The Potential Effects of Single-Phase Power Electronic-Based Loads on Power System Distortion and Losses

Volume 1: Current Harmonics Produced by Distributed Single-Phase Power Electronic Loads

Technical Report

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Volume 1: Current Harmonics Produced by Distributed Single-Phase Power Electronic Loads

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Cosponsors
Reliant Energy
P. O. Box 1700
Houston, TX 77251

Principle Investigator
S. Jackson

Salt River Project
P. O. Box 52025
Phoenix, AZ 85284

Principle Investigator
R. Thallam

EPRI Project Manager
A. Sundaram

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

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CITATIONS

This report was prepared by

University of Texas at Austin
Department of Electrical and Computer Engineering
Austin, TX 78712

Principal Investigator
W. Grady

Investigator
A. Mansoor
EPRI PEAC Corporation

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REPORT SUMMARY

Utilities have traditionally considered harmonics due to single large loads the main harmonics problem in power systems. However, the increase in size and proliferation of single-phase power electronics-based loads has created a need for developing analytical tools for analyzing the impact of distributed nonlinear loads on electrical equipment and on the distribution system as a whole. This report focuses on methods to sum the harmonic currents produced by a large numbers of single-phase power electronic loads connected to a distribution system.

Background

The number and effect of single-phase nonlinear harmonic-producing devices connected to the power system have increased significantly over the past few years. While individual large single-phase power electronic loads do not pose a problem for electric utilities, harmonics generated by many distributed loads accumulate in the power system. The possible implications of large numbers of single-phase devices in distribution systems and in customer facilities are a growing concern for utilities and customers. This volume is the first part of a five-volume report that summarizes the results of an extensive research effort to analyze the impact of distributed harmonic sources on the utility system and on equipment. It focuses on analyzing the summation of harmonic currents produced by a large number of single-phase electronic loads and developing load models for small distributed harmonic sources.

Objective

To investigate the summation of harmonic currents produced by a large numbers of single-phase power electronic loads connected to a distribution system.

Approach

The project team first developed complete analytical models for calculating harmonic components of the input current of two basic load types, capacitor filtered diode-bridge rectifiers and thyristor-controlled incandescent lighting loads. The next step was to mathematically define two basic aggregation factors, diversity and attenuation, that impact the net current injected by distributed single-phase nonlinear loads. The team then used the models to investigate the range of these aggregation factors based on variability of system and load components. This work led to the development of cumulative harmonic models for the two basic load groups addressed in this report.

Results

Diversity and attenuation are very important factors in predicting the behavior of distributed single-phase power electronic loads, especially for the higher-order harmonics. The commonly

used “fixed harmonic current injection” model can significantly overestimate the cumulative harmonic currents produced by these loads and their impact on the distribution system, especially for higher-order harmonics beyond the 7th. The cumulative harmonic currents for the 9th multiple and above experience appreciable phase cancellation due to individual and/or composite variations in power level, impedance magnitude, impedance X/R ratio, and smoothing capacitance. Because the 3rd and 5th harmonics show little phase cancellation, the total harmonic distortion (THD) of the summed current is only slightly less than that obtained by using superposition. There is also significant attenuation of current harmonics above the 3rd multiple when a number of identical loads, such as televisions and desktop computers, share a common source impedance. The THD of current in this case is approximately one-half of that obtained using superposition of individual load currents. However, the 3rd harmonic, which is responsible for most harmonic-related neutral conductor overloading problems, experiences only slight attenuation.

EPRI Perspective
By providing utilities with analytical tools and methodologies to assess the impact of single-phase nonlinear loads, EPRI is enabling utilities to understand how these loads may impact the power system in the future. The results of this research should also help industries and utilities define meaningful and practical limits for harmonic current injection from single-phase nonlinear loads. These limits will ultimately benefit end users by improving the quality of the voltage supplied to end-use loads and minimizing the impact of harmonics voltage on equipment performance.

Keywords
Power Quality
Harmonics
Cancellation
Attenuation
Single-Phase Loads

ABSTRACT

The number and significance of nonlinear harmonic producing devices connected to the power system has increased significantly over the past few years. Traditionally, harmonics due to single large loads have been considered as the main harmonics problem in power systems. However, with the increase in size and proliferation of single-phase power electronic-based loads, this scenario of concentrated sources of harmonics is gradually changing. While one large single-phase power electronic load does not pose a problem for electric utilities, the cumulative harmonics produced by distributed loads are, to some extent, additive. The possible implications of large numbers of single-phase devices in distribution systems is a growing concern for utility engineers.

The simulation method that is currently used to investigate the impact of these types of loads does not take into account the diversity in phase angles and the effect of voltage distortion on harmonic currents. Consequently, a fixed injection current model is used to estimate their effect on power system distortion. It is the intent of this research effort to investigate the summation of harmonic currents produced by a large number of single-phase electronic loads and to develop load models for distributed small harmonic sources.

Complete analytical models for calculating harmonic components of the input current of two basic load types, capacitor filtered diode-bridge rectifiers and thyristor-controlled incandescent lighting loads, are derived as part of this research. The models are then used to investigate the harmonic cancellation and attenuation of large numbers of distributed harmonic sources and to develop cumulative harmonic current injection models for these load types. This work leads to a better understanding of the harmonic cancellation effect that exists among distributed sources. The cancellation effect is of primary importance in any harmonic penetration study dealing with single-phase distributed power electronic-based loads.

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INTRODUCTION

1.1 Motivation

Today, most electrical energy is consumed by linear loads such as air conditioners, heaters, lights, household appliances, and motors. These traditional linear loads tend to draw sinusoidal currents from the power system. There are exceptions, such as aluminum reduction plants, television/radio transmitters and receivers, and fluorescent lamps. But for the most part, traditional loads do not cause appreciable current or voltage distortion on distribution feeders and are not important sources of power system harmonics.

The composition of power system loads is, however, changing rapidly [1]. Distortion levels on distribution systems are increasing [2,3]. Many traditional linear loads are gradually being replaced by high-efficiency, nonlinear power electronic loads. Notable examples are adjustable-speed drives (ASDs) that makes use of an electronically commutated motor to achieve variable speed control, high-efficiency lighting, computers, light dimmers, copiers, uninterruptible power supplies, battery chargers, and virtually all other loads that employ ac/dc converters. Power electronic loads are popular because of their efficiency and controllability. The trend toward more power electronic loads will accelerate as future generations of residential air conditioners, heat pumps, refrigerators, and household appliances are equipped with ASDs to improve efficiencies, and when (or if) battery chargers for electric vehicles become an appreciable fraction of the load.

An example of a large energy-saving electronic load is the single-phase ASD heat pump. They have the potential to save large amounts of energy by matching their output precisely to the demand, yielding higher efficiency and greater comfort. Seasonal energy efficiency ratios (SEERs) in the range of 14 - 15 are possible (compared to 10 - 11 for conventional heat pumps and air conditioners). Although they are presently quite expensive, the attractiveness of ASD heat pumps will improve as greater numbers are produced, as the cost of energy gradually rises, and as higher efficiency loads are mandated by law.

Despite their many advantages, there is a "downside" to power electronic loads – namely, voltage and current harmonic distortion. Figure 1-1 shows the measured current waveform and the corresponding total harmonic distortion (THD) for an ASD air conditioner. THD is defined as the ratio of the root-mean-square of the harmonic content to the root-mean-square value of the fundamental quantity expressed as a percent of the fundamental. The harmonics in the highly distorted current waveform, which do little or no useful work, cause extra losses in the distribution system feeders, transformers, and capacitor banks. Figure 1-2 shows the measured voltage and current waveform of a residence with an ASD heat pump. While one large single-phase power electronic load in a residence does not pose a problem for the utility, cumulative harmonics produced by distributed loads are, to a great extent, additive. The possible implications of having large numbers of residence with loads having waveforms as shown in Figure 1-2 is of concern to many electric utility engineers.

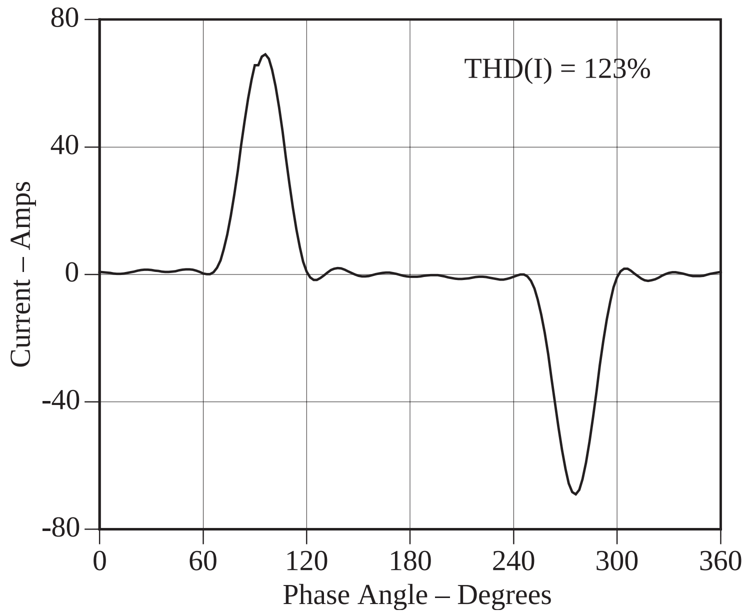

Figure 1-1
Measured Current Waveform of ASD Heat Pump Operating at Full Load (Fundamental Current = 14.4 A)

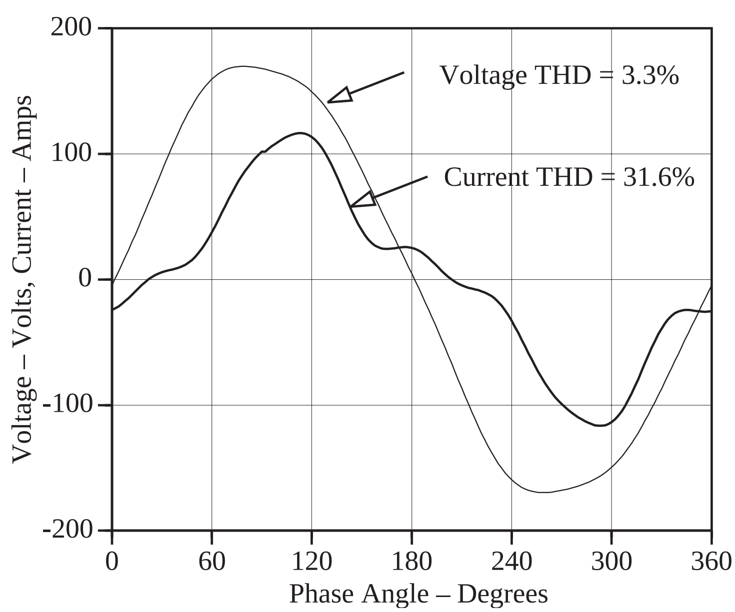

Figure 1-2
"Whole House" Voltage and Current Waveforms for a Residence with ASD Heat Pump

This concern led to an Electric Power Research Institute (EPRI) project to examine issues related to distortion produced by single-phase power electronic loads. This work investigates the cumulative harmonic current characteristics of distributed power electronic based loads.

1.2 Objective

Traditionally, harmonics due to a single large load have been considered as a problem in power systems. However, with increasing size and proliferation of single-phase power electronic based loads, this scenario of concentrated source of harmonics is gradually changing. The simulation method that is currently used to investigate the impact of these type of loads does not take into account the diversity in phase angles of a large number of harmonic currents and the effect of voltage distortion on input current waveshapes. As a result, the cancellation and the attenuation effect of distributed harmonic loads are neglected.

The focus of this research is to investigate the summation of harmonic currents produced by a large numbers of single-phase power electronic loads connected to a distribution system. The capacitor filtered diode bridge rectifier, which is the interface to the ac power system for a majority of single-phase power electronic based loads [4], including television receivers, personal computers and ASDs is considered as the basic load model. A complete analytical model to calculate the input harmonic current spectrum for nonsinusoidal voltage excitation is developed. The variability in phase angles of individual harmonic currents due to variations in parameters originating from the system side (e.g., system impedance or X/R ratio), or from load side (e.g., power level, circuit components) are investigated and quantified as 'Diversity Factor' numbers for individual harmonics. The interaction of system impedance and harmonic current when several loads share a common impedance is studied by investigating the effect of voltage distortion on current harmonics. By simultaneously taking into account attenuation and diversity factors, the net harmonic currents produced by large numbers of single-phase desktop computers in a facility, such as a commercial office building are studied.

An additional load model addressed in this thesis is the thyristor-controlled single-phase rectifier. The most common application of this device is in incandescent lighting control. By taking into account the variability in firing angles of different light dimmers, a diversity-adjusted fixed injection current model for this load group is developed.

1.3 Existing Models for Distributed Harmonic Loads

The basis of harmonic penetration studies is to take information on the supply network, and on the harmonic currents generated by distorting loads, and calculate the harmonic voltage distortion at key system busbars. Given that the admittance matrix at any harmonic may be derived from the network, and that a current vector may be produced for the distorted loads, the problem is reduced to solving a set of simultaneous equations of the form $\mathbf{I} = [\mathbf{Y}]\,\mathbf{V}$. These equations are solved for $\mathbf{V}$ when the current vector $\mathbf{I}$ is known. For those harmonic generators distinctly affected by voltage harmonics, the load nonlinearity on voltage and current harmonics is accounted for in the active and the reactive power flow equations of the system.

For single source harmonic problems primarily caused by large power converters, the power flow iterative method which is incorporated into simulation software like HARMFLO (harmonic power flow program) is used [5]. However, harmonic penetration studies for large numbers of single phase power electronic based loads are primarily based on current injection models. The power flow approach has not been used because a suitable nonsinusoidal model for these loads has not been available and because of the complexity required to model all the loads within any reasonable degree of accuracy.

In the fixed injection model, distributed single-phase power electronic loads are treated as a lumped load that has the same current spectrum of a single load. The fundamental component of the load current is adjusted proportionally with the power level of the load group. Harmonic penetration studies based on this fixed-injection model have been widely published in the literature [6,7,8,9], and so far, fixed injection has been the only viable model for predicting the impact of proliferating nonlinear loads in distribution systems. The two major assumptions that are associated with fixed current injection models are:

1. There is no diversity in harmonic phase angles of individual loads within the load group, consequently leading to an arithmetic summation of harmonic currents.

2. The harmonic current spectrum of individual load is independent of supply voltage distortion, thereby neglecting any interaction of system impedance with harmonic currents.

These assumptions introduce significant errors in estimating net harmonic currents produced by distributed harmonic sources. Practically no published work has appeared in IEEE transactions or other related journals on the diversity effect of single-phase power electronic loads. A number of papers have been published in IEE conferences as part of the CIRED effort to investigate the diversity effect among distributed small harmonic producing loads[10,11,12]. Most of these works are based on experimental measurements of individual and combined harmonic current spectra of different types of individual loads, from which diversity factors are calculated. However, the effects of network variability and voltage distortion have not been taken into account in any of these works. Also, variable power ASD loads, which are different from fixed power loads in the sense that their harmonic spectrum changes with power level, have not been studied in these works. In the absence of analytical models, the published works are based completely on measurements and are very limited because of the complexities in separating the external factors in an actual network.

1.4 Organization of Research

In this section, a brief description of each of the major areas covered in the later chapters is presented. Chapter 2 describes the complete analytical model for calculating the input harmonic current for a single-phase capacitor filtered diode bridge rectifier and for a thyristor controlled incandescent lighting load. The analytical models presented in this chapter form the basis of two general purpose FORTRAN programs for performing Monte Carlo studies of distributed loads. These programs are used in subsequent chapters to quantify the diversity and attenuation effects for large numbers of distributed single-phase power electronic based loads.

In Chapter 3, the cancellation effect of multiple loads due to system and load side parameter variations is illustrated with the load models developed in Chapter 2. For diode bridge rectifier loads, diversity numbers corresponding to certain ranges of parameter variations are presented. For incandescent lighting load, a simplified model is developed to predict the cumulative harmonic current injection levels. The materials covered in this chapter also appear in [13,14].

Chapter 4 presents the effect of nonsinusoidal voltage on the input current harmonics of single-phase diode bridge rectifier loads. The effect of supply voltage harmonic magnitudes and phase angles on input current THDI is investigated. A simplified empirical equation is developed to predict the THDI from the supply voltage crest factor. The self-compensating effect of voltage harmonics on input current distortions is also illustrated. The results obtained in this chapter are documented in [15].

In Chapter 5, the nonsinusoidal effect and the diversity effect are simultaneously taken into account by expanding the analytical model and solution procedure developed in Chapter 2 to permit iterative updates of voltage harmonics. To assure that the ranges of modeling parameters are credible, the results of two sets of harmonic measurements are incorporated into the study. The relative interaction of the two effects are investigated by simulating a realistic scenario of a large number of single-phase desktop computers sharing a common impedance, as is the case in a typical commercial building. Results of this simulation are also documented in [16].

Chapter 6 gives a brief review of this work and describes the significant contributions. A direction for possible future research on distributed single-phase power electronic based loads is also presented. A brief description and listings of the FORTRAN codes of the two programs used for this research, SPCONV and TRIAC, are documented in the Appendices.

2
ANALYTICAL MODEL DEVELOPMENT

2.1 Single-Phase Capacitor Filtered Diode Bridge Rectifier Model

Power supply for dc-circuits used in most of the single-phase power electronic devices are the main source of harmonics in distribution systems [16]. Television receivers, personal computers, printers, copiers, fax machines, entertainment systems, ASDs and many other loads typically used in residential and commercial environments are equipped with a capacitor-filtered rectifier (CFR). The circuit model for harmonic analysis of a single-phase power electronic load is shown in Figure 2-1.

The various circuit components are:

V_{th} : Thevenin equivalent system voltage,

R_{th}, L_{th} : Thevenin equivalent system impedance parameters (includes the service transformer),

R_l, L_l : Local line impedance parameters (beginning from the load side of the service transformer),

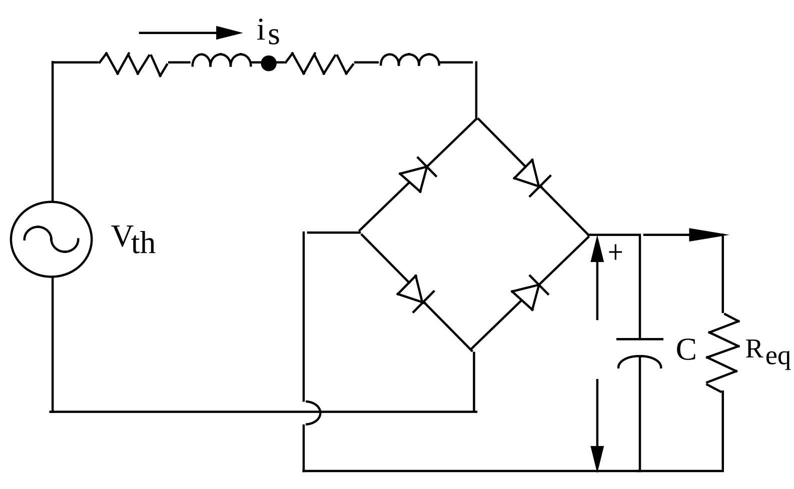

Figure 2-1
Capacitor-Filtered Diode Bridge Rectifier Model

C: Smoothing capacitor,

R_{eq}: Equivalent load resistance.

Under nonsinusoidal operating condition, the Thevenin equivalent voltage is

$$V_{th} = \sqrt{2}\sum E(n)\sin\{n\theta + \phi(n)\} .$$

The input current of these converters flows only during the short capacitor charging period and hence has a discontinuous, pulsating waveform as shown in Figure 2-2. Using the Laplace transformation method [17,18], the analytical expressions for the output voltage $V_0(\theta)$ and input current $i_s(\theta)$ will be derived in terms of circuit parameters and the forcing function $V_{th}(\theta)$.

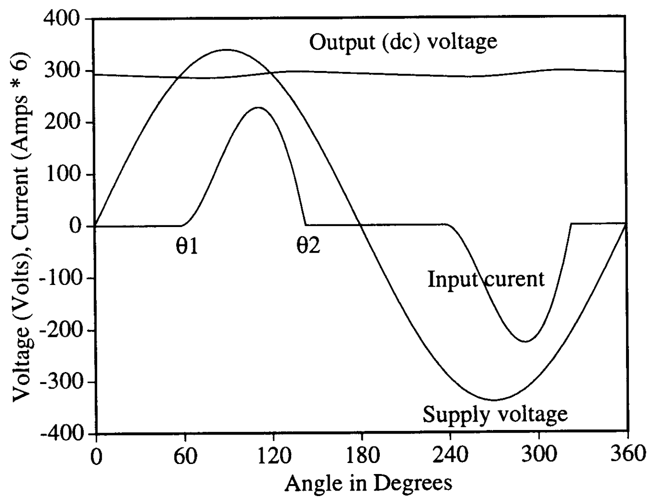

Figure 2-2
Supply Voltage $V_{th}(\theta)$, Input Current $i_s(\theta)$, and Output Voltage $V_0(\theta)$ for the Circuit in Figure 2-1

2.1.1 Circuit Analysis and Solution Procedure

The circuit in Figure 2-1 operates in two modes - charging and discharging. Input current flows only during the charging mode, which corresponds to $(\theta_1 \le \theta \le \theta_2)$ in Figure 2-2. By shifting the axis at $\theta = \theta_1$ the circuit equations for the charging mode can be written as

$$V_{th}(\theta) = R_t i_s + \omega L_t \frac{di_s}{d\theta} + V_0(\theta), \tag{2-1}$$

$$i_s(\theta) = \omega C \frac{dV_0}{d\theta} + \frac{V_0(\theta)}{R_{eq}}, \tag{2-2}$$

where

$$V_{th}(\theta) = \sqrt{2}\sum E(n)\sin\{n\theta + \phi(n) + n\theta_1\}$$
$$= \sqrt{2}\sum E(n)\sin\{n\theta + \delta(n)\},$$

$R_t = R_{th} + R_l$, $L_t = L_{th} + L_l$.

