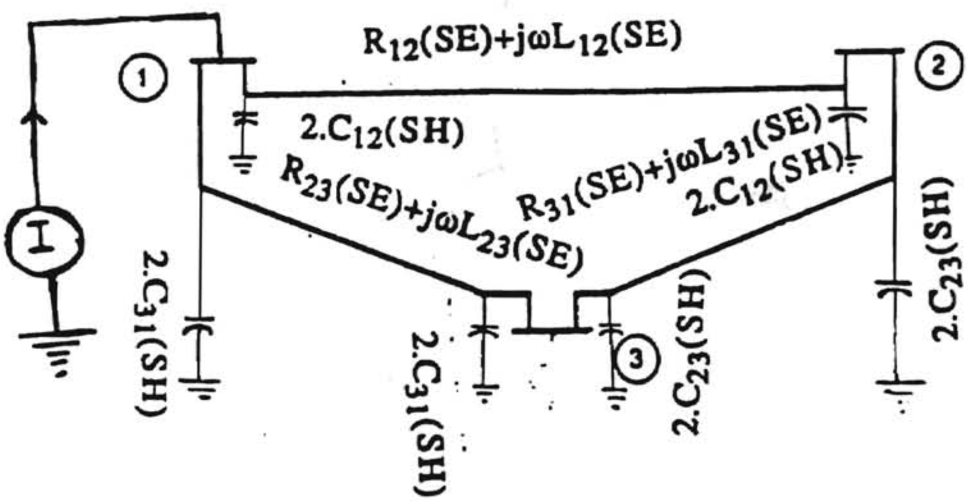
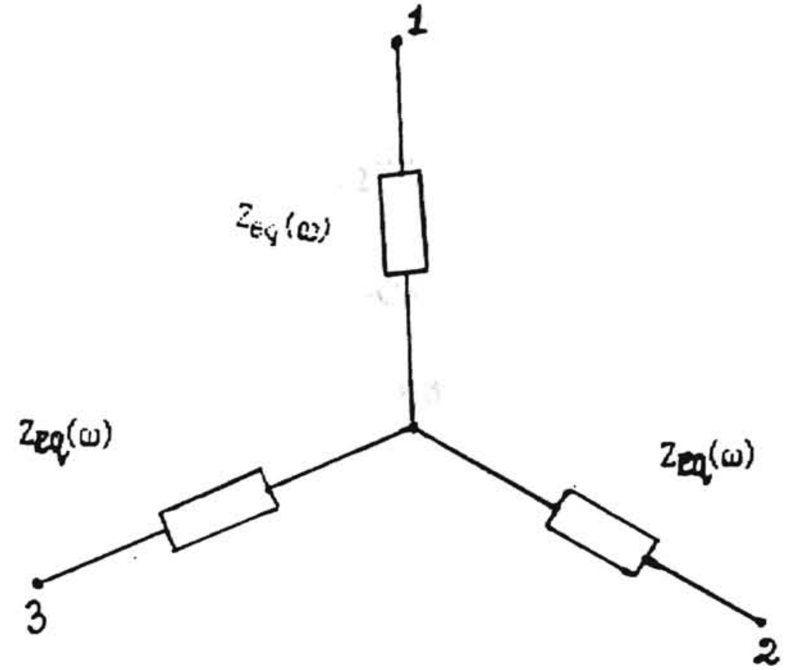


Figure21. Three bus power system



$$Z_{eq}(\omega)=\frac{Z_{SE}(\omega)Z_{SH}(\omega)}{(Z_{SE}(\omega)+Z_{SH}(\omega))},$$

Figure22. The equivalent Star network

Proceeding for evaluation of Hartley Coefficient B_n by integration we have,

$$B_n=\frac{2}{T}\int_0^T f(t).Casn\omega t.dt$$

$$=\frac{2}{T}\int_0^T f(t).(Cosn\omega t + Sinn\omega t).dt$$

$$=\frac{2}{T}\int_0^T f(t).(\sqrt{2}).(\frac{1}{\sqrt{2}}.Cosn\omega t + \frac{1}{\sqrt{2}}.Sinn\omega t).dt$$

$$B_n=\frac{2\sqrt{2}}{T}\int_0^T f(t).(Sin(\pi/4).Cosn\omega t + Cos(\pi/4).Sinn\omega t).dt$$