Equations (2-1) and (2-2) can be expressed in matrix form as

$$\frac{d}{d\theta}[\mathbf{Y}] = \alpha\mathbf{Y} + \beta\mathbf{V}, \qquad (2\text{-}3)$$

where

$$\mathbf{Y} = \begin{bmatrix} i_s(\theta) \\ V_0(\theta) \end{bmatrix},$$

$$\mathbf{V} = [V_{th}(\theta)] = [\sqrt{2}\sum E(n)\sin\{n\theta + \delta(n)\}],$$

$$\alpha = \begin{bmatrix} -R_t/\omega L_t & -1/\omega L_t \\ 1/\omega C & -1/\omega C R_{eq} \end{bmatrix} = \begin{bmatrix} -\alpha_1 & -\alpha_2 \\ \alpha_3 & -\alpha 4 \end{bmatrix},$$

$$\beta = \begin{bmatrix} 1/\omega L_t \\ 0 \end{bmatrix} = \begin{bmatrix} \alpha_2 \\ 0 \end{bmatrix}.$$

Laplace transforming (2.3) and rearranging terms yields

$$\mathbf{Y}(s) = (s\mathbf{I} - \alpha)^{-1}\mathbf{Y}(\theta_1) + (s\mathbf{I} - \alpha)^{-1}\beta\mathbf{V}(s), \qquad (2\text{-}4)$$

where the initial value of $\mathbf{Y}(\theta_1)$ is

$$\mathbf{Y}(\theta_1) = \begin{bmatrix} i_s(\theta_1) \\ V_0(\theta_1) \end{bmatrix} = \begin{bmatrix} 0 \\ \sqrt{2}\sum E(n)\sin\{\delta(n)\} \end{bmatrix}. \qquad (2\text{-}5)$$

The characteristic roots of $(s\mathbf{I} - \alpha)^{-1}$in (4) are given by $S_{1,2} = a \pm b$,where

$$a = -(\alpha_1 + \alpha_4)/2,\ b = \sqrt{(1/4)(\alpha_1 - \alpha_4)^2 - \alpha_2\alpha_3}\,.$$

Inverse transforming (2-4) under the presumption of real roots yields

$$
\begin{aligned}
i_s(\theta) = {} & \sqrt{2}\alpha_2 \sum_n E(n)\left[\frac{1}{s_1 - s_2}\Big\{\big(-\sin\{\delta(n)\} - C_2(n)s_1 + C_3(n)\big)e^{s_1\theta}\right. \\
& \left. -\big(-\sin\{\delta(n)\} - C_2(n)s_2 + C_3(n)\big)e^{s_2\theta}\Big\} + C_2(n)\cos(n\theta) + \frac{C_4(n)}{n}\sin(n\theta)\right],
\end{aligned}
\tag{2-6}
$$

$$
\begin{aligned}
V_0(\theta) = {} & \sum_n \sqrt{2}E(n)\left[\frac{1}{s_1 - s_2}\Big\{(s_1 + \alpha_1)\sin\{\delta(n)\} + \alpha_2 C_5(n)s_1\right. \\
& + \alpha_2 C_6(n)\Big\}e^{s_1\theta} - \frac{1}{s_1 - s_2}\Big\{(s_2 + \alpha_1)\sin\{\delta(n)\} + \alpha_2 C_5(n)s_2 \\
& \left. + \alpha_2 C_6(n)\Big\}e^{s_2\theta} - \alpha_2 C_5(n)\cos(n\theta) + \alpha_2 \frac{C_7(n)}{n}\sin(n\theta)\right].
\end{aligned}
\tag{2-7}
$$

The constants $C_1(n)$, $C_2(n)$, ···· , $C_7(n)$ in Equation 2-6 and 2-7 are defined as

$$
C_1(n) = \frac{1}{4a^2n^2 + (n^2 - a^2 + b^2)^2},
$$

$$
\begin{aligned}
C_2(n) = {} & C_1(n)\Big[\big\{-2an^2 + \alpha_4(a^2 - b^2 - n^2)\big\}\sin\{\delta(n)\} + \\
& (a^2 - b^2 - n^2 + 2a\alpha_4)\; n\cos\{\delta(n)\}\Big],
\end{aligned}
$$

$$
\begin{aligned}
C_3(n) = {} & C_1(n)\Big[(a^2 - b^2)(a^2 - b^2 - n^2 + 2a\alpha_4)\sin\{\delta(n)\} + \\
& \big\{(3a^2 + b^2 + n^2)\alpha_4 + 2a(a^2 - b^2)\big\}\, n\cos\{\delta(n)\}\Big],
\end{aligned}
$$

$$
\begin{aligned}
C_4(n) = {} & C_1(n)\Big[(n^2 - a^2 + b^2 - 2a\alpha_4)n^2\sin\{\delta(n)\} \\
& + \big\{(a^2 - b^2 - n^2)\alpha_4 - 2an^2\big\}\, n\cos\{\delta(n)\}\Big],
\end{aligned}
$$

$$
C_5(n) = \alpha_3 C_1(n)\Big[(n^2 - a^2 + b^2)\sin\{\delta(n)\} - 2an\cos\{\delta(n)\}\Big],
$$

$$
C_6(n) = \alpha_3 C_1(n)\Big[2a(a^2 - b^2)\sin\{\delta(n)\} + (3a^2 + n^2 + b^2)n\cos\{\delta(n)\}\Big],
$$

$$
C_7(n) = \alpha_3 C_1(n)\Big[-2an^2\sin\{\delta(n)\} + (a^2 - b^2 - n^2)n\cos\{\delta(n)\}\Big].
$$

Conduction angles θ_1 and θ_2 can be determined by simultaneously solving the following two boundary conditions:

$$i_s(\theta_2) = 0, \tag{2-8}$$

$$V_0(\theta_2)\exp\{(\theta_2 - \theta_1 - \pi)\alpha_4\} = \sqrt{2}\sum E(n)\sin\{n\theta_1 + \phi(n)\}. \tag{2-9}$$

Newton-Raphson method was found to be unsuitable for solving (2.8) and (2.9) because they have multiple zero crossings, because accurate initial estimates are difficult to obtain, and because angles θ_1 and θ_2 vary widely between 0^o and 180^o, depending upon circuit parameters and operating power level. This difficulty was overcome by solving for θ_1 and θ_2 using a simpler Gauss-Seidel approach, which is

a) Find an initial value of θ_1 for which $i_s(\theta)$ has a zero crossing between θ_1 and 180^o,

b) Solve (2-8) for θ_2, using the bisection method,

c) Using θ_2 from b), solve (2-9) with bisection to obtain an updated value of θ_1,

d) Repeat steps b) and c) until both (2-8) and (2-9) are satisfied.

This technique has proven to be very effective, reaching convergence in 3 to 4 iterations, and it is rather insensitive to the initial value chosen for θ_1 in step a).

Now, consider the case where output power P_{out} is known instead of R_{eq}. In this case, R_{eq} is found after using the following iterative procedure:

1) Estimate a starting value of R_{eq} from $R_{eq} = \dfrac{1.5E^2}{P_{out}}$,

2) Calculate θ_1 and θ_2 using the method described above,

3) Calculate digitized values of $i_s(\theta)$, $V_0(\theta)$, and the rms value of $V_0(\theta)$, (defined as $V_{0,rms}$),

4) Check $\left|\dfrac{V_{0,rms}^2}{R_{eq}} - P_{out}\right| \le \varepsilon$ for convergence,

5) If not converged, update R_{eq} using $R_{eq} = \dfrac{V_{0,rms}^2}{P_{out}}$, and continue from step (2) until convergence is reached.

Convergence is usually reached in 2 to 3 iterations.

2.1.2 Fourier Analysis

The standard Fourier series a_k and b_k coefficients for input current $i_s(\theta)$ (Eq. 2-6) is derived as follows:

Defining

$$C_8(n) = \frac{\sqrt{2}\alpha_2 E(n)}{s_1 - s_2}\left(-\sin\{\delta(n)\} - C_2(n)s_1 + C_3(n)\right),$$
$$C_9(n) = \frac{\sqrt{2}\alpha_2 E(n)}{s_1 - s_2}\left(\sin\{\delta(n)\} + C_2(n)s_2 - C_3(n)\right),$$

and simplifying (2-6) yields

$$i_s(\theta) = \sum_n C_8(n)e^{s_1\theta} + \sum_n C_9(n)e^{s_2\theta} + \sqrt{2}\alpha_2 \sum_n E(n)C_2(n)\cos(n\theta)$$
$$+\sqrt{2}\alpha_2 \sum_n E(n)\frac{C_4(n)}{n}\sin(n\theta).$$

For the 1st term, $\sum\limits_n C_8(n)e^{s_1\theta}$:

$$a_{k1} = \sum_n \frac{2C_8(n)}{\pi(s_1^2 + k^2)}\left[e^{s_1\theta_2}\left(s_1\cos(k\theta_2) + k\sin(k\theta_2)\right) - s_1\right],$$
$$b_{k1} = \sum_n \frac{2C_8(n)}{\pi(s_1^2 + k^2)}\left[e^{s_1\theta_2}\left(s_1\sin(k\theta_2) - k\cos(k\theta_2)\right) + k\right].$$

For the 2nd term, $\sum\limits_n C_9(n)e^{s_2\theta}$:

$$a_{k2} = \sum_n \frac{2C_9(n)}{\pi(s_2^2 + k^2)}\left[e^{s_2\theta_2}\left(s_2\cos(k\theta_2) + k\sin(k\theta_2)\right) - s_2\right],$$
$$b_{k2} = \sum_n \frac{2C_9(n)}{\pi(s_2^2 + k^2)}\left[e^{s_2\theta_2}\left(s_2\sin(k\theta_2) - k\cos(k\theta_2)\right) + k\right].$$

For the 3rd term, $\sqrt{2}\alpha_2 \sum_n E(n)C_2(n)\cos(n\theta)$:

$$a_{k3} = \frac{\sqrt{2}\alpha_2 E(k)C_2(k)}{2\pi}\left[2\theta_2 + \frac{1}{k}\sin(2k\theta_2)\right] + \sum_{n\neq k}\frac{\sqrt{2}\alpha_2 E(n)C_2(n)}{\pi}\left[\frac{\sin(n+k)\theta_2}{(n+k)} + \frac{\sin(n-k)\theta_2}{(n-k)}\right],$$

$$b_{k3} = \frac{\sqrt{2}\alpha_2 E(k)C_2(k)}{2k\pi}\left[1-\cos(2k\theta_2)\right] + \sum_{n\neq k}\frac{\sqrt{2}\alpha_2 E(n)C_2(n)}{\pi}\left[\frac{\cos(n-k)\theta_2}{(n-k)} - \frac{\cos(n+k)\theta_2}{(n+k)} - \frac{2k}{n^2-k^2}\right].$$

For the 4th term, $\sqrt{2}\alpha_2 \sum_n E(n)\frac{C_4(n)}{n}\sin(n\theta)$:

$$a_{k4} = \frac{\sqrt{2}\alpha_2 E(k)C_4(k)}{2k^2\pi}\left[1-\cos(2k\theta_2)\right] + \sum_{n\neq k}\frac{\sqrt{2}\alpha_2 E(n)(-C_4(n))}{n\pi}\left[\frac{\cos(n+k)\theta_2}{(n+k)} + \frac{\cos(n-k)\theta_2}{(n-k)} - \frac{2n}{n^2-k^2}\right],$$

$$b_{k4} = \frac{\sqrt{2}\alpha_2 E(k)C_4(k)}{2k\pi}\left[2\theta_2 - \frac{1}{k}\sin(2k\theta_2)\right] + \sum_{n\neq k}\frac{\sqrt{2}\alpha_2 E(n)C_4(n)}{n\pi}\left[\frac{\sin(n-k)\theta_2}{(n-k)} - \frac{\sin(n+k)\theta_2}{(n+k)}\right].$$

Summing the four terms yields $a_k = a_{k1} + a_{k2} + a_{k3} + a_{k4}$, and $b_k = b_{k1} + b_{k2} + b_{k3} + b_{k4}$.

2.1.3 Model Verification

The circuit equation along with the Fourier analysis were coded into a general purpose FORTRAN program SPCONV. A description of the program along with the listing of the input code is provided in the Appendix. The simulation results were verified with experimental results. Figure 2-3 and 2-4 shows the simulated and experimental input current waveform for sinusoidal and nonsinusoidal excitation, respectively. A 1200 μF capacitor bridge was used for the purpose of the experiment. For the sinusoidal case, the measured and simulated THDI were 121% and 126% respectively. For the nonsinusoidal excitation, a transformer was used in series with the supply at a reduced voltage to create a distorted voltage. In this case the measured and the simulated THDI were 83% and 79% respectively.

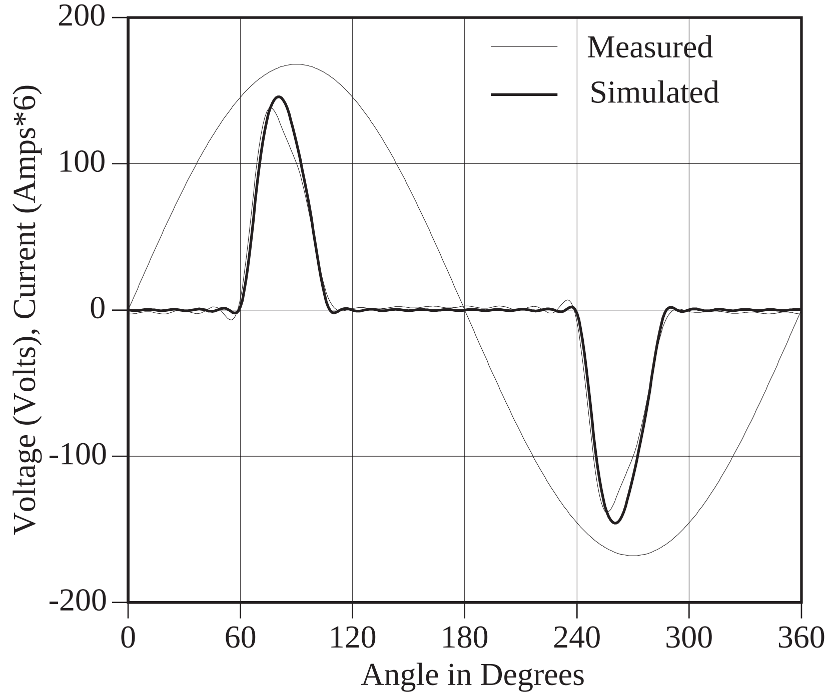

Figure 2-3
Verification of CFR Model for Sinusoidal Excitation

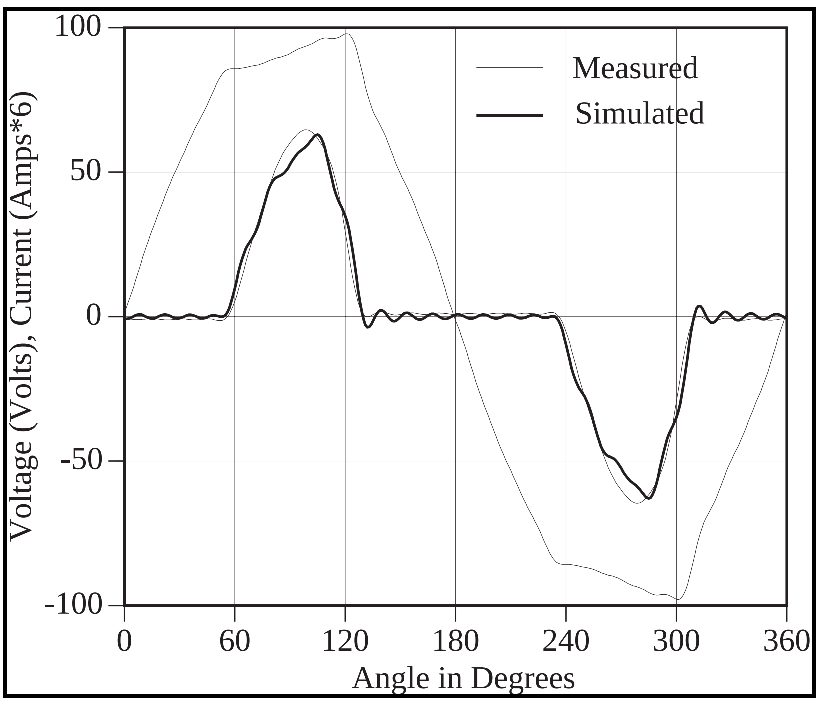

Figure 2-4
Verification of CFR Model for Nonsinusoidal Excitation

2.2 Thyristor-Controlled Incandescent Lighting Load Model

AC voltage controllers of the type shown in Figure 2-5 regulate the power delivered to a load by varying the rms value of the applied load voltage. The most common single-phase application of these devices is in incandescent lighting control. The thyristors, along with their gate-control circuitry, regulate power flow by adjusting the firing angle at which conduction begins in each half cycle. The resulting ac current, as shown in Figure 2-6 for resistive load, contains significant levels of odd-ordered harmonic.

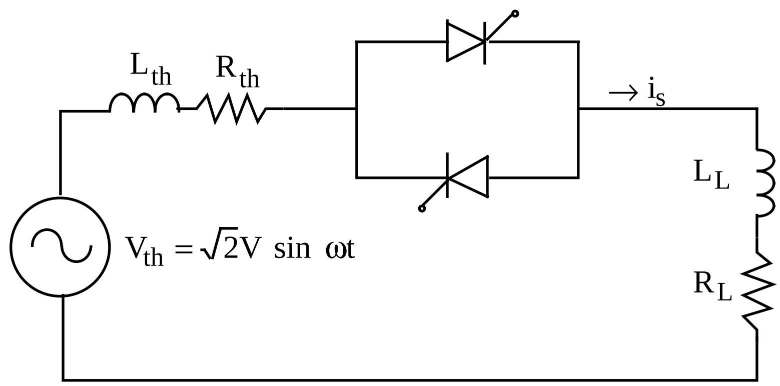

Figure 2-5
Generalized Model of Single-Phase, Full-Wave, Thyristor-Controlled Load

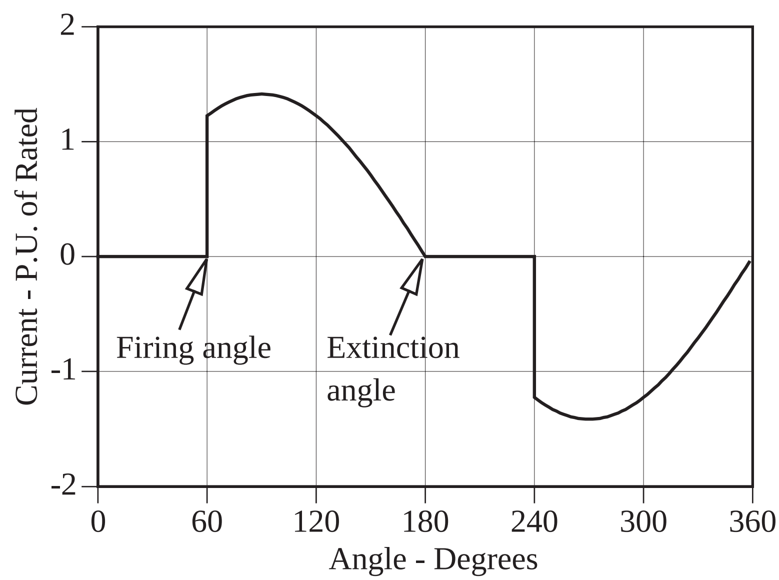

Figure 2-6
Corresponding ac Current Waveshape for Resistive Load

2.2.1 Circuit Analysis and Solution Procedure

The circuit model for harmonic analysis of a single-phase, full-wave, thyristor-controlled load is shown in Figure 2-5. The circuit components are

V_{th} : Thevenin equivalent ac system voltage,

R_{th}, L_{th}: Thevenin equivalent system impedance parameters,

R_L, L_L: Load impedance parameters.

During the conduction period, the circuit equation is

$$V_{th} = \sqrt{2}V \sin \omega t = L\frac{di_s}{dt} + Ri_s, \qquad (2\text{-}10)$$

where

$L = L_{th} + L_L$, $R = R_{th} + R_L$.

The solution of (2.10) for the initial condition $i_s(t = \alpha/\omega) = 0$ is [19]

$$i_s(t) = \frac{\sqrt{2}V}{Z}\left\{\sin(\omega t - \theta_z) - e^{-\frac{R}{L}\left(t - \frac{\alpha}{\omega}\right)}\sin(\alpha - \theta_z)\right\}, \qquad (2\text{-}11)$$

where

$$Z = \sqrt{\left[R^2 + (\omega L)^2\right]}\,\Omega\ ,\ \theta_z = \tan^{-1}\frac{\omega L}{R}\ .$$

If the circuit contains no inductance, extinction angle $\beta = 180^{o}$. Otherwise, β is greater than 180^{o} and can be determined by iteratively solving (2.11), so that $i_s(t = \beta/\omega) = 0$.

Typically, output power P_{out} , instead of α, is the known quantity. For this case, α can be solved to yield the correct power by means of the following iterative algorithm:

1. Estimate a starting value of α using the straight-line approximation for Pout, which is

$$\alpha = \left(1 - \frac{P_{out}}{P_{rated}}\right) \bullet 180^{o}\ .$$

2. Determine β from (2.11) using the boundary condition

   $i_S(t = \beta/\omega) = 0.$

3. Calculate the rms value of the ac line current and check for power convergence, (i.e., $\left| I^2 R_L - P_{out} \right| \le \varepsilon$), where we chose ε = 0.002 p.u.

4. Using a bisection procedure to update α, repeat steps 2) and 3) until convergence is reached.

2.2.2 Fourier Analysis

The standard Fourier series coefficients a_k and b_k for input current $i_S(t)$ given in (2-11) is derived as follows:

For the 1st term of (2-11), i.e., $\frac{\sqrt{2}V}{Z}\left\{\sin\left(\omega t - \theta_z\right)\right\}$, when k = 1, then

$$a_{11} = \frac{\sqrt{2}V}{Z}\left[(\beta - \alpha)\cos(\theta_z) - 0.5 \bullet \left\{\sin\left(2\beta - \theta_z\right) - \sin\left(2\alpha - \theta_z\right)\right\}\right],$$

$$b_{11} = \frac{\sqrt{2}V}{Z}\left[(\alpha - \beta)\sin(\theta_z) + 0.5 \bullet \left\{-\cos\left(2\beta - \theta_z\right) + \cos\left(2\alpha - \theta_z\right)\right\}\right],$$

and when k = 3, 5, 7, ··· , then

$$a_{k1} = \frac{\sqrt{2}V}{\pi Z}\left[-\frac{\sin\{(1+k)\beta - \theta_z\}}{1+k} + \frac{\sin\{(1-k)\beta - \theta_z\}}{1-k} + \frac{\sin\{(1+k)\alpha - \theta_z\}}{1+k} - \frac{\sin\{(1-k)\alpha - \theta_z\}}{1-k}\right],$$

$$b_{k1} = \frac{\sqrt{2}V}{\pi Z}\left[-\frac{\cos\{(1+k)\beta - \theta_z\}}{1+k} - \frac{\cos\{(1-k)\beta - \theta_z\}}{1-k} + \frac{\cos\{(1+k)\alpha - \theta_z\}}{1+k} + \frac{\cos\{(1-k)\alpha - \theta_z\}}{1-k}\right].$$

For the 2nd term of (2-11), i.e., $\frac{\sqrt{2}V}{Z}\left\{-e^{-\frac{R}{L}\left(t - \frac{\alpha}{\omega}\right)}\sin\left(\alpha - \theta_z\right)\right\}$, we let $\delta = \frac{R}{L\omega}$, and we obtain

$$a_{k2} = \frac{2 \bullet \sqrt{2} V \bullet \omega}{\pi Z} \sin(\theta_z - \alpha) e^{\alpha\delta} \left[\frac{e^{-\alpha\delta}\{\omega\delta \sin(k\alpha) + k\omega \cos(k\alpha)\}}{(\omega\delta)^2 + (k\omega)^2} \right.$$
$$\left. - \frac{e^{-\beta\delta}\{\omega\delta \sin(k\beta) + k\omega \cos(k\beta)\}}{(\omega\delta)^2 + (k\omega)^2} \right],$$

$$b_{k2} = \frac{2 \bullet \sqrt{2} V \bullet \omega}{\pi Z} \sin(\theta_z - \alpha) e^{\alpha\delta} \left[\frac{e^{-\beta\delta}\{-\omega\delta \cos(k\beta) + k\omega \sin(k\beta)\}}{(\omega\delta)^2 + (k\omega)^2} \right.$$
$$\left. - \frac{e^{-\alpha\delta}\{-\omega\delta \cos(k\alpha) + k\omega \sin(k\alpha)\}}{(\omega\delta)^2 + (k\omega)^2} \right].$$

Summing the first and second terms yields $a_k = a_{k1} + a_{k2}$ and $b_k = b_{k1} + b_{k2}$.

2.2.3 Incandescent Lamp Model

The resistance of an incandescent filament lamp is voltage dependent. Therefore, R_L is actually a function of lamp power. An empirical relationship between lamp voltage and power is shown in [20] to be

$$\frac{P_{out}}{P_{rated}} = \left(\frac{V_{lamp}}{V_{rated}} \right)^{1.6}, \qquad (2\text{-}12)$$

from which we obtain the resistance-power relationship

$$\frac{R_L}{R_{rated}} = \left(\frac{P_{out}}{P_{rated}} \right)^{0.25}. \qquad (2\text{-}13)$$

Figure 2-7 shows this empirical relationship along with the measured resistance of the test 120 V, 150 W incandescent lamp.

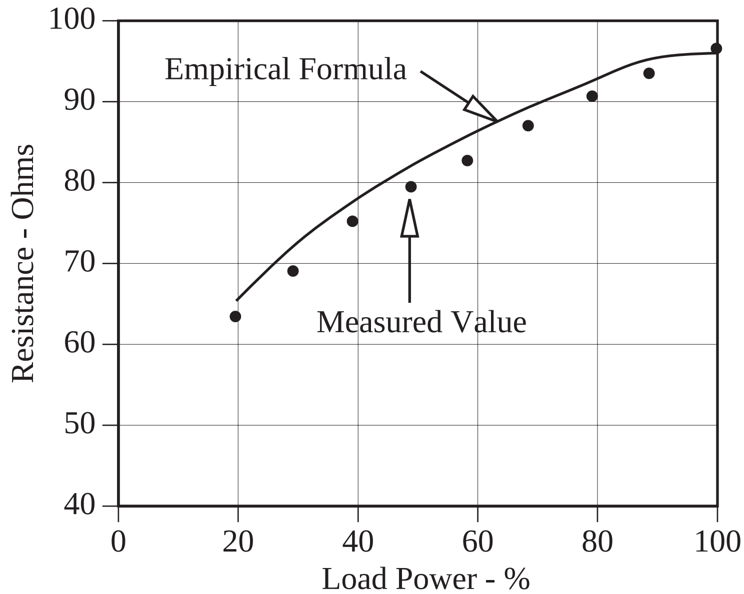

Figure 2-7
Power-Dependent Resistance of Incandescent Lamp (Note - the Solid Line Denotes Empirical Equation (2.13), and the Points Denote Measured Values)

2.2.4 Model Verification

The circuit equation along with the Fourier analysis were coded into a FORTRAN program TRIAC. A description of the program along with the listing of the input code is provided in the Appendix. The simulation results using the program TRIAC were verified with experimental results. Figure 2-8 shows experimental and simulated current waveform for a dimmer operating a 330 W incandescent lighting load at an output power level of 200 W. The experimental and the simulated THDI for this case were 55.6% and 54.3% respectively. For both the simulated and the measured case the time domain waveforms were reconstructed by using a cut-off frequency of 25th harmonic. This is the reason for the presence of high frequency component in the time domain waveforms.

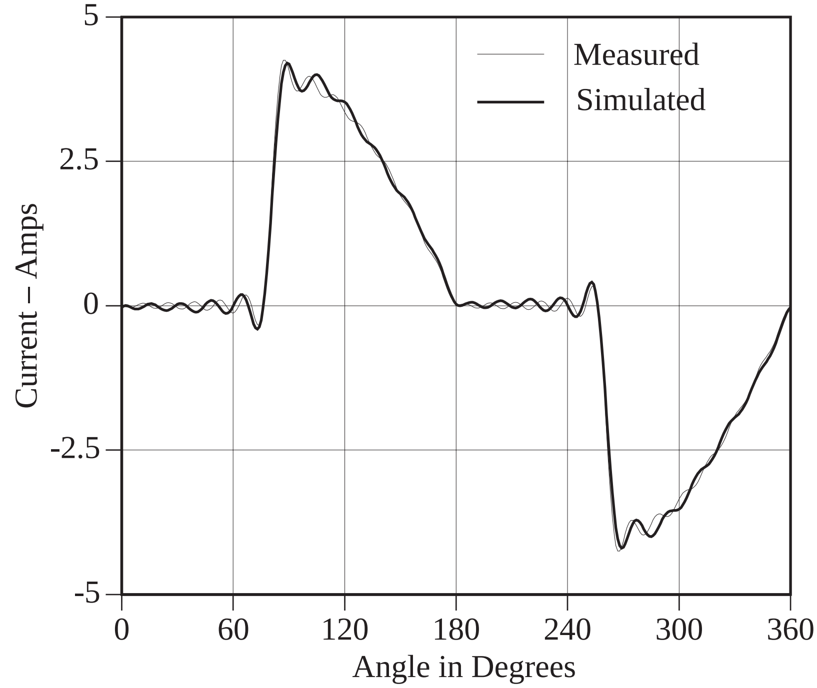

Figure 2-8
Verification of Light Dimmer Model

3
HARMONICS ATTENUATION AND DIVERSITY AMONG DISTRIBUTED LOADS

3.1 Harmonics Characteristics of Single-Phase Capacitor Filtered Diode Bridge Rectifier

In Chapter 2 the complete analytical model for calculating the harmonics of input current of a CFR was derived. The effect of system and load side parameter variation on input current spectrum will be investigated in this chapter using the model developed earlier. The system side parameters that will be studied in this parametric variation are system impedance Z, and X/R ratio of system impedance. The load side parameters are load power P and dc filter capacitor C.

The base case simulation was performed for a single-phase, 3 kW, 240 V ASD that operates over a 20-100% power range. The ASD has smoothing capacitor C = 4200 μF, (corresponding to approximately 6% ripple in dc voltage), Thevenin equivalent impedance $Z_{th} = R_{th} + jX_{th} = 5\ \% \angle 45^{o}$, and local line impedance $Z_l = R_l + jX_l = 3\% \angle 45^{o}$ (both impedances expressed on a base of 240 V, 5 kVA). System and load side parameters were varied from this nominal value to investigate their effect on input current spectrum.

3.1.1 Effect of X/R Ratio and DC Filter Capacitance

Figure 3-1 shows the effect of X/R ratio for total system impedance on input current waveshape of a CFR. As X/R ratio decreases, the pulse becomes shorter and more skewed to the left, whereas for increasing X/R ratio the pulse becomes wider and skewed to the right. Compared to the base case THDI of 74.6% for X/R = 1, the THDI for X/R = 0.1 was 96.0% and for X/R = 5.0 was 70.8%.

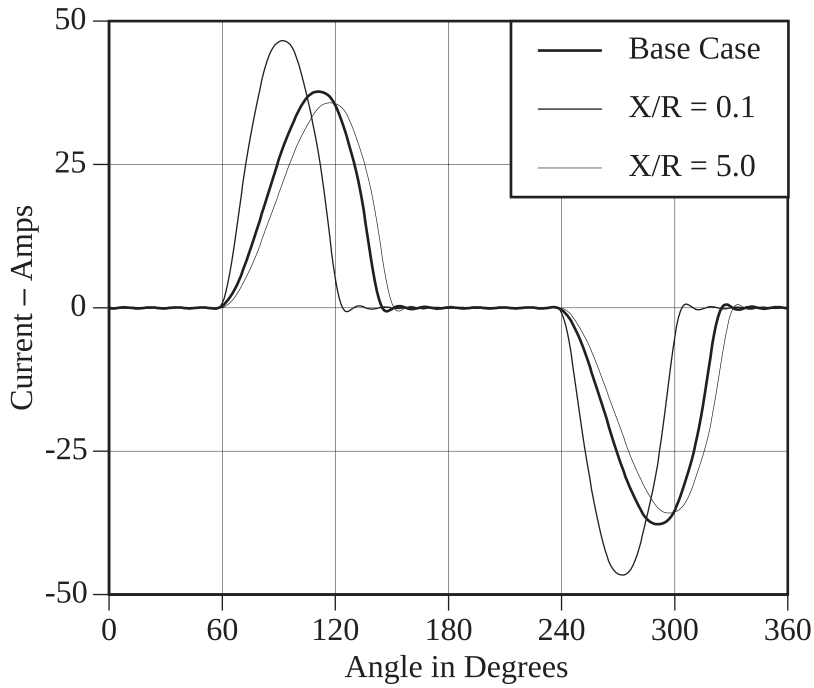

Figure 3-1
Input Current Waveshape for Variation in X/R Ratio

Figure 3-2 shows the current and DC voltage waveshape for the base case corresponding to 4200 μF capacitor and 2100 μF capacitor, respectively. The input current waveshape is essentially unchanged, and the ripple in the dc bus voltage for the 2100 μF case increased slightly. Therefore, variation in dc filter capacitance changes the ripple factor of the output voltage but has negligible effect on input current harmonics

3.1.2 Effect of System Impedance and Load Power

Figure 3-3 shows the current waveshape for the base case and for half power and half system impedance (4% Z) case. The corresponding Fourier spectra is shown in Figure 3-4. For both thecases the nominal THDI increased from 74.6% to 91.3% for half power and 92.4% for half Z case. Power P and impedance Z have similar effects on THDI – as P increases, THDI decreases, and as Z increases, THDI decreases.

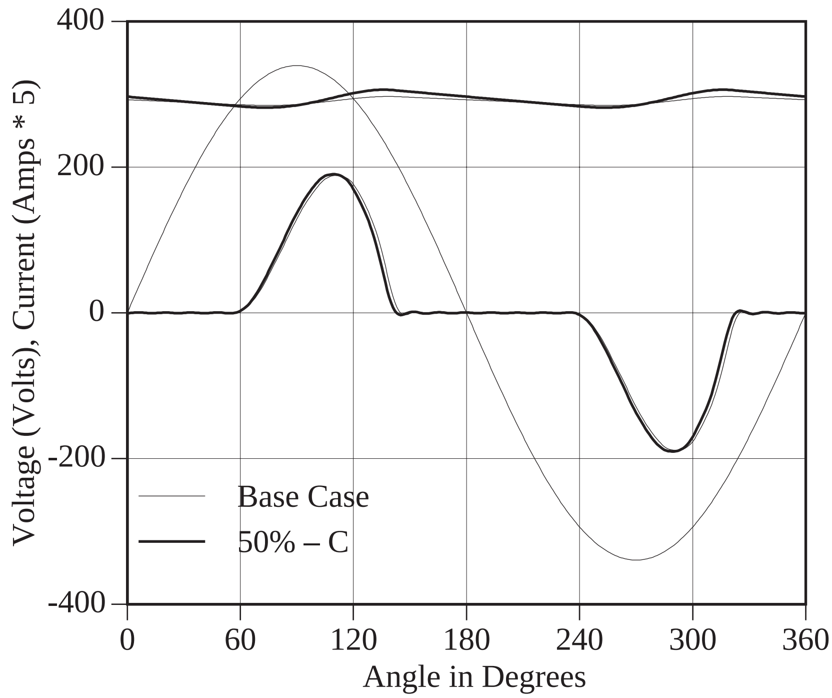

Figure 3-2
Input Current Waveshape for Variation in DC Filter Capacitor

The effect of power variation on current harmonics is given in Figures 3-5 and 3-6, where the variations in percent magnitudes and phase angles are plotted for the 20-100% power range. Note that as power increases, there is an attenuation effect on harmonic current magnitudes (in percent of fundamental), and a significant impact on phase angles, especially for higher-order harmonics. Similar variations occur with changes in system impedance magnitude and X/R ratio.

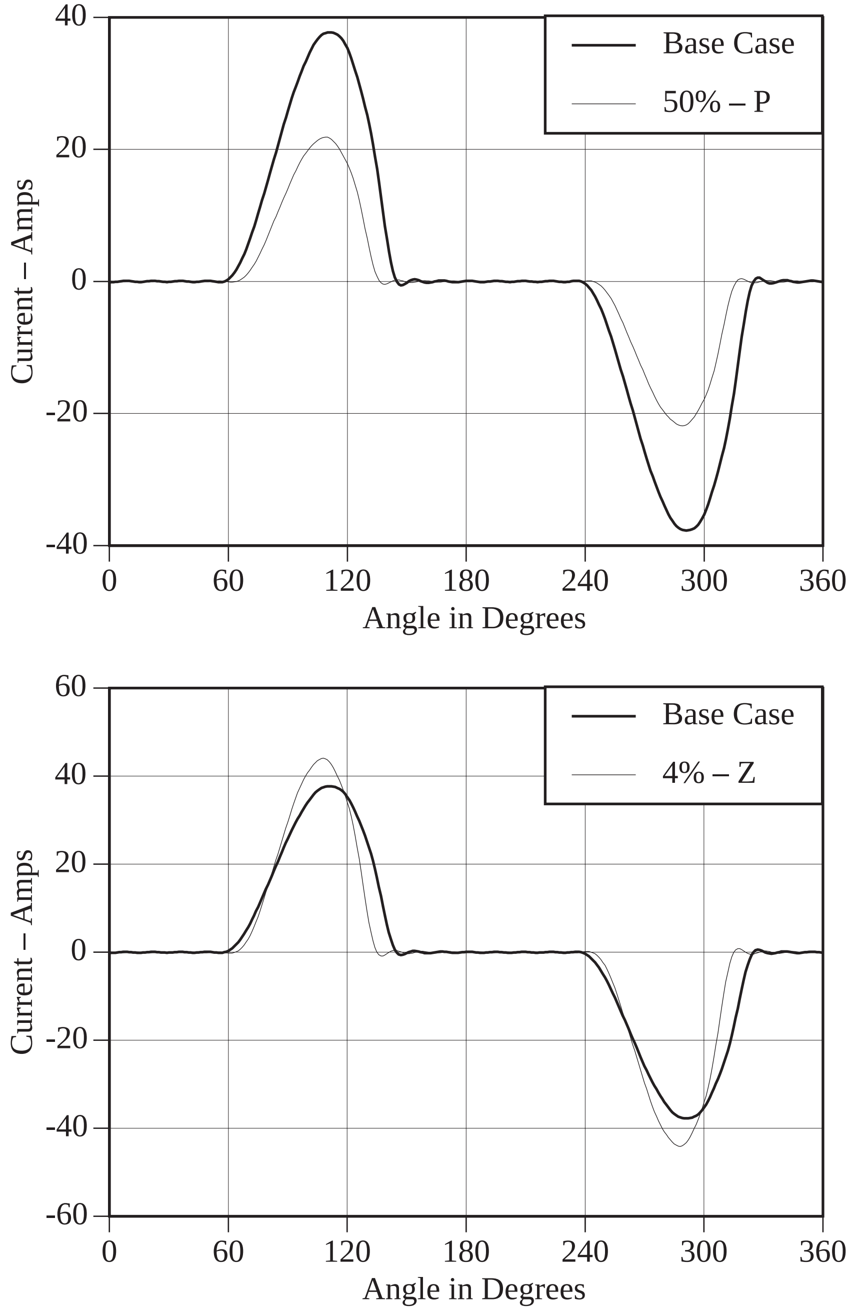

Figure 3-3
Input Current Waveshape for a) Half Power Case, b) Half System Impedance (4%) Case

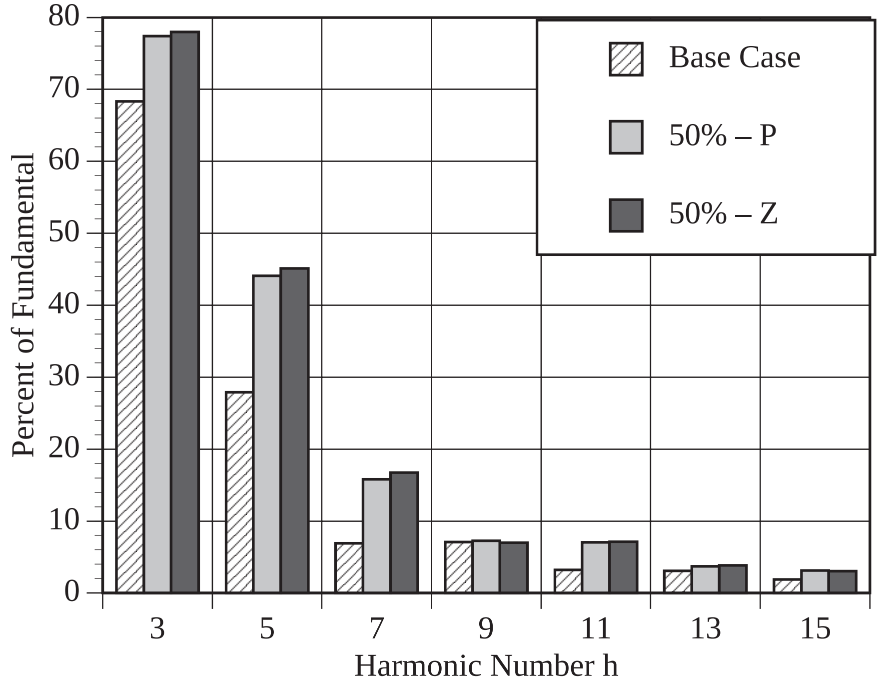

Figure 3-4
Individual Current Harmonics Spectrum of Waveshapes Corresponding to Figure 3-3

The magnitude reductions in Figure 3-5 imply that there will be an attenuation effect when a number of identical loads are served through a shared system impedance. The phase angle variations in Figure 3-6 make possible significant cancellation due to the circulation of harmonic currents among multiple loads with different power levels, especially for higher-order harmonics. If attenuation and cancellation are ignored, as in a simple application of fixed harmonic current injection, harmonics-related problems may be overestimated. This overestimation may be unimportant when studying the harmonics impact of one nonlinear load, but can be very significant for a group of loads. The significance of attenuation and cancellation are examined in the following sections.