[By trigonometric identity ($Sin\delta\, Cos\beta+Sin\beta.Cos\delta)=Sin(\delta+\beta)$, here $\beta=\pi/4$ and $\delta=n\omega t$)]

$$B_n=\frac{2\sqrt{2}}{T}\int_0^T f(t).Sin(n\omega t+\pi/4).dt$$

$$=\frac{2\sqrt{2}}{T}[\int_0^{T/6} 0.5Sin(n\omega t+\pi/4).dt+$$

$$\int_{T/6}^{T/3} 1.Sin(n\omega t+\pi/4).dt+\int_{T/3}^{T/2} 0.5.Sin(n\omega t+\pi/4).dt+$$

$$\int_{T/2}^{2T/3}(0.5).Sin(n\omega t+\pi/4).dt+\int_{2T/3}^{5T/6}(1).Sin(n\omega t+\pi/4).dt+\int_{5T/6}^{T}(0.5).Sin(n\omega t+\pi/4).dt$$

]

$$=\frac{2\sqrt{2}}{T}[(-0.5/n\omega)\{Cos(n\omega t+\pi/4)\}_0^{T/6}+\frac{(-1)}{n\omega}\{Cos(n\omega t+\pi/4)\}_{T/6}^{T/3}+\frac{0.5}{(-n\omega)}$$

$$\{Cos(n\omega t+\pi/4)\}_{T/3}^{T/2}+\frac{(-0.5)}{n\omega}\{Cos(n\omega t+\pi/4)\}_{T/2}^{2T/3}+\frac{(-1)}{(-n\omega)}\{Cos(n\omega t+\pi/4)\}_{2T/3}^{5T/6}+$$

$$\frac{(-0.5)}{(-n\omega)}\{Cos(n\omega t+\pi/4)\}_{5T/6}^{T}]$$

$=\frac{2\sqrt{2}}{n\omega T}[-0.5\{Cos(n\omega T/6+\pi/4)-Cos(\pi/4)\}-1\{Cos(n\omega T/3+\pi/4)-$

$Cos(n\omega T/6+\pi/4)\}-0.5\{Cos(n\omega T/2+\pi/4)-$

$Cos(n\omega T/3+\pi/4)\}+0.5\{Cos(2n\omega T/3+\pi/4)-$

$Cos(n\omega T/2+\pi/4)\}+1\{Cos(5n\omega T/6+\pi/4)-Cos(2n\omega T/3+\pi/4)\}+$

$0.5\{Cos(n\omega T+\pi/4)-Cos(5n\omega T/6+\pi/4)\}]$

$=\frac{\sqrt{2}}{n\pi fT}[-0.5\{Cos(2n\pi fT/6+\pi/4)-Cos(\pi/4)\}-\{Cos(2n\pi fT/3+\pi/4)-$

$Cos(2n\pi fT/6+\pi/4)\}-0.5\{Cos(2n\pi fT/2+\pi/4)$

$Cos(2n\pi fT/3+\pi/4)\}+0.5\{Cos(4n\pi fT/3+\pi/4)-$

$Cos(2n\pi fT/2+\pi/4)\}+1\{Cos(10n\pi fT/6+\pi/4)-$

$Cos(4n\pi fT/3+\pi/4)\}+0.5\{Cos(2\pi nfT+\pi/4)-Cos(10n\pi fT/6+\pi/4)\}]$

$=\frac{\sqrt{2}}{n\pi fT}[0.5Cos(2n\pi fT/6+\pi/4)+0.5Cos(\pi/4)-0.5Cos(2n\pi fT/3+\pi/4)-$

$Cos(2n\pi fT/2+\pi/4)+0.5Cos(4n\pi fT/3+\pi/4)+0.5Cos(10n\pi fT/6+\pi/4)$

$+0.5Cos(2n\pi fT+\pi/4)]$

$=\frac{\sqrt{2}}{n\pi}[0.5Cos(n\pi/3+\pi/4)+0.5Cos(\pi/4)-0.5Cos(2n$

$\pi/3+\pi/4)-Cos(n\pi+\pi/4)+0.5Cos(4n\pi/3+\pi/4)+0.5Cos(5n\pi/3+\pi/4)+$

$0.5Cos(2n\pi+\pi/4)]$

$B_n=\frac{\sqrt{2}}{2n\pi}[Cos(n\pi/3+\pi/4)+Cos(\pi/4)-Cos(2n\pi/3+\pi/4)-2Cos(n\pi+\pi/4)-$

$Cos(4n\pi/3+\pi/4)+Cos(5n\pi/3+\pi/4)+Cos(2n\pi+\pi/4)]$ (85)

(Here T=0.0166sec & fT=1)

From B_n the positive current sequence I_n^+ (In this case, $I_n^+= B_n$) is obtained. In order to construct the Hartley current I_n, both positive sequence current I_n^+ and negative sequence current I_n^- are needed.

This aforementioned sequence I_n^+ can be obtained by substituting n=1, 2, 3, 4, 5.....63, 64 etc, on the right hand side of eq.85 ($I_1^+=0.955$, $I_2^+=0.000$, $I_3^+=0.000$, $I_4^+=0.000$, $I_5^+=0.191$....... $I_{63}^+=0.000$, $I_{64}^+=0.000$ etc) as shown in the results of computer program in the appendix . Due to typical odd symmetry of the current waveform(absence of cosine coefficients in the sequence in case of Fourier series expansion) the aforementioned positive current sequence I_n^+ is arranged in reverse order to obtain the negative sequence (such as for n=1,2, 3, 4.,5 ...63, 64; $I_1^-=0.000$, $I_2^-=0.000$, $I_3^-=0.016$, $I_4^-=0.000$, $I_5^-=0.016$,......

$I_{63}^-=0.955$, $I_{64}^-=0.000$, etc.) I_n^- . The subscript n indicates that these currents are function of n, which also represents the order of harmonics. These current sequences I_n^+ and I_n^- are denoted in the computer program as EA(.) and ERA(.) respectively. Moreover If we give the terminology I_n^{even} & I_n^{odd} to the even and odd part of the Hartley current, then $I_n^{even} = \frac{(I_n^+ + I_n^-)}{2}$ and $I_n^{odd} = \frac{(I_n^+ - I_n^-)}{2}$

respectively. These two sequences are used to construct the Hartley current I_n by eq.86 as :

$$I_n = \sqrt{\frac{(I_n^+ + I_n^-)^2}{4} + \frac{(I_n^+ - I_n^-)^2}{4}} \quad . \qquad (86)$$

Next the Hartley transformed impedances $Z_{HT}(n\omega)$ are calculated. In the computer program the Hartley coefficient and currents are represented by B(n) and H(n) respectively. The harmonic voltage response in frequency domain is V_n in volts at bus 2 due to the nonsinusoidal rectifier current and index number n as shown in a graph in appendix. The program and the results are given in appendix .

Thus, in phasor form

$$= \frac{(I_n^+ + I_n^-)}{2} - j.\frac{(I_n^+ - I_n^-)}{2} \quad (87)$$

$$= \sqrt{\frac{(I_n^+ + I_n^-)^2}{4} + \frac{(I_n^+ - I_n^-)^2}{4}} \angle \mathrm{Tan}^{-1}\frac{(I_n^- - I_n^+)}{(I_n^- + I_n^+)} \quad (88)$$