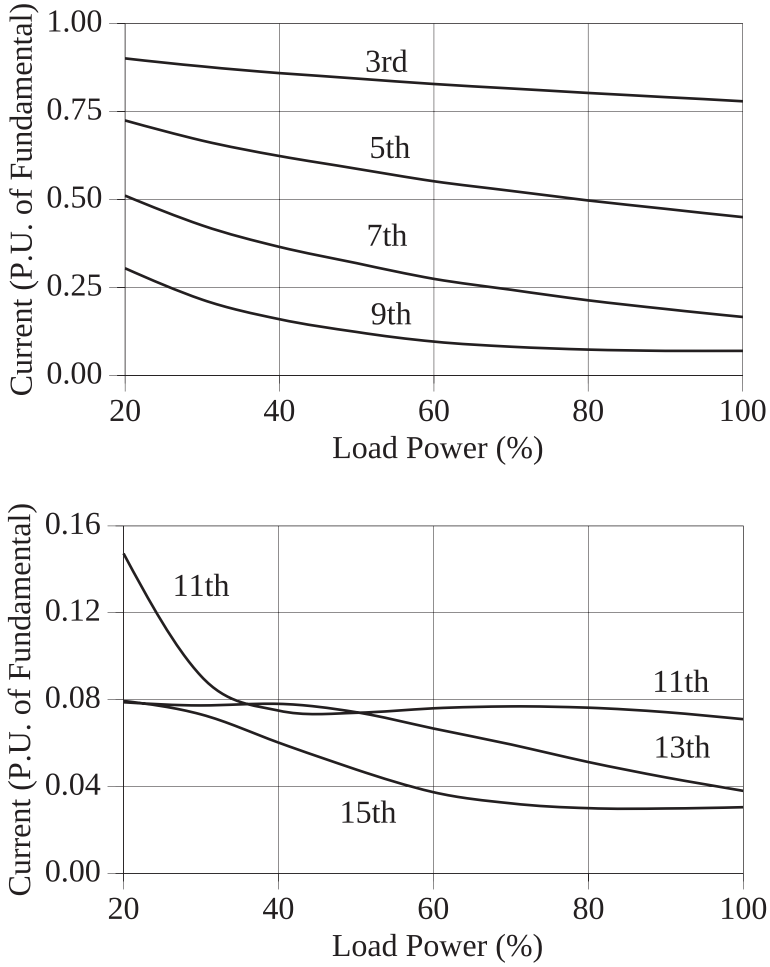

Figure 3-5
Variation of Harmonic Current Magnitudes (in P.U. of Fundamental) with Load Power

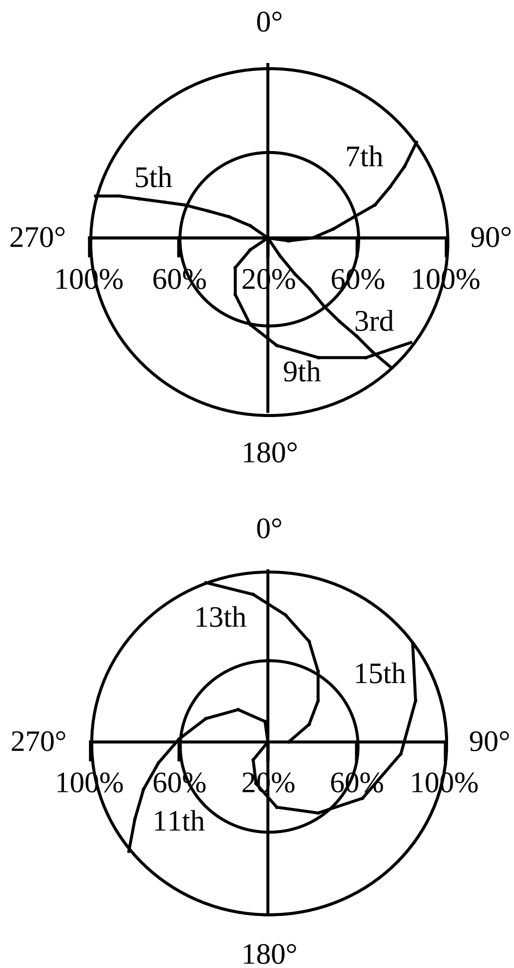

Figure 3-6
Variation of Harmonic Current Phase Angles with Load Power

3.2 Attenuation Due to Shared System Impedance

Consider the case shown in Figure 3-7 where N identical 100 W power electronic loads (for example, televisions or desktop computers with fixed power levels) share a common system impedance. Because of the magnitude variations in Figure 3-5, the harmonic content of total current i_s depends on N. In the method of fixed harmonic current injection, it is customary to assume a fixed spectrum for each load, independent of N, and to apply superposition. The potential error of this technique is examined by defining the following attenuation factor:

$$AF_h = \frac{I_h^N}{N \bullet I_h^1} , \qquad (3\text{-}1)$$

where

I_h^N = Resultant current for harmonic h for N units operating in parallel,

I_h^1 = Current for harmonic h when N = 1.

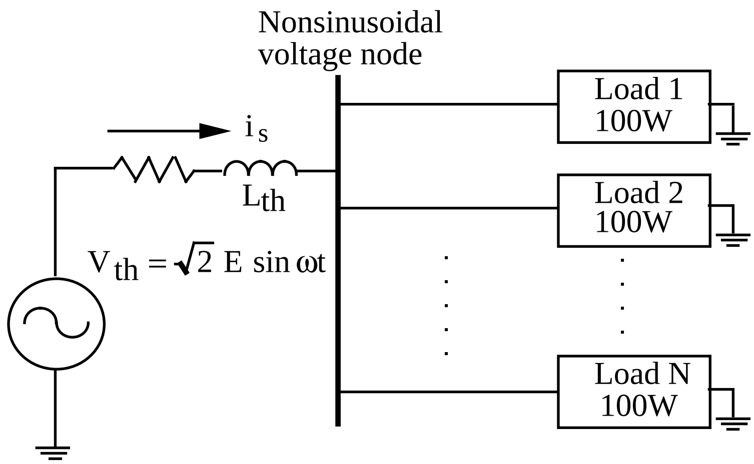

Figure 3-7
N Identical Units with a Shared Thevenin Equivalent System Impedance

Each unit in this study is rated 100 W, 120 V, and has a 370 μF smoothing capacitor. The equivalent system impedance of the shared bus is chosen to be (0.4 + j0.25) Ω, which is representative of a 120 V network. The attenuation factors with 5, 10, and 15 loads operating in parallel are shown in Figure 3-8. Note that, in general, the attenuation (which varies inversely with the attenuation factor, see Eq 3-1) due to a shared system impedance is more pronounced for higher-order harmonics, and tends to increase with N.

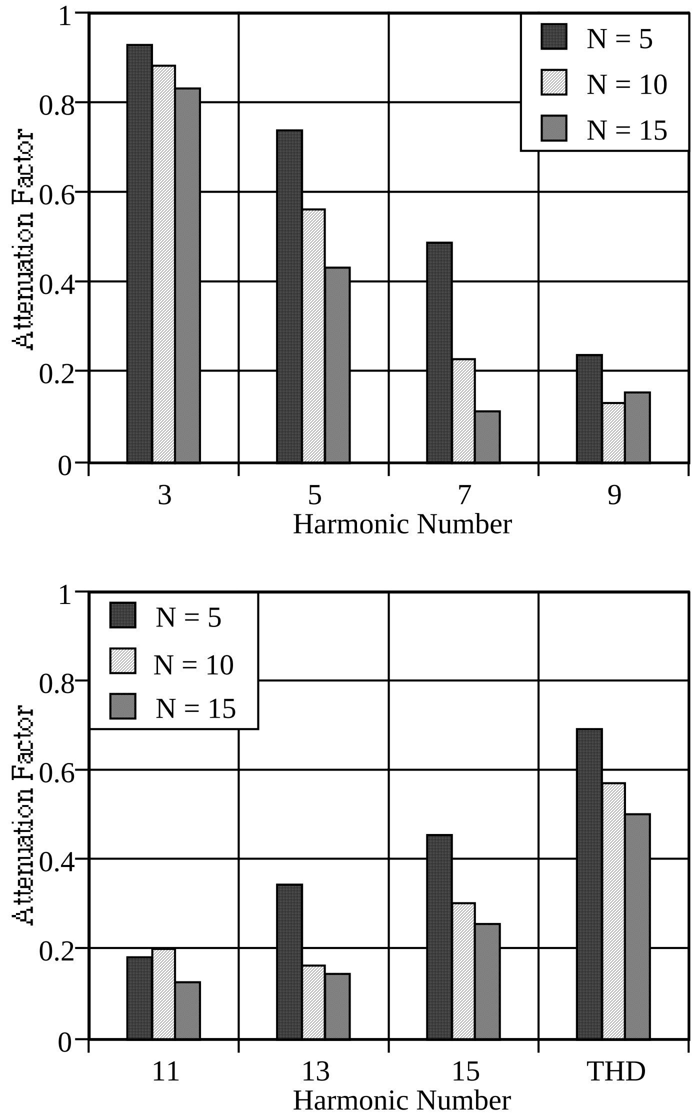

Figure 3-8
Attenuation Factors for Harmonic Currents due to Shared System Impedance

3.3 Diversity Due to Phase Angle Variation

Phase angle dispersion of individual current harmonics, as illustrated in Figure 3-6, occurs mainly due to the following three types of variations: 1) power level, 2) line impedance magnitude, and 3) line impedance X/R ratio. In order to asses the impact of each of these on the cumulative harmonic currents produced by N nonlinear loads, Monte Carlo simulations are performed. The loads are connected in parallel to a common "stiff" bus, as shown in Figure 3-9. Each load is rated 240 V, 3 kW.

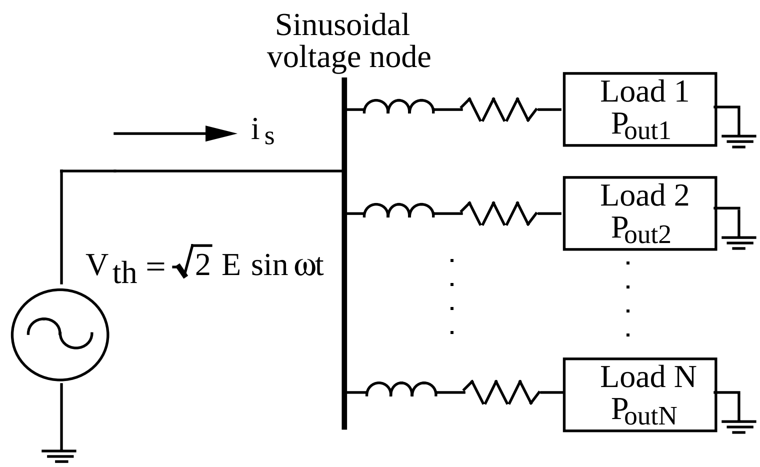

Figure 3-9
N Identical Parallel Loads Sharing a Common "Stiff" Bus

A current harmonic diversity factor is used to quantify the effect of phase angle dispersion on total current i_s. This factor as defined in [21, 22] is,

$$DF_h = \left| \frac{\text{Phasor sum of currents of harmonic h}}{\text{Arithmetic sum of current magnitudes of harmonic h}} \right|$$

$$= \left| \sum_{i=1}^{N} I_h^i \right| \Big/ \sum_{i=1}^{N} \left| I_h^i \right| \quad , \tag{3-2}$$

where

$I_h^i = \left| I_h^i \right| \angle \theta_h^i$ = Harmonic current of order h injected by the i_{th} load (of N loads).

The diversity factor ranges between 0 and 1. A small value implies a significant amount of cancellation due to the circulation of harmonic currents among individual loads.

3.3.1 Power Variation

The effect of power variation is studied by randomly varying the power level of individual loads while holding their impedances at 8% @ 45^o (on a 5 kVA, 240 V base), and their smoothing capacitors at 4200 μF. The power levels are uniformly distributed over a 20% - 100% range. For a given number of loads, ranging from N = 5 to 60, a 300-shot Monte Carlo simulation is performed. For each simulation, the mean harmonic current diversity factors using (3.2) is computed. The results are shown in Figure 3-10, where it is seen that the diversity factors quickly approach asymptotes as N increases.

Corresponding plots of the standard deviations for the N = 10 and N = 60 experiments are given in Figure 3-11. As the harmonic number increases, the standard deviation increases, implying a greater variability in the mean harmonic diversity factors. Furthermore, as the number of loads increases, the standard deviations decrease, and eventually approach zero for very large N.

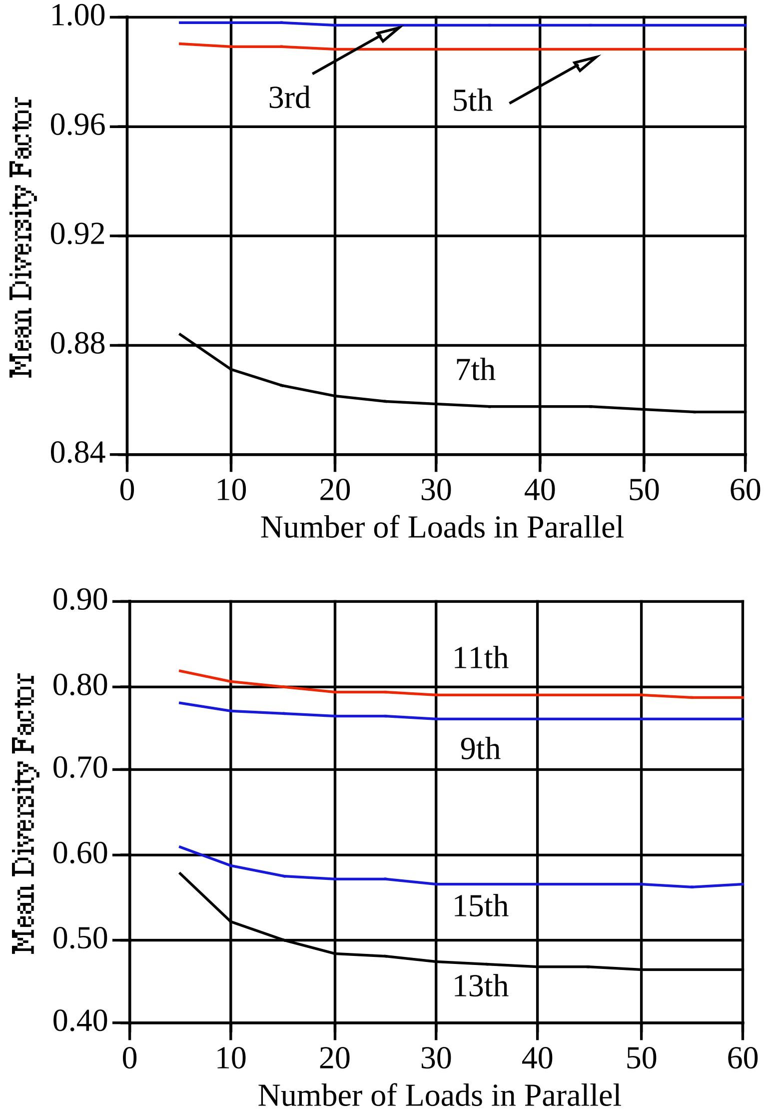

Figure 3-10
Means of Harmonic Current Diversity Factors Versus Number of Loads

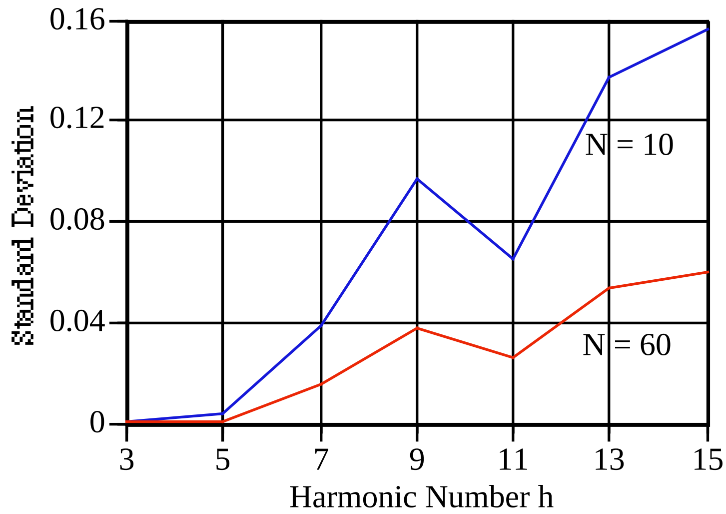

Figure 3-11
Standard Deviations of Harmonic Current Diversity Factors for N= 10 and N = 60 Loads

3.3.2. Impedance Magnitude, X/R Ratio, Capacitor, and Composite Variations

In a similar fashion, the impedance magnitude, X/R ratio, and capacitance is varied individually, and the effect on mean harmonic current diversity factors for large N (i.e., $N \geq 60$) is observed. Nominal values of P, Z, X/R, and C are chosen as 3.0 kW, 8% (on a 5 kVA, 240 V base), 1.0, and 4200 μF, respectively. The ranges of variation are as follows: impedance magnitude, 2 - 10%; X/R ratio, 0.1 - 5.0; capacitance, 1000 - 10000 μF.

The simulation results are shown in Table 3-1, along with the power variation asymptotes from Figure 3-10. Z variation has the greatest effect on diversity factor, X/R yields similar results to P, and C variation has little effect. In general, diversity factor decreases with harmonic order.

All four parameters were also simultaneously varied with uniform distribution assumption within their respective ranges given above. The diversity factors for this composite variation are also given in Table 3-1.

Table 3-1
Asymptotes of Mean Harmonic Current Diversity Factors due to Individual and Combined Variations of Circuit Parameters (Power P, Impedance Magnitude Z, Impedance X/R Ratio, Smoothing Capacitor C).

Harmonic Number h	DF_h Due to P	DF_h Due to Z	DF_h Due to X/R	DF_h Due to C	DF_h Due to Composite P,Z,X/R,C
3	1.00	0.99	0.97	1.00	0.97
5	0.99	0.96	0.89	0.99	0.90
7	0.86	0.57	0.69	0.96	0.59
9	0.76	0.57	0.84	0.97	0.18
11	0.79	0.39	0.59	0.93	0.31
13	0.46	0.11	0.78	0.95	0.12
15	0.56	0.08	0.62	0.90	0.05

3.4 Harmonic Current Characteristics of Thyristor Controlled Loads

The circuit model, solution procedure, Fourier expressions, and lamp resistance model developed in Chapter 2 will be employed to investigate the effect of power variation on the ac current harmonics produced by a thyristor-controlled 120 V, 150 W lamp.

Figures 3-12 and 3-13 show the effect that 20-100% power variation has on harmonic current magnitudes and phase angles. The solid lines are spline curve-fits through the simulated results, which were obtained from measured bulb resistances. Discrete points in the figures denote measured harmonic values. Note in Figure 3-12 that the harmonic current injection, expressed in p.u. of rated current, is approximately constant throughout the power range because of the partially offsetting effects of increasing THD_I, and decreasing fundamental current, as lamp power decreases.

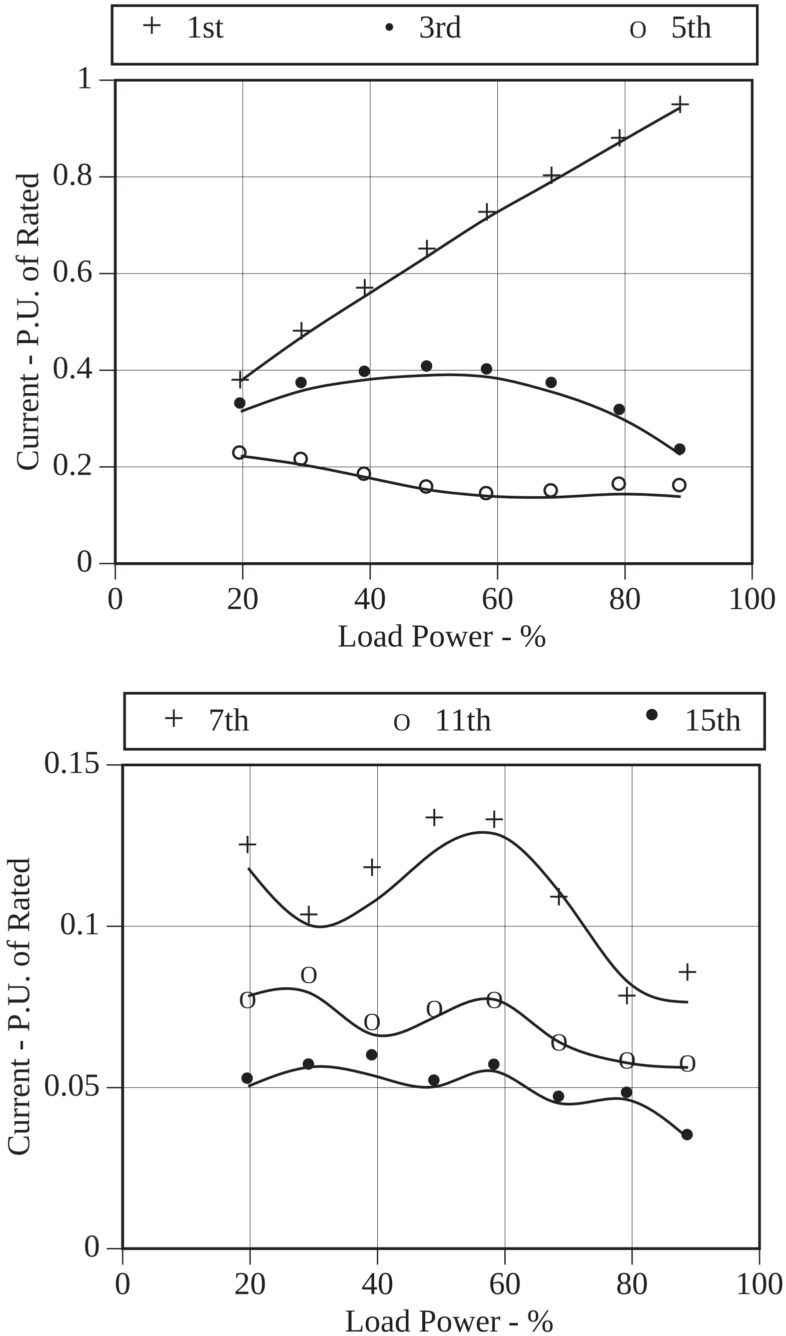

Figure 3-12
Variation of Harmonic Current Magnitudes (in p.u. of Rated Current) with Load Power

The phase angle variations in Figure 3-13 make possible significant cancellation due to the circulation of harmonic currents among multiple loads at different power levels. Note that the phase dispersion becomes more pronounced as the harmonic order increases. The effect of phase angle variation on the cumulative harmonic currents is examined in the following section.