Where magnitude of Hartley current at nth harmonic is,

$$I_n = \sqrt{(I_n^{even})^2 + (I_n^{odd})^2} \quad (89)$$

and the phase angle

$$= \mathrm{Tan}^{-1}\frac{[-(I_n^{odd})]}{I_n^{even}} \quad (90)$$

Now by using Eq.91 the harmonic voltages are calculated as follows,

$$V_n = [\sqrt{(I_n^{even})^2 + (I_n^{odd})^2}] .[Z_{HT}(n\omega)]. \quad (91)$$

Here n=0, 1, 2, ...64 etc. In the computer simulation the combination is arranged such that positive sequence is EA(n) and the corresponding negative sequence is ERA(64-n). And in the computer program V_n, $Z_{HT}(n\omega)$, I_n^{even}, I_n^{odd} and are represented by V(n), ZHT(n), $\frac{EA(n)+ERA(64-n)}{2}$, $\frac{EA(n)-ERA(64-n)}{2}$ respectively. Now the quantities $V_{(1)}$, $V_{(5)}$, $V_{(7)}$, $V_{(11)}$, $V_{(13)}$, $V_{(17)}$, $V_{(19)}$ are regarded as fundamental, 5th, 7th, 11th, 13th,17th and 19th harmonic voltages respectively. Furthermore the harmonic voltages $V_{(2)}$, $V_{(3)}$, $V_{(4)}$, $V_{(6)}$, $V_{(8)}$, $V_{(9)}$, $V_{(10)}$, $V_{(12)}$, $V_{(14)}$, $V_{(15)}$, $V_{(16)}$, $V_{(18)}$ are found to be equal to zero. The Total Harmonic Distortion (T.H.D) at the 2nd bus due to the nonsinusoidal rectifier current is given by,

$$T.H.D=\frac{\sqrt{V_{(5)}^2+V_{(7)}^2+V_{(11)}^2+V_{(13)}^2+V_{(17)}^2+V_{(19)}^2}}{V_{(1)}} \tag{92}$$

In the computer program the 1st, 2nd, 3rd, 4th, 5th, 6th, 7th, 8th, 9th, 10th, 11th, 12th, 13th, 14th, 15th, 16th, 17th, 18th, 19th harmonic voltages are denoted by V(n) for n=1, ..19 respectively. It has been found that the harmonic voltages decrease rapidly and the numerical contribution of voltages after the nineteenth harmonic is insignificant in calculation of THD and so the analysis is terminated after 19th harmonic. The results of the computer program to calculate the total harmonic distortion (T.H.D) is given in appendix. The plot showing harmonic voltages versus the index number n is also presented in the appendix. The algorithm of the computer program is shown in Table VIII.

TABLE VIII

ALGORITHM SUMMARY

STEP	DESCRIPTION
1.	The network is transformed from delta to its equivalent star network. Now for n=1 to 64 the different values of Hartley impedances ZHT(n) are calculated. This has been done from line number1 to 22 in the computer program.
2.	Next the Hartley coefficient B(n) is calculated by Eq.85 and this has been shown in the program from line number 25 to 37. Subsequently the Hartley current is constructed by Eq.86 and it is shown from line number 38 to 98 in the computer simulation.
3.	Next the Hartley domain impedances ZHT(n) are multiplied by currents H(n) to get the Harmonic voltage V(n) by eq.91 for n=1,..19.; which is obvious from line number 100 to 103.
4.	Now using Eq.92 and the harmonic voltages the T.H.D is calculated as seen from line number104 to 109. It has been found that the contribution of harmonic voltages for calculation of Total Harmonic Distortion after 19th is too small to account for. So for calculation of THD only the voltages up to19th harmonic is included.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The main conclusion of this study is that the Hartley transform offers a computationally efficient procedure for the calculation of the time response of voltage or current waveform. The computational advantages of the HT (Hartley Transform) comparable to the FT (Fourier Transform) are listed below:

(1) The HT is purely real but FT is typically complex in nature (contains imaginary numbers).

(2)There is however a computational advantage of favoring HT over FT is that, HT can transform one real array of length of N data points in half the time that it takes the FFT to process a complex array of [10] same length of N data points.

(3) The Hartley methodology exhibits the same ease and convenience in calculating the inverse transform as in the Fourier approach. The Laplace transform does not offer convenience in calculation of numerical inversion techniques (such as conversion from frequency to time domain and vice-versa).

(4) The Hartley methodology exhibits the same accuracy in calculation as to that of Fourier methodology.

(5) The time required to compute the discrete voltage v(k) using FHT is proportional to N^2. Here N is the number of samples which is an integer (an integral power of 2) . If anyone computes the transforms of impedance z and current i, performs the complex multiplication and then computes the inverse transform of $v(\omega)$, it is found that time required for the computation is proportional to $N \log_2 N$ if FT is [6] implemented.

(6) It is imperative that there are some potential pitfalls (rather errors) in this method and they are identical to those encountered in calculation of FT such as time domain aliasing, time domain smoothing, Picket fence effect and Leakage. Research is in progress to limit the aforementioned errors to a minimum.