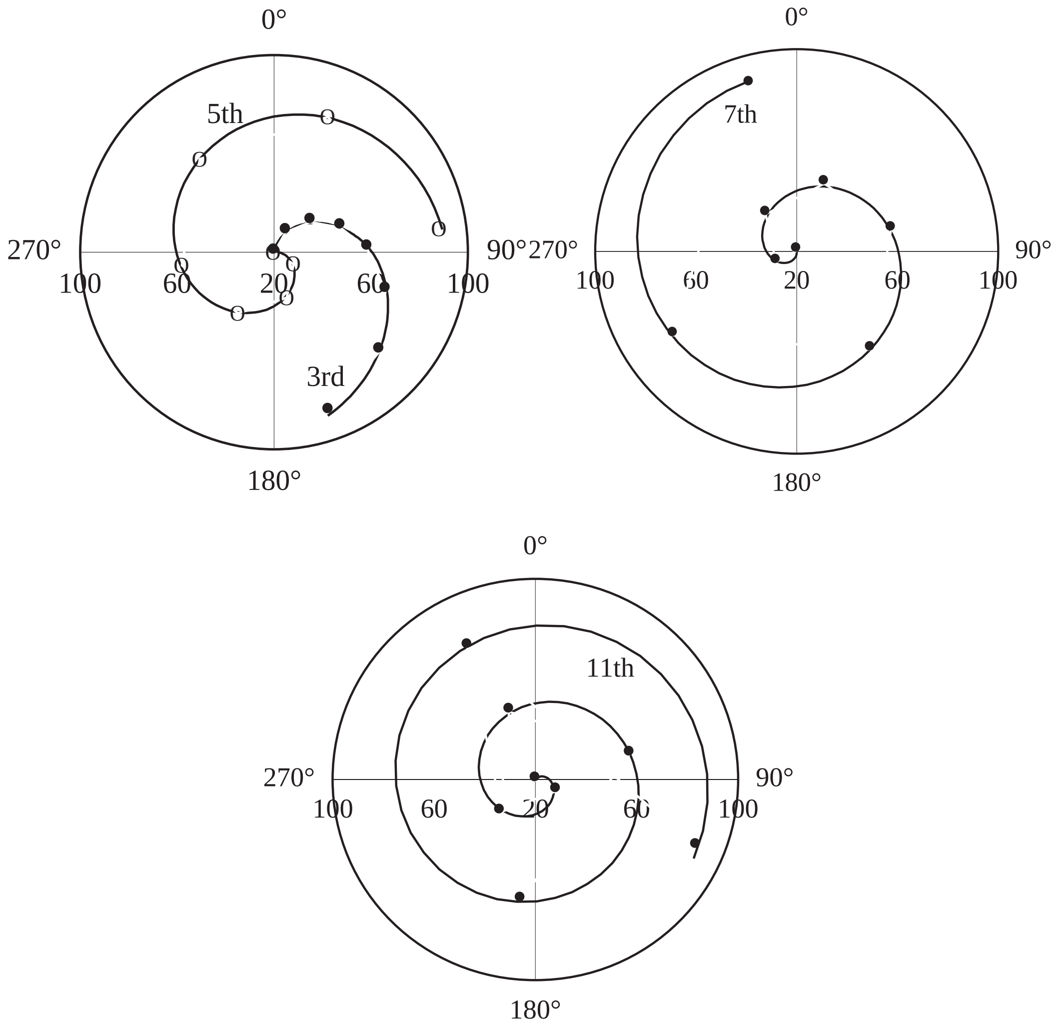

Figure 3-13
Variation of Harmonic Current Phase Angles with Load Power

3.4.1 Diversity Due to Phase Angle Variation

In order to quantify the effect of phase angle dispersion on cumulative current i_s, the current harmonic diversity factor defined in Equation 3-2 is employed. The method described in the previous section is used to calculate the diversity factors for individual harmonic currents due to random variation in firing angle. The 120 V, 150 W incandescent lamp with thyristor controller is selected as the representative load type for this simulation study, where it is assumed that large numbers of these loads are operating in parallel. The random firing angles among the loads are generated assuming a uniform distribution of lumen level in the 20-100% range. The corresponding output power for each randomly-generated p.u. lumen level is computed from the empirical relationship from [20], which is

$$\frac{LU_{lamp}}{LU_{rated}} = \left(\frac{V_{lamp}}{V_{rated}}\right)^{3.4} .$$

Combining with equation 2.12 yields

$$\frac{LU_{lamp}}{LU_{rated}} = \left(\frac{P_{out}}{P_{rated}}\right)^{2.125} . \tag{3-3}$$

The diversity factors of individual harmonic currents for different lumen window widths are shown in Figure 3-14, where, for example, a 20% window width corresponds to a random variation of lumen level over an 80-100% range. Note as the window width increases, the diversity factors decrease because there is more dispersion in phase angles. This effect is more pronounced for lower-order harmonics (i.e., 3rd, 5th, and 7th). The oscillations in diversity factors for the higher-order harmonics are due to the fact that their phase angles may make several rotations of 360^{o} (see Figure 3-13).

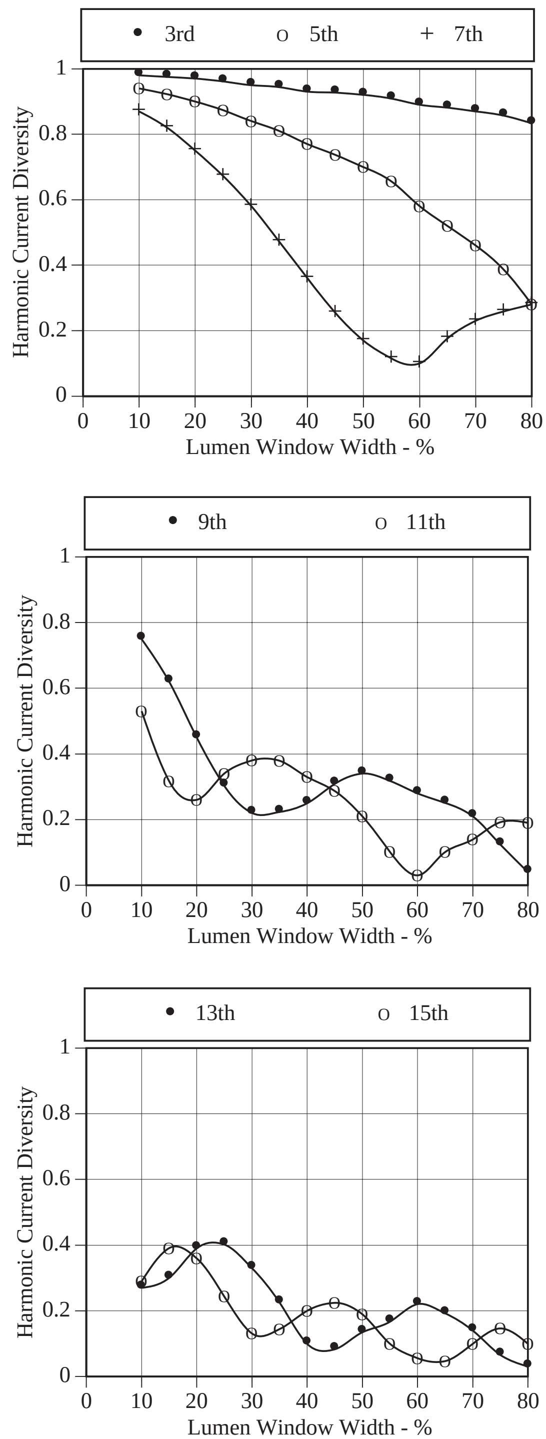

Figure 3-14
Variation of Diversity Factors with Lumen Window Width

3.4.2 Diversity Adjusted Current Injection

From Figure 3-12 it can be noticed that the harmonic current injection, in p.u. of rated current, is almost independent of the firing angle. Moreover, by averaging the diversity factors over the entire 10-80% lumen window width range, representative values for individual harmonics can be determined. Table 3-2 shows the current magnitudes (p.u. Amperes), average diversity factors, and the products of these two numbers for individual harmonics. This product is classified as diversity-adjusted current injection, and it represents the fixed harmonic current injection levels that take into account the randomness of phase angle dispersion in these types of loads.

Figure 3-15 shows that the harmonic current magnitudes can be accurately represented using a $\frac{3}{h^2}$ approximation, in p.u. Amperes, where the base current equals the rated total load current. For example, if we have a large number of 120 V thyristor-controlled lamps, whose total rated power is 10 kW, the base current is 83.3 A, and the diversity-adjusted current injection magnitude for the 11th harmonic, using $\frac{3}{h^2}$, is 2.07 A.

Table 3-2
Average Harmonic Current Magnitudes, Average Diversity Factors, and Diversity-Adjusted Current Injection Magnitudes

Harmonic number h	Average Current Injection (Amperes, p.u. of rated)	Average Current Diversity D_h	Diversity-Adjusted Current Injection (Amperes, p.u. of rated)
3	0.35	0.92	0.32
5	0.17	0.69	0.12
7	0.11	0.41	0.05
9	0.09	0.31	0.03
11	0.07	0.25	0.02
13	0.06	0.20	0.01
15	0.05	0.18	0.01

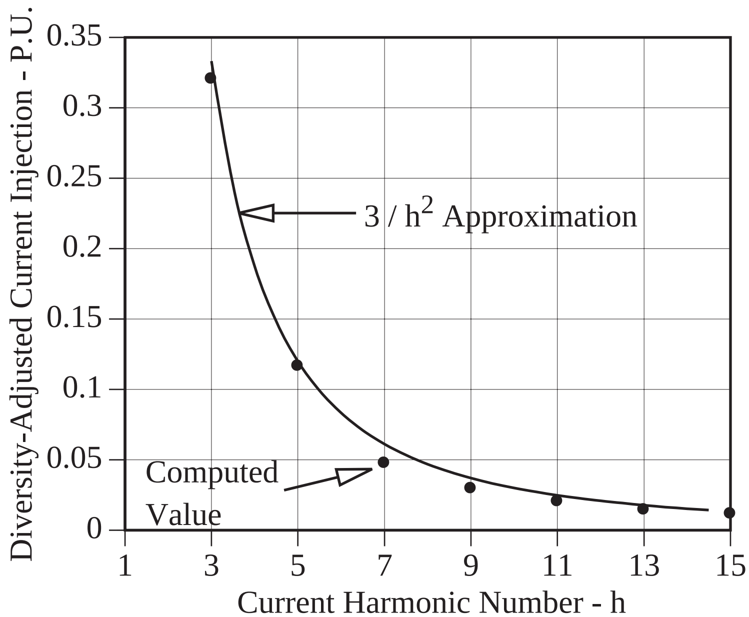

Figure 3-15

Approximation of Diversity-Adjusted Harmonic Current Injection Magnitudes using $\frac{3}{h^2}$

4
EFFECT OF SUPPLY VOLTAGE HARMONICS

4.1 Effect of Supply Voltage Distortion on the Input Current of Capacitor Filtered Rectifier

The fixed harmonic current injection method is based on the assumption that current harmonics are independent of supply voltage distortion. This is accurate *only* when the supply voltage waveform is reasonably sinusoidal. However, computer simulation results in [23] show that distribution feeder THDVs may reach 10% when the ASD heat pump penetration rate is 10%. Therefore, in order to accurately predict future voltage distortion levels, it is necessary to investigate the effect that supply voltage distortion will have on the harmonic currents produced by these loads.

In this Chapter, the equations developed in Chapter 2 for calculating the input current harmonics of capacitor filtered rectifiers will be used to investigate the effect that supply voltage harmonic magnitudes *and* phase angles have on its THDI. The solution technique for nonsinusoidal excitation will be applied to the base case ASD load model described in the previous Chapter.

Figure 4-1 shows the supply voltage and input current waveshapes for 10% 3rd voltage harmonic for both peaking and flattened cases. For the peaking case, the peaks of the fundamental and harmonics coincide. For the flattened case, the negative peak of the harmonic coincides with the positive fundamental peak. It can be seen in Figure 4-1 that for equal power levels, a peaking voltage wave yields a narrower current pulse than does a flattened voltage wave. The THDIs of the current waveforms are 88% and 55%, respectively. This signifies that the input current harmonics are dependent on the phase shift of supply voltage harmonics as well as their magnitudes.

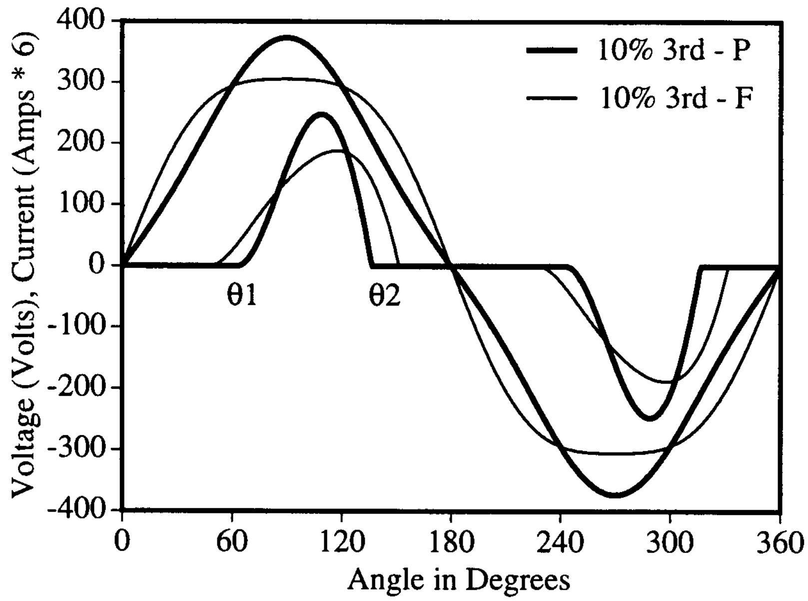

Figure 4-1
Voltage and Current Waveforms using 10% Peaking (P) and Flattened (F) 3rd Harmonic Voltages

Figure 4-2 shows the corresponding harmonic spectra of the current waveforms. The flattened supply voltage waveform significantly lowers the 3rd and 5th current harmonic magnitudes, which together account for most of the THDI reduction.

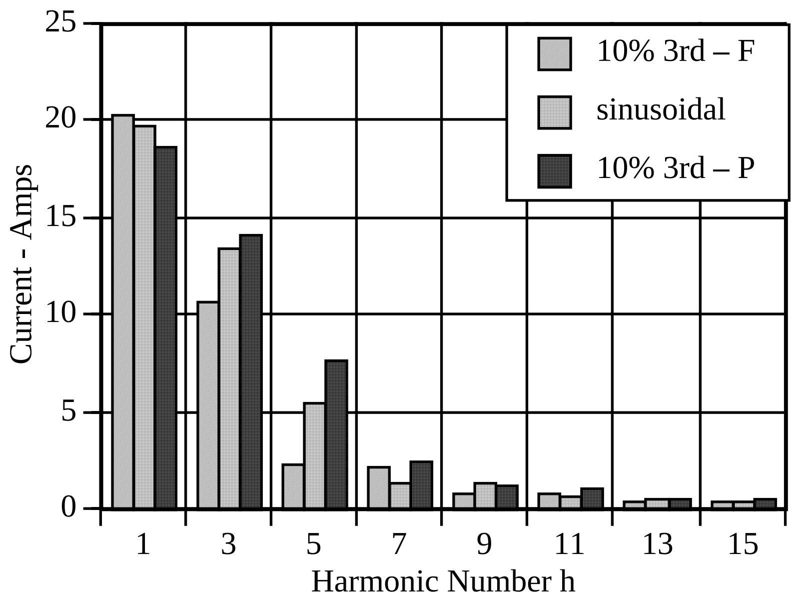

Figure 4-2
Effect of 3rd Harmonic Voltage on Individual Current Harmonics (P Signifies Peaking, F Signifies Flattened)

4.1.1 Effect of Voltage Harmonic Phase Angle on THDI

Depending on the relative phase angle of individual voltage harmonics, the combined supply voltage waveform for the same THDV may have flattened or peaked shape as can be seen from Figure 4-1. Since in bridge rectifiers, diode conduction begin when the dc bus voltage crosses the supply voltage as shown in Figure 4-2, a flat voltage waveform will cause conduction to begin earlier and consequently the current pulseshape will be broadened and THDI will decrease.

This phenomenon is illustrated in Figure 4-3, which shows the effect that phase shift of individual voltage harmonics has on THDI. An angle of 0^o in the figure corresponds to a peaking wave (i.e., fundamental and harmonic peaks are coincident), and 180^o corresponds to a flattened wave. The following three cases are considered: 10% 3rd, 10% 5th, and 10% 7th voltage harmonic. It is seen in the figure that the peaking cases gives good estimates of peak THDI, and the flattened cases gives a good estimates of the minimum THDI, Therefore, peaking and flattened supply voltage waves bound the possible THDI.

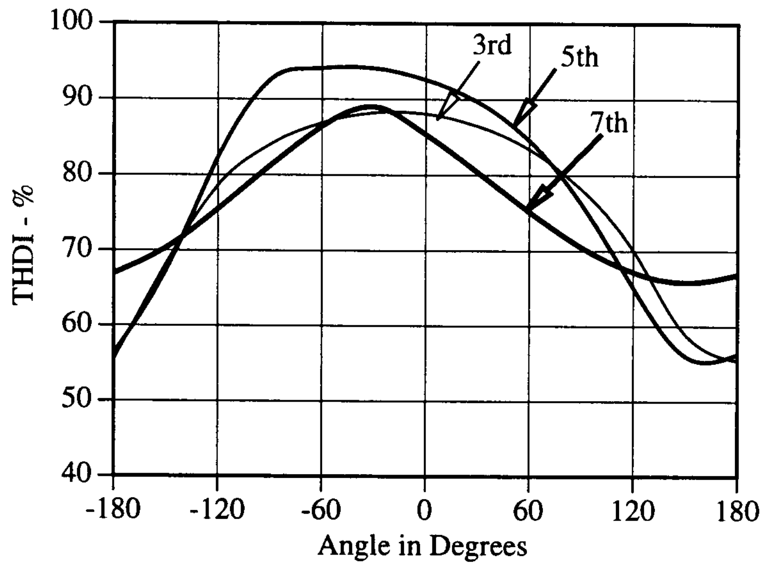

Figure 4-3
Effect of Voltage Harmonic Phase Angle on Current THD (Note – 0° Corresponds to a Peaking Voltage Waveform, 180° Corresponds to a Flattened Voltage Waveform)

Figure 4-4 shows the effect of individual supply voltage harmonics (both peaking and flattened) on THDI for full power (3 kW) and half power (1.5 kW) cases. These curves are plotted for odd harmonics through the 13th, with two possible phase shifts (peaking and flattened) and for 5% and 10% harmonic magnitudes. For both the cases it can be observed that voltage harmonics above the 9th order have very little effect on THDI. However, for lower-order harmonics, the difference between THDI for sinusoidal and nonsinusoidal voltage is very significant. This effect is more prominent for the half power case. It is obvious in this figure that peaking supply voltage increases THDI, and flattened supply voltage decreases THDI.

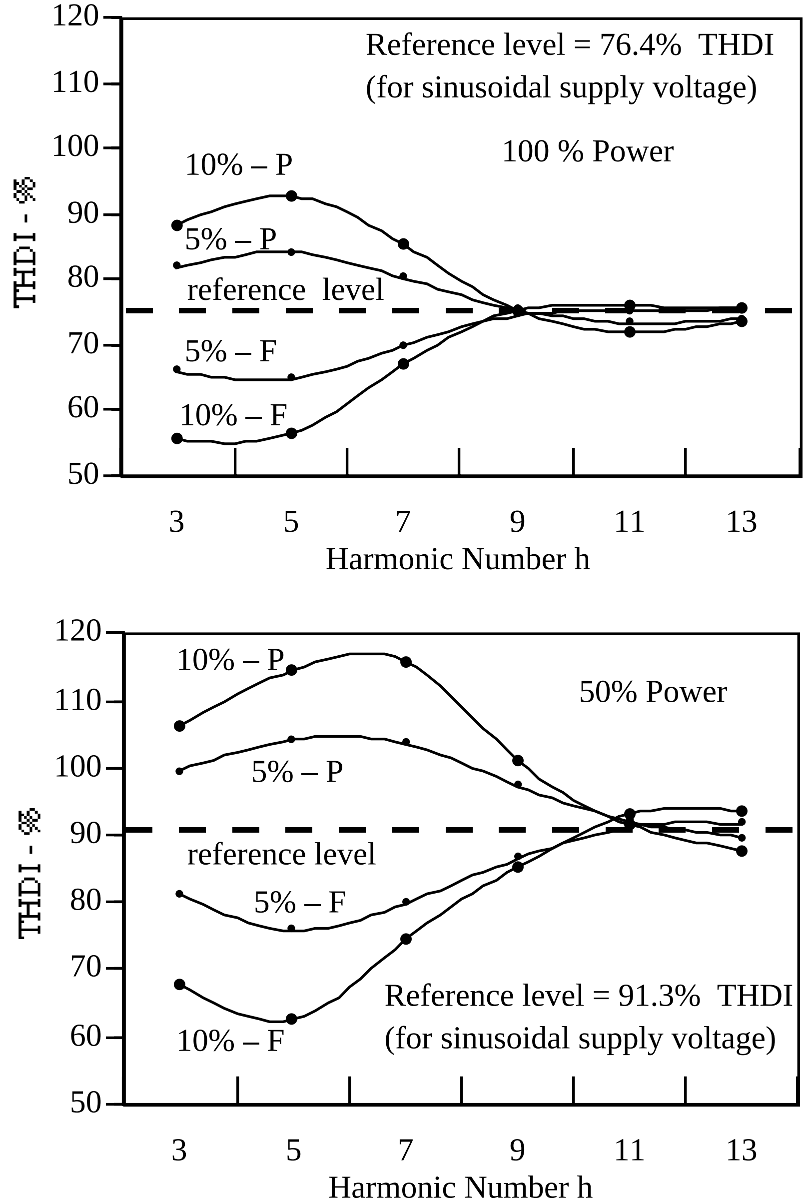

Figure 4-4
Effect of Individual Voltage Harmonics on THDI

4.2 Use of Voltage Crest Factor to Predict Current Distortion

It is obvious in Figure 4-4 that because THDV lacks the phase angle information that differentiates a peaking wave from a flattened wave, it cannot be used to predict THDI. The same THDV can either increase or decrease THDI, depending on the harmonic voltage phase angles. On the other hand, voltage crest factor, which is defined as the ratio of the peak value of a voltage wave to its rms value, does give some quantitative measure of how peaking or flattened the supply voltage waveform actually is. By conducting thousands of simulations with the analytical model, it was determined that THDI is strongly correlated with the supply voltage crest factor, and an empirical relationship between the two was developed.

To illustrate this relationship, consider the scatter plots shown in Figure 4-5, where each point represents one solution of the analytical model for the ASD heat pump example. For each of nine combinations of power and X/R ratio (P = 20%, 60%, 100%), (X/R = 0.1, 0.5, 2.0), 100 values of THDV are randomly assigned, using a uniform distribution over the 0 – 10% range, while including voltage harmonics 3, 5, and 7. Results for five of the nine combinations are shown in the figure. In this figure THDI is plotted against normalized supply voltage crest factor, $V_{\text{crest}}^{\text{norm}}$, which is the ratio of the actual crest factor to the crest factor of a sinusoid $\left(\text{i.e. } \sqrt{2}\right)$.

From the Figure 4-5 it can be see that THDI varies linearly with normalized voltage crest factor for a fixed P and X/R ratio. Furthermore, from the manner in which the slope and intercept of the nine straight-line approximations vary, it is logical to hypothesize that THDI can be expressed as

$$\text{THDI} = \text{m} \bullet V_{\text{crest}}^{\text{norm}} + \text{b} \quad , \qquad (4\text{-}1)$$

where

$$\text{Slope m} = f_1(\text{P, X / R}) \quad ,$$

$$\left.\frac{\partial \text{m}}{\partial \text{P}}\right|_{\text{Const. X/R}} < 0, \text{ and } \left.\frac{\partial \text{m}}{\partial \text{X / R}}\right|_{\text{Const. P}} < 0 \, ,$$

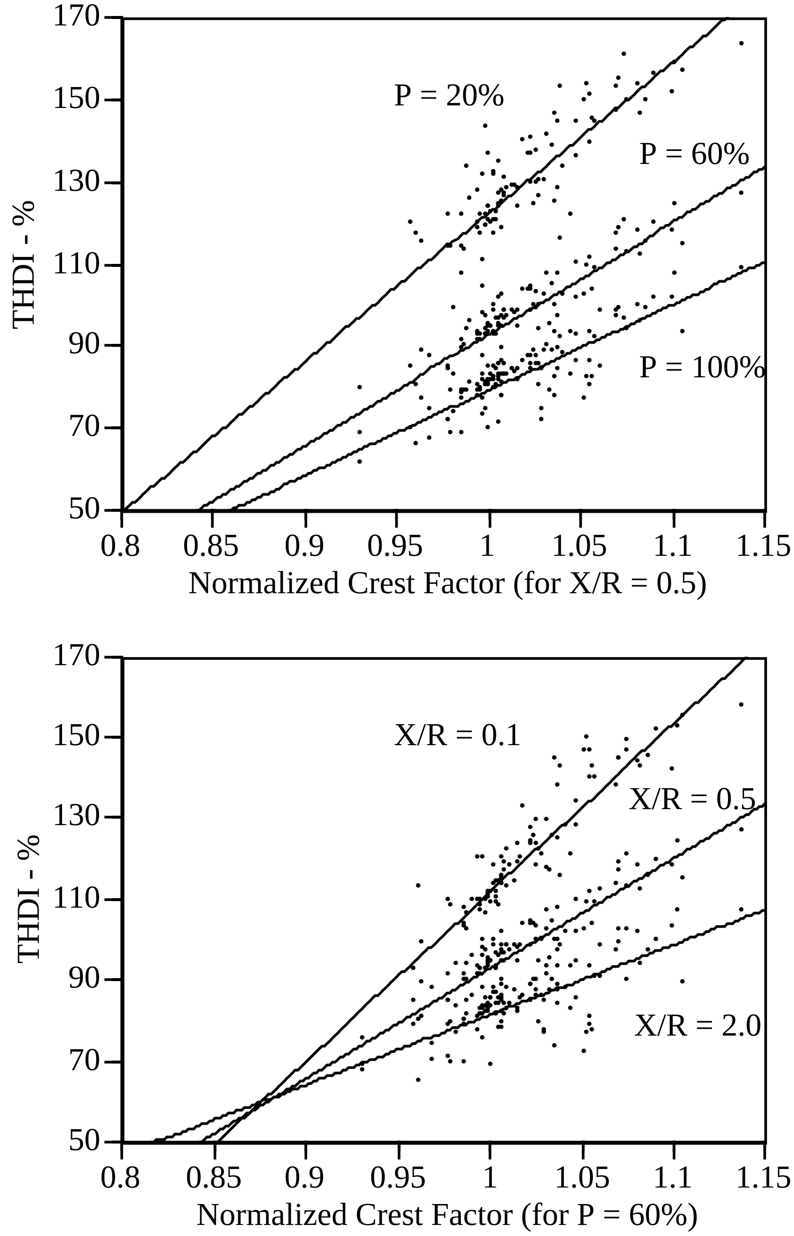

Figure 4-5
Variation of THDI with Supply Voltage Crest Factor

and

$$\text{Intercept b} = f_2(\text{P}, \text{X}/\text{R}) \ ,$$

$$\left.\frac{\partial b}{\partial P}\right|_{\text{Const. X/R}} > 0, \text{ and } \left.\frac{\partial b}{\partial X/R}\right|_{\text{Const. P}} > 0 \ .$$

The slope(m) and intercept(b) values for the nine combinations are given in Table 4-1 and Table 4-2. By plotting the values of slope m and intercept b in Figure 4.6 , it is observed that they appear to be logarithmic functions of the product of P and X/R. Next, if by using the ratio of P / P_{SC} instead of actual power P, where P_{SC} is the short circuit power capability at the point of common coupling, the magnitude of the system impedance can be in the empirical formula, whose final form becomes

$$THDI = C_1 \bullet \log_{10}\left(\frac{P_{SC}}{P \bullet X/R}\right) \bullet V_{crest}^{norm} + C_2 \bullet \log_{10}\left(\frac{P_{SC}}{P \bullet X/R}\right) + C_3 \qquad (4\text{-}2)$$

Table 4-1
Slope (m) for Nine Combinations of Power and X/R Ratio

X/R	P = 3000 W	P = 1800 W	P = 600 W
2.0	122.5	172.4	298.6
0.5	207.8	271.2	364.3
0.1	350.0	415.4	479.2

Table 4-2
Intercept (b) for Nine Combinations of Power and X/R Ratio

X/R	P = 3000 W	P = 1800 W	P = 600 W
2.0	-52.8	-90.9	-189.6
0.5	-128.3	-178.3	-241.6
0.1	-255.1	-303.6	-330.23

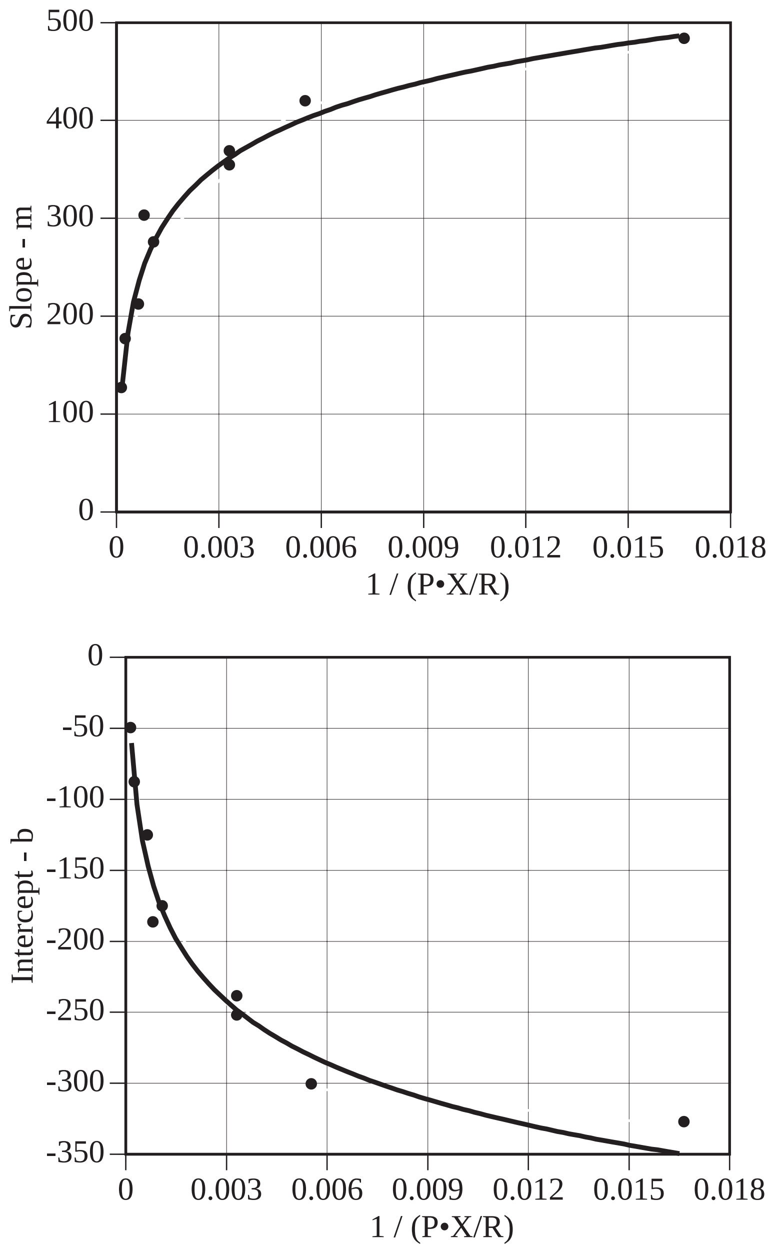

Figure 4-6
Slopes (m) and Intercepts (b) Versus $(P \circ X / R)^{-1}$ for the Straight-Line Approximations

Coefficients C_1, C_2, and C_3 are calculated using regression analysis on several thousand data points obtained by randomly varying P/P_{SC}, X/R, and THDV, which yielded $C_1 = 159.0$, $C_2 = -116.0$, and $C_3 = 23.0$. The accuracy of the empirical equation for 2000 additional random samples is given in Figure 4-7, where it is seen that the empirical equation predicts 70% of the samples within ±10% accuracy (normalized with respect to the model-predicted THDI).

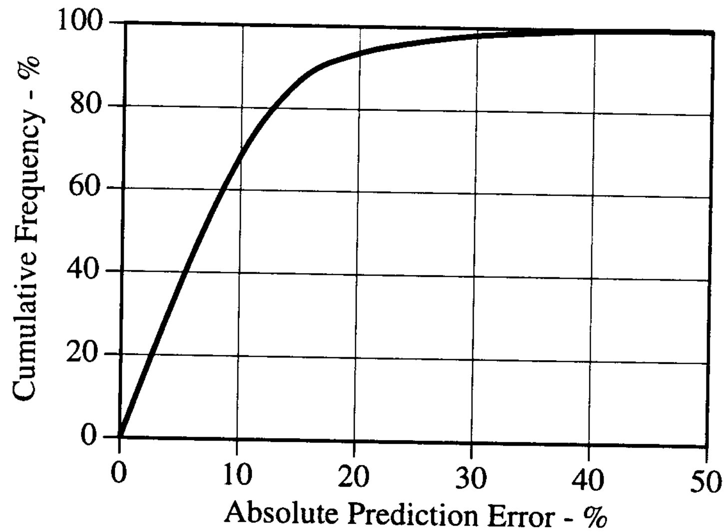

Figure 4-7
THDI Absolute Prediction Errors for 2000 Random Samples

4.3 Self-Compensation Effect of Nonlinear Load Current

So far, it has been observed that the phase angle of supply voltage harmonics can increase or decrease THDI of a capacitor filtered, diode bridge rectifier load. A peaked voltage wave tends to narrow the current pulse and increase THDI, whereas a flattened wave broadens the current pulse and reduces THDI. However, it will be shown that the voltage distortion created by these loads tends to flatten the supply voltage waveform, thereby decreasing THDI.

Consider the case shown in Figure 4-8 where N identical 100 W power electronic loads (for example, televisions or desktop computers with fixed power levels) share a common system impedance. Each unit in this study is rated 100 W, 120 V, and has a 370 µF smoothing capacitor. The equivalent system impedance of the shared bus is chosen to be (0.4 + j0.25) Ω, which is representative of a 120 V network [24].

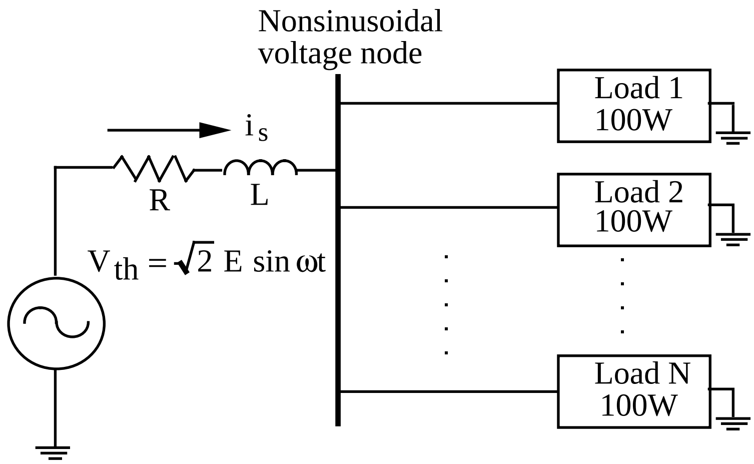

Figure 4-8
N Identical Units with a Shared Thevenin Equivalent System Impedance

Figure 4-9 shows the variation of THDI and the nonsinusoidal voltage node THDV as the number of parallel load increases. It is seen that although THDV increases with the number of units, the increase in THDV is in such a way to decrease THDI, thus illustrating the partial self-correcting effect that nonlinear load currents can have. This partial self-compensating effect does not imply that the proliferation of single-phase power electronic loads will not aggravate harmonic levels on distribution systems. However, neglecting this effect will lead to a significant overestimation of the problem. In this simulation impedance of individual branch circuits were lumped into the system impedance and it was assumed that the total current for all the loads will flow through the system impedance . This resulted in a unrealisticalyy higher (11%) THDV for 15 100W PC. However this assumption does not effect the conclusion reached from the simulation.

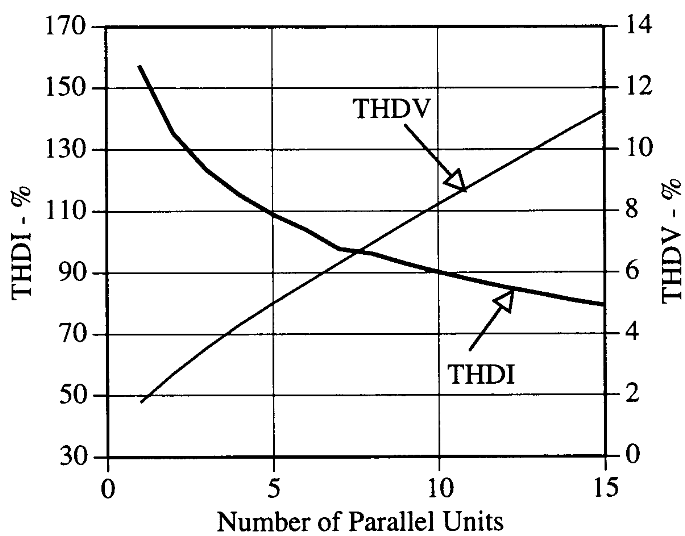

Figure 4-9
Compensating Effect of Parallel Nonlinear Loads

Concerning the response of the current harmonics and THDI of these loads with respect to supply voltage harmonics, it can be concluded that,

1. Lower-order supply voltage harmonics have a significant effect on the harmonic content of the input line current.

2. The harmonics characteristics of the input line current are dependent not only on the magnitudes of the supply voltage harmonics, but also on their phase angles.

3. Supply voltage crest factor is a much better predictor of THDI than is THDV.

4. The current harmonics produced by these loads tend to produce voltage harmonics that partially correct their THDI.

For existing distortion levels in distribution systems, which are generally in the 2 - 3% range, the assumption that these loads draw the same fixed current waveshapes, independent of supply voltage waveform, is reasonable. However, in order to correctly predict the harmonic impact that these loads will have as their penetration levels increase, it will be necessary to take into account the effect of nonsinusoidal supply voltage.

5
COMBINED EFFECT OF ATTENUATION AND DIVERSITY

5.1 Introduction

The net harmonic currents injected by large numbers of single-phase power electronic-based loads that employ diode-bridge rectifiers with DC smoothing capacitors are significantly affected by both attenuation and diversity. Attenuation, which refers to the interaction of voltage and current distortion, is primarily due to shared system impedance. Diversity, which implies the partial cancellation of harmonic currents among different loads due to dispersion in harmonic current phase angles, is primarily due to variations in system and load parameters such as circuit and choke impedances, load power, etc.

In Chapter 3, the separate effects that attenuation and diversity have on the net harmonic current injection of distributed single-phase diode-bridge rectifier loads were illustrated. To observe attenuation due to voltage distortion, identical loads sharing a common system impedance was studied (refer to Figure 3-7). To observe cancellation due to diversity, a stiff bus supplying a large number of these loads with different operating and circuit parameters was studied (refer to Figure 3-9), and the interaction of voltage and current harmonics was neglected. However, in an actual system, many such loads with different operating parameters share a common impedance, and the attenuation and diversity effects should be simultaneously considered when estimating net current injection levels.

In the final step of this research, attenuation and diversity effects are taken into account by expanding the analytical model and solution procedure presented in Chapter 3 to permit iterative updates of voltage harmonics. Therefore, the interactions among current distortion, system impedance, and voltage distortion, which tend to yield "flattened" voltage waveforms and reduced current distortion, are taken into account. To assure that the ranges of modeling parameters are credible, the results of two sets of harmonic measurements are incorporated into the study.

This new procedure is used to estimate the net harmonic currents produced by a large group of single-phase computer loads that share a transformer, as might be found in a commercial facility. The results are presented in two forms: Amps/kW (on a 120 V base), and percent of fundamental current (for the computer loads).

While these studies are based on a simplified electrical system that is less complex than those found in actual facilities, the results are realistic and provide a basis for planning purposes.

5.2 Harmonic Measurements

Two different types of harmonic measurements are performed for single-phase computer loads, where a computer "load" includes both computer and monitor. A spectrum analyzer is used to measure harmonic currents, wall outlet voltage spectrum, and load power. The measurement results are discussed in the following two sections.

5.2.1 Results for Six Different Desktop Computer Models

The results of individual measurements for six different models of desktop computers that are readily available in the marketplace are shown in Figure 5-1 and Figure 5-2. Their power requirements ranged from 55 W to 155 W, with an average power of 108 W. Figure 5-1 shows the phase angle dispersion of individual harmonic currents through the 15th harmonic. Figure 5-2 shows the sums of their harmonic currents (divided by their summed power) in Amps/kW, using both current magnitudes and phasors, thus illustrating harmonic current diversity among these computers.

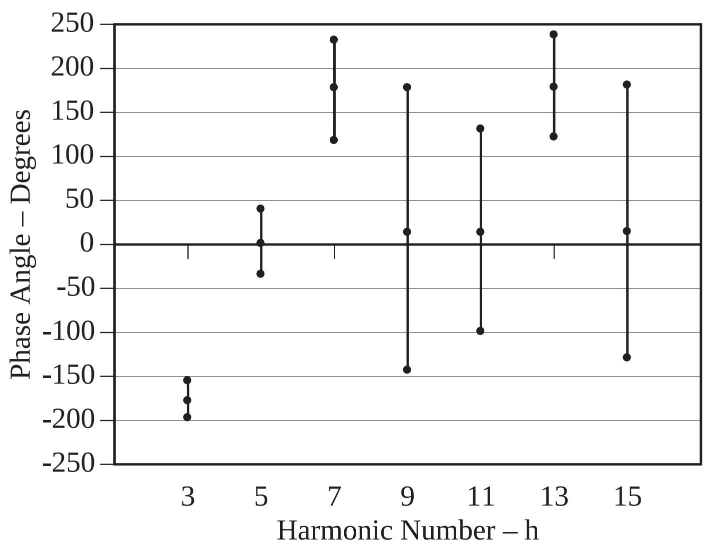

Figure 5-1
Harmonic Current Phase Angle Dispersion for Six Different Desktop Computer Models (Note: Maximum, Minimum, and Average Values are Indicated by • Symbols)

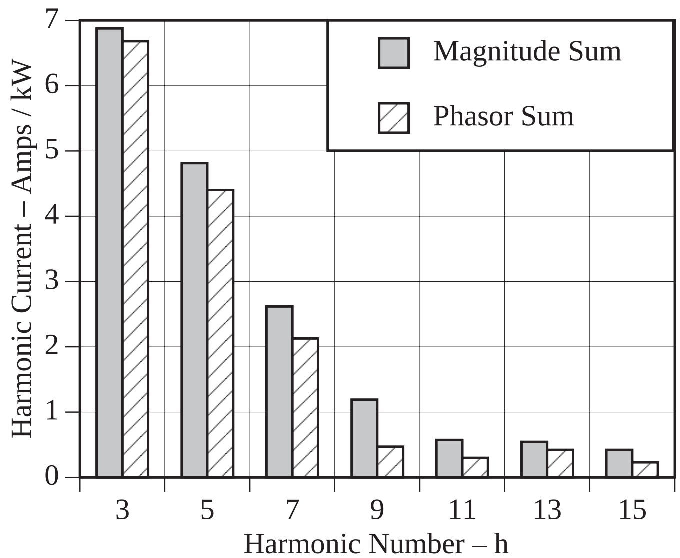

Figure 5-2
Magnitude Sum and Phasor Sum of Total Harmonic Currents for Six Different Desktop Computer Models

By performing simulations using the equations presented in Chapter 3, and adjusting the model parameters of Figure 5.3 to match measured and simulated waveforms, the following electrical parameters for a "typical" 100 W computer connected to a 120 V branch circuit are established:

R_1: Nominal 2.5 Ω, with uniform distribution over the 1.5 – 3.5 Ω range,

L_1: Nominal 1.75 mH, with uniform distribution over the 0.5 – 3.0 mH range,

C: Nominal 250 μF, with uniform distribution over the 200 – 300 μF range,

where R_1 is due mainly to diode bridge resistance, L_1 is due mainly to a series RFI choke, and C represents the dc storage capacitor. The value of C (per W) is somewhat less than that expected for a computer alone because C represents both computer and monitor, and monitors use less capacitance per W than computers. In normalizing these values to 100 W, it was assumed that R_1 and L_1 are inversely proportional to power, while C is proportional to power.

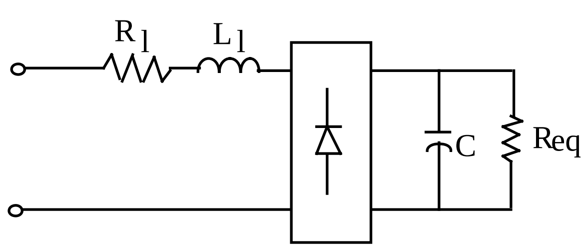

Figure 5-3
Harmonic Model for Typical Single-phase Computer Load

5.2.2 Results for One Desktop Computer Model, Taken at Thirty-Four Different Wall Outlets

Next, the measurements taken for one computer load, but at thirty-four different wall outlets are summarized. The results provide insight on how voltage distortion and circuit impedance affect harmonic currents in computer loads. The key findings of the measurements are:

- Current distortion (THDI) varied from 90% – 114% with most readings between 100% and 110%.
- Voltage distortion (THDV) at the wall outlet varied from 1.4% – 3.1%, with most readings between 1.5% and 2.5%.
- The crest factors of all wall outlet voltage waveforms were below $\sqrt{2}$, showing a definite tendency toward flattened voltage waveforms. This confirms our conclusion drawn in [15] that the natural tendency of single-phase diode-bridge load currents is to create a flattened voltage which has a self-compensating effect on current distortion.