(7) The fast Hartley transform has been proposed for any electric circuit calculation involving convolution in time. The method is especially applicable in cases in which frequency band limitations occur. Such is the case in electric power systems in which power electronic loads cause non sinusoidal load currents and bus voltages to occur.

(8) Eventually there are some interesting areas which are suggested for future research :

(i) A full quantitative assessment and error analysis for real transform solutions of circuit problems.

(ii) A study of novel and fast methods to calculate Z(kν) to avoid the problems of band limitations.

(iii) A serious application in which real time solutions are required.

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APPENDIX

COMPUTER PROGRAM OF APPLICATION OF HARTLEY TRANSFORM FOR POWER QUALITY ANALYSES

```
C*********************************************************************
C ** THESIS PROGRAM                                                   *
C ** NAME OF PROGRAMMER: PARAN JYOTI MAHANTA.                         *
C ** TYPE OF COMPUTER LANGUAGE: VAX FORTRAN.                          *
C** EA(.) IS THE POSITIVE SEQUENCE OF HARTLEY CURRENT.                *
C** ERA(.) IS THE NEGATIVE SEQUENCE OF HARTLEY CURRENT.               *
C** ZHT(.) ARE THE HARTLEY TRANSFORMED IMPEDANCES.                    *
C** B(.) IS THE HARTLEY COEFFICIENT.                                  *
C** H(.) IS THE HARTLEY CURRENT.                                      *
C** V(.) ARE THE THE HARMONIC VOLTAGES.                               *
C** n IS AN INDEX NUMBER.                                             *
C** THD IS THE TOTAL HARMONIC DISTORTION.                             *
C*********************************************************************
      COMPLEX CMPLX,ZSE(64),ZSH(64),ZEQ(64)
      DOUBLE PRECISION R12,X12,C12
      DIMENSIONRR1(64),RR2(64),RR3(64),RR4(64),RR5(64),ERA(64)
      DIMENSION RR6(64),BA(64),EA(64),ZHT(64),ZR(64),ZI(64)
      DIMENSION V(64),H(64)
      PI=3.14159265
      W=2*PI*60
      R12=0.196
      X12=0.00052
      C12=0.0026
      WRITE(*,12)
12    FORMAT(2X,'n',7X,'ZR(n)',10X,'ZI(n)',8X,ZHT(n)')
      DO 22 n=1,64
      ZSE(n)=(1./3)*CMPLX(R12,n*W*X12)
```

```
15  ZSH(n)=(1./(n*C12**W))*(1./CMPLX(0.0,1.0))
16  ZEQ(n)=1./(1./(ZSE(n))+1./(ZSH(n)))
17 ZR(n)=REAL(ZEQ(n))
18  ZI(n)=AIMAG(Z(EQ(n))
19  ZHT(n)=SQRT(ZR(n)**2+ZI(n)**2)
20  WRITE(*,21)n,ZR(n),ZI(n),ZHT(n)
21  FORMAT(2X,I3,3X,F10.6,3X,F10.6,3X,F10.6)
22 CONTINUE
23  WRITE(*,24)
24 FORMAT(4X,'n',5X,'EA(n)')
25  DO 37 n=1,64
26   RR1(n)=COS((n*PI)/3+(PI/4))
27   RR2(n)=COS((n*PI*2)/3+(PI/4))
28  RR3(n)=COS((n*PI)+(PI/4))
29   RR4(n)=COS((n*5*PI)/3+(PI/4))
30   RR5(n)=COS((n*4*PI)/3+(PI/4))
31  RR6(n)=COS((n*2*PI)+(PI/4))
32   B(n)=(1.4142/(2*PI*n))*(COS(PI/4)+RR1(n)-RR2(n)-
33 12*RR3(n)+RR4(n)-RR5(n)+RR6(n))
34  EA(n)=B(n)
35  WRITE(*,36)n,EA(n)
36  FORMAT(2X,I3,3X,F5.3)
37 CONTINUE
38  EA(1)=0.955
39  ZHT(1)=0.065200
40  ERA(63)=0.955
41  EA(2)=0.000
```

```
ZHT(2)=0.064804
ERA(62)=0.000
EA(3)=0.000
ZHT(3)=0.064160
ERA(61)=0.000
EA(4)=0.000
ZHT(4)=0.063290
ERA(60)=0.000
EA(5)=0.191
ZHT(5)=0.062222
ERA(59)=0.191
EA(6)=0.000
ZHT(6)=0.060986
ERA(58)=0.000
EA(7)=0.136
ZHT(7)=0.059617
ERA(57)=0.136
EA(8)=0.000
ZHT(8)=0.058147
ERA(56)=0.000
EA(9)=0.000
ZHT(9)=0.056605
ERA(55)=0.000
EA(10)=0.000
ZHT(10)=0.055019
ERA(54)=0.000
EA(11)=0.087
```

```
ZHT(11)=0.053412
ERA(53)=0.087
EA(12)=0.000
ZHT(12)=0.051804
ERA(52)=0.000
EA(13)=0.073
ZHT(13)=0.050211
ERA(51)=0.073
EA(14)=0.000
ZHT(14)=0.048646
ERA(50)=0.000
EA(15)=0.000
ZHT(15)=0.047117
ERA(49)=0.000
EA(16)=0.000
ZHT(16)=0.045633
ERA(48)=0.000
EA(17)=0.056
ZHT(17)=0.044197
ERA(47)=0.056
EA(18)=0.000
ZHT(18)=0.042813
ERA(46)=0.000
EA(19)=0.050
ZHT(19)=0.041483
ERA(45)=0.050
WRITE(*,96)
```

```
96 FORMAT(5X,'n',5X,'V(n)')
 97  DO 103 n=1,19
  98   H(n)=SQRT((EA(n)+ERA(64-n))/2)**2+((EA(n)-
 99  1ERA(64-n))/2)**2)
100  V(n)=H(n)*ZHT(n)
101   WRITE(*,102)n,V(n)
102  FORMAT(3X,I3,4X,F8.6)
103  CONTINUE
104   WRITE(*,105)
105  FORMAT(4X,'THD')
106   THD=SQRT(V(5)**2+V(7)**2+V(11)**2+V(13)**2+
107  1V(17)**2+V(19)**2)/V(1)
 108 WRITE(*,109)THD
 109 FORMAT(4X,F8.5)
 110 STOP
     END
```