The phase angle dispersion of individual harmonic currents for this set of measurements was much less pronounced than that shown in Figure 5-1. This signifies that harmonic cancellation for single-phase computer loads will occur mainly because of variation in component parameters and power levels among different computer models, rather than variations in branch circuit impedances.

5.3 Modeling

To illustrate the combined effect of attenuation and diversity, the system shown in Figure 5-4 is considered. A large number of 120 V branch circuits, where each branch serves computer loads only, share a transformer. Variations in branch and load parameters cause harmonic current cancellation among the loads, so that a harmonic current magnitude through the transformer is less than the sum of harmonic current magnitudes for the branches. The interaction between net current harmonics and transformer impedance results in a nonsinusoidal voltage at the shared transformer bus, thereby causing harmonic current attenuation.

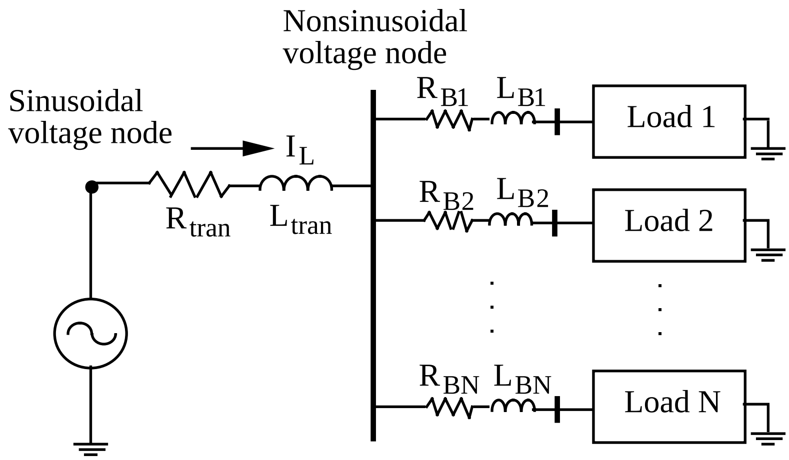

Figure 5-4
N Branch Circuits with Computer Loads Sharing a Transformer

5.3.1 System and Loads

The power system for the study is represented by the impedance of the shared transformer (Z_{tran} = R_{tran} + jωL_{tran}), where the X/R ratio is chosen as unity to represent low-voltage transformers. The magnitude of Z_{tran} is adjusted to represent different transformer loading conditions. The branch circuits are represented by wiring resistance R_B and inductance L_B (see Figure 5-4). The nominal value of wiring impedance for 120 V branch circuits is typically in the range of 0.098 + j0.0188 Ω (@ 60 Hz) [25]. To allow for diversity caused by variation in circuit length, branch circuit resistance R_B and inductance L_B are uniformly distributed over 0.05 – 0.15 Ω, and 0.01 – 0.03 mH, respectively. It is also assumed that each branch circuit serves from 1 – 5 of the typical 100 W computer loads, in uniformly distributed discrete 100 W steps.

5.3.2 Solution Procedure

The solution procedure described in Chapter 3 is modified to handle the situation in Figure 5-4 where the voltage at "nonsinusoidal voltage node" is unknown. The steps for the new iterative method are:

1. Calculate harmonic currents for each individual nonlinear load, assuming sinusoidal voltage at the shared transformer bus.
2. Add all phasor load currents to yield the net current I_L that flows through the shared transformer.
3. Use I_L and Z_{tran} to calculate the nonsinusoidal voltage at the shared transformer bus.
4. Stop if the magnitude change for each voltage harmonic is less than 0.03% of fundamental.
5. Use the updated nonsinusoidal voltage at the shared transformer bus to calculate the individual load currents. Return to Step 2.

This procedure has proven to be stable because increases in voltage distortion tend to decrease current distortion. Convergence is typically reached within 10 - 20 iterations. This procedure was incorporated into program SPCONV. This program is listed in the Appendix.

5.4 Simulation Results

Monte Carlo simulation is performed as described in [13] to investigate the combined effect of attenuation and diversity. The system and the load parameters are varied with uniform distributions within the ranges described in the previous section. For each simulation corresponding to a particular loading level of the transformer defined by the ratio of short circuit current to fundamental-frequency load current (I_{SC} / I_{L1}), the magnitude and phasor sum of harmonic currents injected by the loads, as well as the voltage distortion at the shared transformer bus and at the branch circuit end, are calculated.

Table 5-1 shows the net harmonic current flowing through the common transformer impedance for different loading levels – ranging from a "stiff bus" (i.e., no impedance) to an I_{SC} / I_{L1} ratio of 40. Table 5-1 is arranged in both the IEEE-519 format, with individual harmonics shown as percent of fundamental current, and in the IEC-555 format, where individual harmonic current injections are shown in Amps/kW of nonlinear load. The current injection for the "single-unit" case is based on sinusoidal voltage input to a computer load with nominal values of model parameters, as described in the previous section.

As can be seen in Table 5.1, the individual harmonic current injections decrease from those of the single unit case as the system becomes more heavily loaded. The voltage distortion at the common bus, however, increases as I_{SC} / I_{L1} decreases. The effect of voltage distortion on individual load current is illustrated in Figure 5.5 for the following two values of I_{SC} /I_{L1} ratio: 120 and 40. Note that the tendency of the voltage waveform is to become more flattened as system load increases, and that this flattening decreases THDI.

Table 5-1
Net Harmonic Current Injection in Percent of Fundamental Current (and Amps/kW) for a Range of Short Circuit Ratios

I_{SC}/I_{L1}	I_3	I_5	I_7	I_9	I_{11}	I_{13}	I_{15}	THD_I	THD_V
	Percent of Fundamental Current – I_{L1} (Amps/kW)							% at Transformer Bus	
40	74 (6.6)	38 (3.3)	10 (0.9)	7 (0.6)	5 (0.5)	2 (0.2)	3 (0.2)	84	5.8
60	78 (6.7)	45 (3.9)	16 (1.4)	5 (0.4)	6 (0.5)	3 (0.2)	2 (0.2)	92	4.3
80	80 (6.8)	49 (4.2)	20 (1.7)	4 (0.4)	6 (0.5)	4 (0.3)	2 (0.2)	96	3.4
100	81 (6.9)	51 (4.4)	23 (1.9)	5 (0.4)	6 (0.5)	4 (0.4)	2 (0.2)	99	2.8
120	82 (6.9)	53 (4.5)	24 (2.1)	6 (0.5)	6 (0.5)	5 (0.4)	2 (0.2)	101	2.4
Stiff	87 (7.3)	64 (5.3)	38 (3.2)	16 (1.4)	2 (0.2)	4 (0.3)	4 (0.4)	115	0.0
Single Unit	88 (7.4)	68 (5.7)	44 (3.7)	22 (1.8)	6 (0.5)	5 (0.4)	6 (0.5)	122	0.0

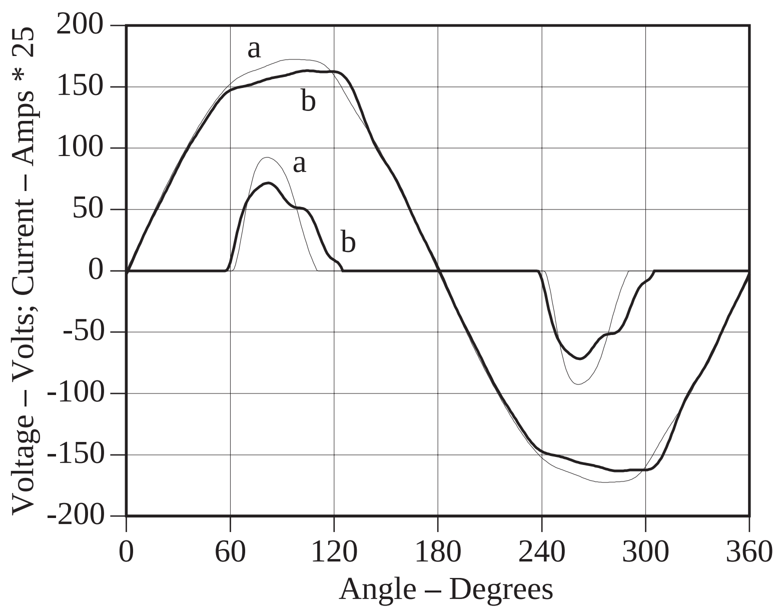

Figure 5-5
Attenuation Effect for Two Different Short Circuit Ratios (a. I_{SC} / I_{L1} = 120, THDV = 2.4%, THDI = 121.8%; b. I_{SC} / I_{L1} = 40, THDV = 5.8%, THDI = 91.1%)

The variations of THDI and THDV at the shared bus and at the branch circuit for different values of system loading level are shown in Figure 5-6 and Figure 5-7. The THDI of the total load current flowing through the common transformer impedance decreases from 115% for a "stiff bus" to 84% for I_{SC} / I_{L1} ratio equal 40. The maximum branch circuit THDV ranges from 3.0% to 6.4% for variations in I_{SC} / I_{L1} ratio from 120 to 40. These results show a comparatively smaller increase in voltage THD with increasing loading level than the studies given in [4], [7]. The interaction between voltage and current THD, which has been neglected in all the previous studies of harmonic estimation of distributed loads, is the main reason for this difference.

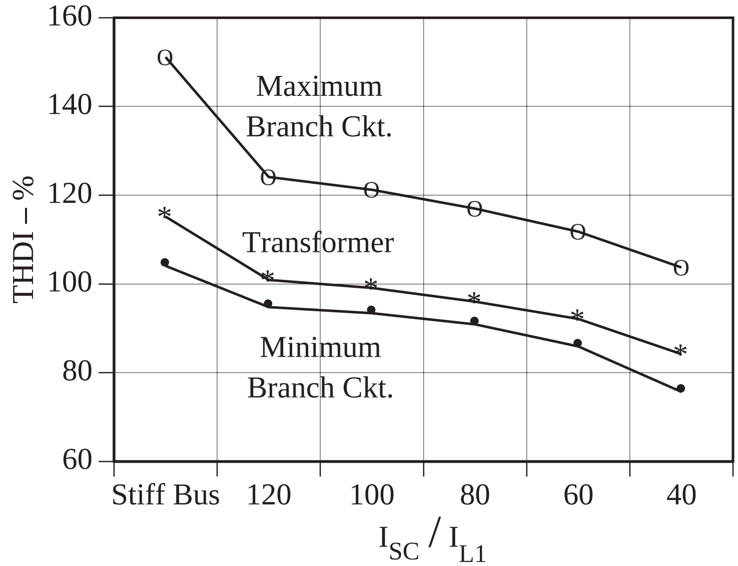

Figure 5-6
THDI in the Branch Circuits and at the Transformer versus Short Circuit Ratio

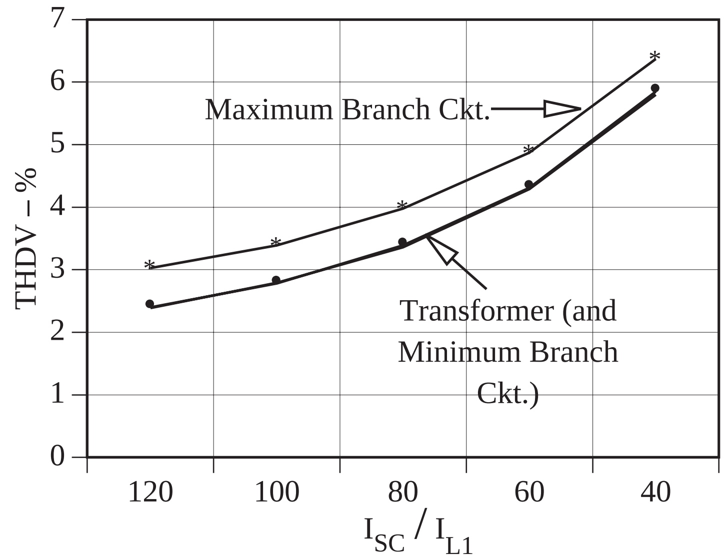

Figure 5-7
THDV in the Branch Circuits and at the Transformer versus Short Circuit Ratio

5.4.1 Reduction in Harmonic Currents due to Attenuation and Diversity

The reduction in harmonic currents in Table 5-1 from the "single unit" case to the "stiff bus" case, where multiple units with different operating parameters are supplied from a stiff source, is due to cancellation of individual harmonic currents resulting from phase angle variation. However, when multiple units share a common impedance, two phenomena work together to reduce the net harmonic current injection:

- As the voltage at the nonsinusoidal bus becomes more distorted due to increased loading level, the THDI of each unit decreases, as shown in Figure 5.5. This effect is described as attenuation, and even identical loads with no parametric variations will be affected by the voltage distortion at the common bus.
- Variations in harmonic phase angles of individual loads result in a decrease in the net harmonic current. This effect, known as diversity, is mainly due to differences in system and load parameters of individual loads.

Figure 5-8 shows the reduction in harmonic Amps/kW due to attenuation and diversity for the 3rd, 5th, and 7th harmonic currents at different loading levels. The "actual" level, which represents the net current injection levels given in Table 5-1, includes both attenuation and diversity effects. The length of each bar for a particular harmonic is constant for different loading levels and represents the total current injection if 1) there is no variation in system and load parameters (i.e., no diversity), and 2)if all loads are supplied from an infinite stiff bus (i.e., no attenuation). As can be seen in Figure 5-8, the Amps/kW reduction due to diversity is almost constant for different load levels, whereas the reduction due to attenuation increases substantially with loading level.

Regarding the harmonic characteristics of a large group of single-phase computer loads, the following conclusions are drawn:

- The reduction in harmonic Amps/kW due to diversity is relatively independent of voltage distortion.
- The reduction in harmonic Amps/kW due to voltage distortion is highly dependent on system loading level and accounts for most of the total reduction in harmonic currents.

The cancellation of harmonic currents due to phase angle variation is not as significant as shown in Chapter 3 for ASD loads because computer loads lack the power variation and have a smaller range of impedances than those assumed in Chapter 3. Furthermore, the internal series resistance and inductance of the computers dilute any variation in branch circuit impedance that causes dispersion in harmonic phase angles among individual loads.

Based on the measurements and simulations, it is recommended that the numbers in Table 5-2 be used for planning purposes when predicting the net harmonic injection currents due to distributed single-phase computer loads. These numbers are the averaged values of Table 5-1 and are conservative because they disregard the cancellation effect of other nonlinear loads and the damping effect of nearby linear loads within a facility. Note that these values derived from simulations agree very well with the measurements for six computers given in Figure 5-2.

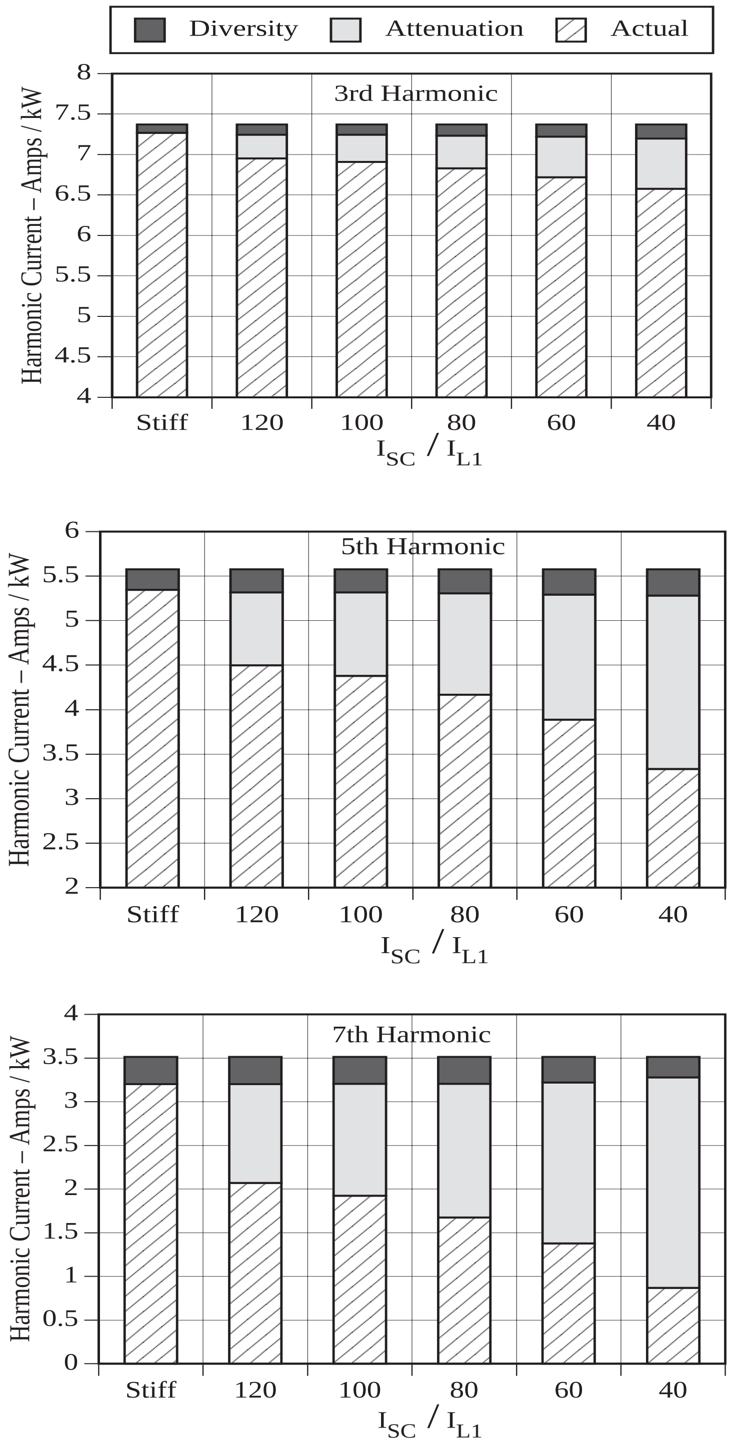

Figure 5-8
Reduction in 3rd, 5th, and 7th Harmonic Currents Due to Attenuation and Diversity for Different Short Circuit Ratios

Table 5-2
Estimates of Net Harmonic Current Injection Levels for Large Numbers of Distributed Single-Phase Computer Loads

Harmonic	Percent of Fundamental Current	Harmonic Amps/kW*
I_3	81	6.9
I_5	53	4.5
I_7	25	2.1
I_9	9	0.8
I_{11}	5	0.5
I_{13}	4	0.3
I_{15}	3	0.3

* on 120 V base.

6
CONCLUSIONS AND RECOMMENDATIONS

6.1 Overview

Complete analytical models for calculating current harmonics of single phase power electronic loads employing capacitor filter bridge rectifiers and tyristor controlled rectifiers have been developed and incorporated into general purpose digital computer program SPCONV and TRIAC. For capacitor filtered rectifiers (CFRs) the effect of nonsinusoidal supply voltage on input current harmonics is investigated and an iterative technique is incorporated into program SPCONV to take into account the interactions among current distortion, system impedance, and voltage distortion.

For CFR loads, The effect of system and load parameters on current harmonics is studied and the relative phase dispersion of individual harmonics due to parametric variation is quantified by performing Monte Carlo simulations on a large number of distributed loads and calculating diversity factors for each harmonics. The effect of system impedance on similar loads is quantified by defining attenuation factors. To observe attenuation due to voltage distortion, identical loads sharing a common system impedance is studied. To observe cancellation due to diversity, a stiff bus supplying a large number of these loads with different operating and circuit parameters is studied. To investigate the combined effect of attenuation and diversity, which is the case in actual systems where many such loads with different operating parameters share a common impedance, an iterative scheme is employed to take into account the interaction of system impedance and voltage distortion.

For thyristor controlled lighting loads, the cumulative harmonic current characteristics of a large number of light dimmers is investigated. The effect of firing angle on harmonic current magnitude and phase angle is studied, and Monte Carlo simulation is employed to calculate the cumulative current and diversity factors for a large number of these loads. A simplified diversity adjusted current injection formula is developed to characterize the cumulative harmonic current produced by these loads.

6.2 Key Contributions and Conclusions

Traditionally, only the harmonics produced by large loads have been considered a problem for power systems. However, due to the increasing sizes and proliferation of smaller distorting loads this scenario of concentrated sources of harmonics is gradually changing. The key contribution of this research is the studying of the cumulative current harmonics produced by distributed single-phase power electronic-based loads. Simulation methods currently used for investigating the cumulative impact of these type of loads does not take into account the diversity in phase angles of a large number of harmonic currents and consequently use an arithmetic summation for current injection models.

This report represents the first work in analytically quantifying this diversity effect for distributed loads. While this work alone does not answer all the uncertainties such as simultaneity, daily, weekly, or seasonal load variation associated with predicting the harmonic impact of distributed single phase loads, it does address the question of summation of harmonic currents due to a large number of sources. The diversity numbers can be used as a measure of the additive nature of individual harmonics caused by large numbers of loads connected throughout a distribution system. This work leads to a better understanding of the harmonic cancellation effect that exists among distributed sources and serves as a building block for further investigation into this subject matter. The cancellation and attenuation effects must be taken into account for any harmonic penetration study dealing with single-phase distributed power electronic-based loads.

The conclusions reached during the course of this research work can be summarized into three broad categories. Regarding the effect of attenuation and diversity on cumulative current harmonics produced by distributed capacitor filtered rectifier loads, the following conclusions can be reached based on studies performed within the scope of this report:

- There is significant attenuation of current harmonics above the 3rd multiple when a number of identical loads, such as televisions and desktop computers, share a common source impedance. The THDI of current in this case is approximately one-half of that obtained using superposition of individual load currents. However, the 3rd harmonic, which is responsible for most harmonic-related neutral conductor overloading problems, experiences only slight attenuation (i.e., 0.8 - 0.9) .
- The cumulative harmonic currents for the 9th multiple and above experience appreciable phase cancellation due to individual and/or composite variations in power level, impedance magnitude, impedance X/R ratio, and smoothing capacitance. Since the 3rd and 5th harmonics show little phase cancellation, the THDI of the summed current is only slightly less than that obtained by using superposition.
- The reduction in harmonic Amps/kW due to diversity is relatively independent of voltage distortion.
- The reduction in harmonic Amps/kW due to voltage distortion is highly dependent on system loading level and accounts for most of the total reduction in harmonic currents.