RESULTS OF THE COMPUTER PROGRAM

n	ZR(n)	ZI(n)	ZHT(n)
1	0.065067	-0.004167	0.065200
2	0.064279	-0.008233	0.064804
3	0.063008	-0.012105	0.064160
4	0.061310	-0.015705	0.063290
5	0.059258	-0.018974	0.062222
6	0.056929	-0.021874	0.060986
7	0.054402	-0.024387	0.059617
8	0.051751	-0.026512	0.058147
9	0.049043	-0.028265	0.056605
10	0.046333	-0.029671	0.055019
11	0.043666	-0.030759	0.053412
12	0.041076	-0.031566	0.051804
13	0.038589	-0.032125	0.050211
14	0.036220	-0.032473	0.048646
15	0.033980	-0.032640	0.047117
16	0.031873	-0.032657	0.045633
17	0.029899	-0.032549	0.044197
18	0.028056	-0.032340	0.042813
19	0.026340	-0.032048	0.041483
20	0.024744	-0.031691	0.040207
21	0.023263	-0.031284	0.038985
22	0.021888	-0.030837	0.037816
23	0.020614	-0.030362	0.036698

24	0.019432	-0.029866	0.035631
25	0.018336	-0.029356	0.034612
26	0.017320	-0.028837	0.033639
27	0.016376	-0.028315	0.032709
28	0.015500	-0.027792	0.031822
29	0.014685	-0.027272	0.030975
30	0.013928	-0.026758	0.030166
31	0.013223	-0.026250	0.029392
32	0.012566	-0.025750	0.028652
33	0.011953	-0.025260	0.027945
34	0.011381	-0.024780	0.027268
35	0.010846	-0.024310	0.026620
36	0.010346	-0.023852	0.025999
37	0.009878	-0.023405	0.025404
38	0.009439	-0.022969	0.024833
39	0.009027	-0.022545	0.024285
40	0.008640	-0.022132	0.023759
41	0.008277	-0.021731	0.023254
42	0.007935	-0.021341	0.022768
43	0.007612	-0.020962	0.022301
44	0.007309	-0.020593	0.021852
45	0.007022	-0.020235	0.021419
46	0.006751	-0.019887	0.021002
47	0.006495	-0.019549	0.020600
48	0.006253	-0.019220	0.020212
49	0.006024	-0.018901	0.019838
50	0.005806	-0.018591	0.019477

51	0.005600	-0.018290	0.019128
52	0.005404	-0.017997	0.018791
53	0.005219	-0.017712	0.018465
54	0.005042	-0.017435	0.018149
55	0.004874	-0.017166	0.017844
56	0.004714	-0.016904	0.017549
57	0.004561	-0.016649	0.017263
58	0.004416	-0.016401	0.016985
59	0.004277	-0.016160	0.016716
60	0.004145	-0.015925	0.016456
61	0.004018	-0.015696	0.016203
62	0.003897	-0.015474	0.015957
63	0.003782	-0.015257	0.015718
64	0.003671	-0.015045	0.015487

n	EA(n)
1	0.955
2	0.000
3	0.000
4	0.000
5	0.191
6	0.000
7	0.136
8	0.000
9	0.000
10	0.000

11	0.087
12	0.000
13	0.073
14	0.000
15	0.000
16	0.000
17	0.056
18	0.000
19	0.050
20	0.000
21	0.000
22	0.000
23	0.042
24	0.000
25	0.038
26	0.000
27	0.000
28	0.000
29	0.033
30	0.000
31	0.031
32	0.000
33	0.000
34	0.000
35	0.027
36	0.000
37	0.026

38	0.000
39	0.000
40	0.000
41	0.023
42	0.000
43	0.022
44	0.000
45	0.000
46	0.000
47	0.020
48	0.000
49	0.019
50	0.000
51	0.000
52	0.000
53	0.018
54	0.000
55	0.017
56	0.000
57	0.000
58	0.000
59	0.016
60	0.000
61	0.016
62	0.000
63	0.000
64	0.000

n	V(n)
1	0.094065
2	0.000000
3	0.000000
4	0.000000
5	0.093425
6	0.000000
7	0.028761
8	0.000000
9	0.000000
10	0.000000
11	0.009252
12	0.000000
13	0.006308
14	0.000000
15	0.000000
16	0.000000
17	0.003552
18	0.000000
19	0.002806

THD

1.04710

TABLE IX

HARMONIC VOLTAGES VERSUS HARMONIC ORDER

Harmonic Order (n)	Harmonic Voltages V(n)
1	0.094065
2	0.000000
3	0.000000
4	0.000000
5	0.093425
6	0.000000
7	0.028761
8	0.000000
9	0.000000
10	0.000000
11	0.009253
12	0.000000
13	0.006308
14	0.000000
15	0.000000
16	0.000000
17	0.003552
18	0.000000
19	0.002806

Total Harmonic Distortion (T. H. D)= 104.71%

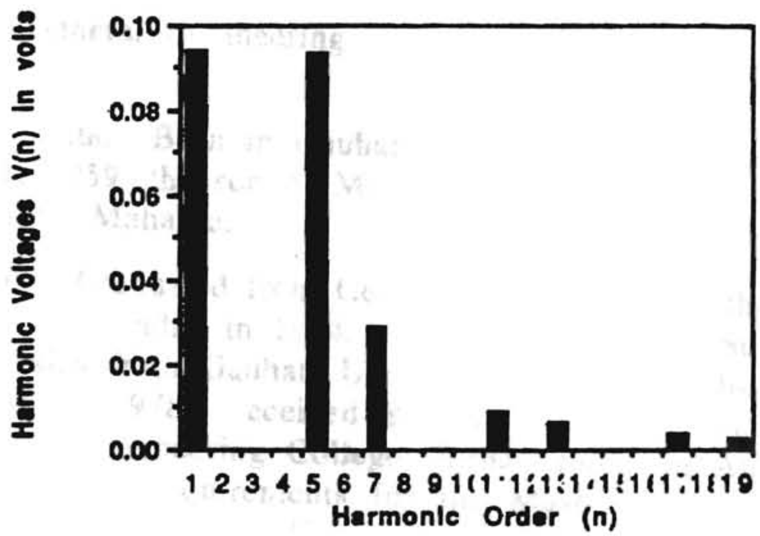

Figure23. Plot of Harmonic voltages

VITA

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