Concerning the response of the current harmonics and THDI of these loads with respect to supply voltage harmonics, it is shown that

- Lower-order supply voltage harmonics have a significant effect on the harmonic content of the input line current.
- The harmonics characteristics of the input line current are dependent not only on the magnitudes of the supply voltage harmonics, but also on their phase angles.

- Supply voltage crest factor is a much better predictor of THDI than is THDV.
- The current harmonics produced by these loads tend to produce voltage harmonics that partially correct their THDI.

For thyristor controlled incandescent lighting loads the following general conclusions are reached:

- The harmonic current (in p.u. of rated current) injected by these types of loads is approximately independent of firing angle.
- There is appreciable phase dispersion of individual harmonic current phase angles due to random distribution of firing angles.
- By defining diversity-adjusted current injection, it is shown that for uniformly-distributed lumen levels, the cumulative harmonic current injection levels can be approximated by $\frac{3}{h^2}$ p.u. Amperes, on the total rated load current base.

6.3 Recommendations

The principal recommendations concerning this work center on four areas: improvement of load models, improvements of the estimate on the range of parameter variation based on statistical data, investigation of the effect of correlation between individual loads, and harmonic cancellation between different load groups.

The diode bridge rectifier model developed is based on the operation of a single current pulse for each half cycle of voltage waveshape. However under unusual operating condition it is possible to have multiple current pulses. In this case, the solution process must be restarted for each current pulse, and the model must be extended for multiple pulse operation.

In the absence of any statistical data, uniform distribution was assumed on the ranges of parameter variation. Also it was assumed that individual loads within a load group are completely uncorrelated. However, in the actual scenario there will be some correlation between load parameters based on external factors such as outside temperature and ASD power level. The effect of load correlation on diversity factors is a possible future research scope.

Because of the 30º phase shift between the delta and wye sides of low voltage transformers, similar types of loads connected to the 120V bus through the wye side of the transformer and to the 277V bus through the delta side of the transformer will cause appreciable phase cancellation. A possible scenario is computers, printers, connected to the 120V circuit and compact Fluorescent lamps connected to the 277V service. Cancellation between different load groups should be investigated to account for this effect. Finally, the effect of distribution networks on the cumulative harmonic levels should be investigated by performing a series of system studies that employ the models developed in this report.

A
APPENDIX A

Overview

Program SPCONV calculates the harmonic components of the input current of a capacitor-filtered diode bridge rectifier, using circuit parameters, load level, and source voltage as input variables. The program is capable of performing Monte Carlo simulations for calculating the current harmonic diversity factors for variations in circuit parameters. It also has the capability of solving multiple nonlinear loads at different operating condition sharing a common source impedance, by permitting iterative updates of voltage harmonics.

Screen-Based Data Input Format for Program SPCONV

The program uses a combination of screen based input and data file input. A description of the screen based input data requirement is given below. The words in *italic* denote the actual screen messages and words in **bold** denote input data options.

enter the number of voltage update iterations

Input **0** or any positive integer, usually between **10-15**. A **0** input signifies an infinite source and does not permit updates of voltage iterations as described in Chapter 5.

enter the desired method number

The available input options are:

1: use random seeding of one variable

2: use random seeding of one variable by using table look-ups

3: one-shot solution for specific case

For method number **3**,

enter the value of rs(ohm), ls(mh), pspec(watt), cl(microf),rl(ohm)

rs(ohm),**ls**(ohm): Input resistance in ohms and inductance in millihenries

pspec(watt): dc output power in watts

cl(microf): dc filter capacitance in micofarads

rl(ohm): If **pspec** is **0**, then enter the load resistance **rl** in ohm. If **pspec > 0** then input **0** for **rl**

For method number **1** or **2** or **3**

enter the fund. voltage magnitude and angle, volts – rms, angle – degrees

For example if the fundamental source voltage is 120V at 0 degree phase angle, then the input data will be,

120, **0.0**

For method number **1** or **2**

enter the desired variable number

The available input options are:

1: vary power p

2: vary impedance magnitude z

3: vary x/r ratio xr

4: vary dc capacitance c

5: vary p, z, xr, and c simultaneously

6: vary voltage harmonics (not permitted for **method number 2** or for **voltage iteration > 1**)

For variable number **6**

enter the highest voltage harmonic

Voltage harmonic upto **25th** is permitted in the program for this version. However by changing the **nh1max** variable in the program this number can be changed

For method number **1** or **2**

enter the total number of trials and spacing

For example if there are 60 loads in a group and a 300 shot Monte Carlo simulation is to performed then **total number of trials** will be **18000** and the **spacing** will be **60**.

Input Data File Format for Program SPCONV

For nonsinusoidal excitation, The harmonic spectrum of source voltage is read from data file **vspect**. The input data format is,

Harmonic # Voltage magnitude(% of fundamental) Angle (degrees)

the last line of the spectrum data file is delimited by **0**, **0**, **0**

Output Files for Program SPCONV

Several output files are created by the program. A brief description of the output files follows:

Summary.div: For each call to the 'subroutine bridge', that actually calculates the line current harmonic spectrum, the summary file contains the data for the circuit parameter, calculated THDI, start and stop angle for input current pulse, ripple factor, output dc power, and input power for each harmonic.

Fourier.div: This file contains the Fourier spectra of the input line current. The magnitude is given in peak values and the phase angle in degrees.

Plot.div: This file contains the time domain data of supply voltage, output dc voltage, and line current for one complete cycle discretized at 1 degree interval.

Itsum.div: The iteration summary for calculating the start and the stop angle of the input line current is provided mainly for debugging purpose.

Diverse.div: This file contains the current harmonic diversity numbers for each individual odd harmonic upto the 15th.

Vspect.div: This file acts both as an input and out put file. The fourier spectra of the supply voltage is provided in this datafile. Also, the updated voltage harmonics for each iteration is also listed.

Ispect.div: Spectrum of line current in Amps/kW for each iteration is listed in this file.

Listing of Program SPCONV

```
c
c  spconv.for
c
c  program spconv.for calculates the harmonic content of the input
c  line current of a single-phase diode bridge rectifier with dc filter
c  capacitor. the input parameters are input voltage spectrum, line impedance,
c  dc filter capacitor or ripple factor, load power or load resistance. A one
c  shot simulation or a Monte Carlo simulation can be performed to calculate
c  the diversity factors for individual harmonics.
c
      dimension e(25),phase(25),harmg(25),haran(25),sup(361),cur(361),
```

```
     1 hcur(361),vol(361),csreal(25,2),csimag(25,2),csmag(25,2),
     2 diver(25,2),hmtab(50,25),hatab(50,25),htabv(50,4),htaba(4),
     3 sqsum1(3),sqsum2(25,2),a(25),aphase(25),vold(25)
      real ls,lls,ltran,l1dum,l2dum
      double precision rmsv,rmsc,csreal,csimag,csmag,diver,
     1 pavg,zavg,xravg,cclavg,htaba,sqsum1,sqsum2
      double precision r1avg,r2avg,l1avg,l2avg
      integer*2 is1,is2,is3,is4
      logical unix,ltrue,lfalse,rlvar
      real l1,l2,l1min,l1max,l2min,l2max,l1diff,l2diff
      complex volts,amps,ztran,vold,vinf
      common /bridge1/ rmsv,rmsc,e,phase,harmg,haran,sup,cur,hcur,vol,
     1 rs,ls,pspec,cl,rl,fr,rpl,thdi,iflag,isolt,th1,th2,icount,
     2 jcount,kcount,pout
      common /bridge2/ nhar1,nhar2,nhar3,pi,dr,eps6,sqrt2
      data sqsum1/3 * 0.0/,sqsum2/50 * 0.0/,nsqsum/0/
      data e,phase/50 * 0.0/,a,aphase/50 * 0.0/,vold/25 * (0.0,0.0)/
      data accel/0.5/,nflags/0/
      data ltrue/.true./,lfalse/.false./
      data thdimn,thdimx,thdvmn,thdvmx/4 * 0.0/,v1min,v1max/2 * 0.0/
      data xrmin,xrmax,zmin,zmax/4 * 0.0/
      data rtran,ltran/2 * 0.0/
      eps6      = 1.0e-06
      pi        = 4.0 * atan(1.0)
      dr        = 180.0 / pi
      sqrt2     = sqrt(2.0)
c
c ---------------------------------------------------------------------
c
c  set unix  = ltrue for unix, unix = lfalse for pc-fl32
c
c     unix   = ltrue
      unix   = lfalse
c
c  set rlvar = ltrue  if you want to vary r1,l1,r2,l2.
c  set rlvar = lfalse if you want to vary zmag,xr.
c
      rlvar  = ltrue
c     rlvar  = lfalse
c
c ---------------------------------------------------------------------
c
c  nhar1 - highest harmonic of input voltage (set initially to 1, but
c          can be reset as high as nh1max by file vpsect)
c  nhar2 - highest harmonic of bridge current
c  nhar3 - highest harmonic written to current diversity spectrum file
c  fr    - system frequency
c
      nhar1     = 1
      nhar2     = 25
      nhar3     = 15
      nh1max    = 25
      fr        = 60.0
c
      ztran = cmplx(0.0,0.0)
      write(6,*) ' enter the number of voltage update iterations'
      read(5,*) mexmax
      if(mexmax .lt. 1) mexmax = 1
      write(6,*) ' ok, number of voltage update iterations = ',mexmax
c
      iflag     = 0
      pavg      = 0.0
      zavg      = 0.0
```

```
      xravg     = 0.0
      cclavg    = 0.0
      r1avg     = 0.0
      l1avg     = 0.0
      r2avg     = 0.0
      l2avg     = 0.0
      javg      = 0
      sqsum1(1) = 0.0
      sqsum1(2) = 0.0
      sqsum1(3) = 0.0
      nsqsum    = 0
      is4       = 0
c
      do 1 j      = 1,nhar3
      e(j)        = 0.0
      phase(j)    = 0.0
    1 continue
c
c ----------------------------------------------------------------------
c
c  comment-out the next five statements if you want to use the same
c  set of random numbers each time spconv3 is executed
c
      if(.not.unix) call gettim(is1,is2,is3,is4)
      if(unix) then
        seedp   = secnds(10.0)
        is4     = int(mod(seedp,1.0) * 1.0e+06)
      endif
c
c ----------------------------------------------------------------------
c
      do 301 mexec = 1,mexmax
c
c  reset the random seed point so that each mexec iteration
c  starts with the same random number
c
      if(unix) iseed = is4
      if(.not.unix) call seed(is4)
c
c      write(6,*) 'voltage update iteration = ',mexec
c      if(mexec .gt. 1) then
c      do 302 j = 1,nhar1
c      write(6,*) 'voltage harmonic ',j,e(j),phase(j) * dr
c  302 continue
c      do 303 j = 1,nhar3
c      write(6,*) 'current harmonic ',j,a(j),aphase(j) * dr
c  303 continue
c      endif
      do 304 j      = 1,nhar3
      do 304 k      = 1,2
      sqsum2(j,k) = 0.0
      csreal(j,k) = 0.0
      csimag(j,k) = 0.0
      csmag(j,k)  = 0.0
  304 continue
c
c  imeth = 1, use random seeding of one variable
c  imeth = 2, use random seeding of one variable by using table look-ups
c  imeth = 3, one-shot solution for specific case
c
c  for imeth = 1 or 2, then
c    ivar = 1, vary power p
c    ivar = 2, vary impedance magnitude z
```

```
c    ivar = 3, vary x/r ratio xr
c    ivar = 4, vary dc capacitance c
c    ivar = 5, vary p, z, xr, and c simultaneously
c    ivar = 6, vary voltage harmonics (not permitted for imeth = 2)
c
      if(mexec .eq. 1) then
c
      open(unit=1,file='summary.div',status='unknown')
      open(unit=2,file='fourier.div',status='unknown')
      open(unit=3,file='plot.div',status='unknown')
      open(unit=4,file='itsum.div',status='unknown')
      open(unit=8,file='diverse.div',status='unknown')
      open(unit=9,file='square.div',status='unknown')
      open(unit=10,file='invars.div',status='unknown')
      open(unit=11,file='vspect',status='unknown')
      open(unit=12,file='ispect',status='unknown')
      write(1,500)
      write(2,500)
      write(3,500)
      write(4,500)
      write(8,500)
      write(9,500)
      write(10,500)
      write(12,500)
  500 format(1x)
      rewind 11
      rewind 12
      rewind 1
      rewind 2
      rewind 3
      rewind 4
      rewind 8
      rewind 9
      rewind 10
c
c  end mexec if
c
      endif
      rewind 3
      rewind 9
      rewind 10
      write(1,*) 'voltage update iteration = ',mexec
      write(2,*) 'voltage update iteration = ',mexec
      write(3,*) 'voltage update iteration = ',mexec
      write(4,*) 'voltage update iteration = ',mexec
      write(8,*) 'voltage update iteration = ',mexec
      write(8,*) ' seed point = ', iseed
      write(9,*) 'voltage update iteration = ',mexec
      write(10,*) 'voltage update iteration = ',mexec
      write(12,*) 'voltage update iteration = ',mexec
      if(mexec .eq. 1) then
      write(6,*) ' enter the desired method number'
      read(5,*)    imeth
      write(6,*) ' imeth = ',imeth
      write(1,*) ' imeth = ',imeth
      if(imeth .le. 0 .or. imeth .gt. 3) stop
        if(mexmax .gt. 1) then
          write(6,*) ' enter the shared transformer',
     1     ' r ohms, l millihenries'
          read(5,*) rtran,ltran
          write(6,*) ' ok, rtran,ltran = ',rtran,ltran
          write(1,*) ' ok, rtran,ltran = ',rtran,ltran
          write(8,*) ' ok, rtran,ltran = ',rtran,ltran
```

```
          xtran  = 2.0 * pi * fr * ltran / 1.0e+03
          ztran  = cmplx(rtran,xtran)
        endif
        write(6,*) ' seed point = ',is4
        write(1,*) ' seed point = ',is4
        write(8,*) ' seed point = ',is4
c
c  end mexec if
c
      endif
c
c  imeth = 3 (one shot solution for a specific case)
c
      if(imeth .eq. 3 .and. mexec .eq. 1) then
        jjmax     = 1
        jjspac    = 1
        write(6,*)'enter the value of rs(ohm), ls(mh), pspec(watt),',
     1  ' cl(microf), rl(ohm)'
        read(5,*) rs, lls, pspec, ccl, rl
c
c  if isolt = 1, solve for pspec using the specified rl.
c  if isolt = 2, solve for rl using the specified pspec.
c
        isolt     = 0
        if(abs(rl)    .gt. eps6 .and. abs(pspec) .lt. eps6) isolt = 1
        if(abs(pspec) .gt. eps6 .and. abs(rl) .lt. eps6)    isolt = 2
        if(isolt .eq. 0) then
          write(6,505)
          stop
        endif
  505 format(1x,'specify either pspec or rl, but not both')
        xxx       = 2.0 * pi * fr * lls / 1.0e+03
        xr        = xxx / rs
        write(6,*) ' enter the fund. voltage magnitude and angle',
     1 ' volts - rms, angle - degrees'
        read(5,*) e(1),phase(1)
        write(6,*) ' ok, ',e(1),' volts, with phase angle = ',phase(1)
        efund    = e(1)
        phase(1) = phase(1) / dr
        afund    = phase(1)
        zmag      = sqrt(rs * rs + xxx * xxx)
        zang      = atan2(xxx,rs)
        ztran     = ztran
      endif
c
c  for imeth = 1, 2, and 3
c
      if(mexec .eq. 1) then
        if(imeth .eq. 1 .or. imeth .eq. 2) then
          write(6,*) ' enter the fund. voltage magnitude and',
     1    ' angle, volts - rms, angle - degrees'
          read(5,*) e(1),phase(1)
          write(6,*) ' ok, ',e(1),' volts, with phase angle = ',phase(1)
          efund    = e(1)
          phase(1) = phase(1) / dr
          afund    = phase(1)
        endif
        write(6,*) ' now, enter the harmonic voltages and ',
     1  'phase angles (sine reference) as follows -'
        write (6,*) ' harmonic, voltage magnitude (% of fundamental),'
     1  ,' phase angle (degrees).'
        write(6,*) ' terminate with 999 999 999.'
        ihmax       = 0
```

```
c
c  read the harmonic voltage spectrum from file vspect
c
   90   read(11,*,end=92) ihar,eem,eep
        if(ihar .eq. 0) go to 91
        write(6,583) ihar,eem,eep
  583   format(' harmonic, mag, phase = ',i5,2f10.2)
        if((ihar .gt. nh1max) .or. ihar .eq. 1 .or.
     1    ihar / 2 .eq. int(ihar / 2.0 + 0.51)) then
          write(6,*) ' ignore the last one'
          go to 90
        endif
c
c  for emx, the voltage spectrum is read in actual volts instead
c  of percent of fundamental
c
        e(ihar)     = e(1) * eem / 100.0
        phase(ihar) = eep / dr
        if(ihar .gt. ihmax) ihmax = ihar
        go to 90
   92   backspace 11
        write(11,*) '0 0 0'
   91   if(ihmax .ne. 0) nhar1 = ihmax
        write(6,*) ' ok, now solving, using maximum voltage harmonic ='
     1  ,' ',nhar1
        if(nhar1 .gt. nhar2) then
          write(6,*) ' this harmonic is larger than ',nhar2,'.  stop'
          stop
        endif
        write(11,*) ' seed point = ',is4
        write(12,*) ' seed point = ',is4
        write(11,*) ' ok, rtran,ltran = ',rtran,ltran
        write(12,*) ' ok, rtran,ltran = ',rtran,ltran
c
c  end mexec if
c
      endif
      if(imeth .eq. 3) go to 13
c
c  for imeth = 1 or 2
c
      if(mexec .eq. 1) then
      write(6,*) ' enter the desired variable number'
      read(5,*)    ivar
      write(6,*) ' variable = ',ivar
      write(1,*) ' variable = ',ivar
      if(ivar .le. 0 .or. ivar .gt. 6) stop
      if(imeth .eq. 2 .and. ivar .eq. 6) then
        write(6,*) ' table method does not allow voltage harmonic ',
     1   'variation'
        read(5,*)
        stop
      endif
      if(ivar .eq. 6) then
        if(mexmax .gt. 1) then
          write(6,571)
  571 format(1x,'iterations not permitted when randomly varying '
     1 'voltages')
          read(5,*)
          stop
        endif
        write(6,*) ' enter the highest voltage harmonic'
        read(5,*) nhv
```

```
          if(nhv .le. 1 .or. nhv .gt. nh1max) then
            write(6,*) ' this input harmonic is out of range'
            read(5,*)
            stop
          endif
          nhar1 = nhv
        endif
        write(6,*) ' enter the total number of trials and spacing'
        read(5,*)    jjmax,jjspac
        write(6,*) ' trials = ',jjmax,', spacing = ',jjspac
        write(1,*) ' trials = ',jjmax,', spacing = ',jjspac
c
        rl        = 0.0
        isolt     = 2
c
c  watts, ohms (at fr hz), millihenries, microfarads
c
        if(.not.rlvar) then
c
c  default values for 240v, 3000w heat pump.  zmag,xr are for the
c  total bridge.  r1,l1,r2,l2 are not specified, but rather are
c  lumped into zmag,xr.
c
          pspec     = 3000.0
          zmag      = 0.9216
          xr        = 1.0
          ccl       = 4200.0
          r1        = 0.0
          l1        = 0.0
          r2        = 0.0
          l2        = 0.0
c
c  ranges for heat pump
c
          pmin      = 600.0
          pmax      = 3000.0
          zmin      = 0.2304
          zmax      = 1.3824
          xrmin     = 0.1
          xrmax     = 5.0
          cclmin    = 1000.0
          cclmax    = 10000.0
          r1min     = 0.0
          r1max     = 0.0
          l1min     = 0.0
          l1max     = 0.0
          r2min     = 0.0
          r2max     = 0.0
          l2min     = 0.0
          l2max     = 0.0
        endif
        if(rlvar) then
c
c  default values for 120v, 100w pc + monitor.  zmag,xr are not
c  specified, but rather are contained in r1,l1,r2,l2.
c
c  r1 and l1 are from the wall outlet back to the shared transformer,
c  r2 and l2 are from the wall outlet to the dc side of the dbr.
c  r1 and l1 should have the same ratio, regardless of length.
c
          pspec     = 100.0
          zmag      = 0.0
          xr        = 0.0
```

```
        ccl       = 250.0
        r1        = 0.10
        l1        = r1 / 5.0 / 2.0 / pi / fr * 1.0e+03
        r2        = 2.5
        l2        = 1.75
c
c  ranges for pc
c
        pmin      = 100.0
        pmax      = 500.0
        cclmin    = 200.0
        cclmax    = 300.0
c
c  for a generic 120V wall outlet
c
c       r1min     = 0.01
c       r1max     = 0.10
        r1min     = 0.05
        r1max     = 0.15
c
c  observe 13.33:1 ratio in r1,l1 (ratio of ohms)
c
c       l1min     = r1min / 13.33 / 2.0 / pi / fr * 1.0e+03
c       l1max     = r1max / 13.33 / 2.0 / pi / fr * 1.0e+03
c
c  observe 5.0:1 ratio in r1,l1 (ratio of ohms)
c
        l1min     = r1min / 5.0 / 2.0 / pi / fr * 1.0e+03
        l1max     = r1max / 5.0 / 2.0 / pi / fr * 1.0e+03
c
c  for a generic 100w pc + monitor
c
        r2min     = 1.5
        r2max     = 3.5
        l2min     = 0.5
        l2max     = 3.0
      endif
c
      pdiff     = pmax    - pmin
      zdiff     = zmax    - zmin
      xrdiff    = xrmax   - xrmin
      cdiff     = cclmax  - cclmin
      r1diff    = r1max   - r1min
      l1diff    = l1max   - l1min
      r2diff    = r2max   - r2min
      l2diff    = l2max   - l2min
c
      if(imeth .eq. 2) then
c
c  method 2 - generate 50 equally-spaced values for the table (does
c  not apply to r1,l1,r2,l2 variations)
c
        write(6,*) ' building the table'
        if(rlvar) then
          write(6,*)' table method does not allow r1,l1,r2,l2 variation'
          read(5,*)
          stop
        endif
        do 27  jj = 1,50
        if(ivar .eq. 1) pspec = pmin   + (jj - 0.5) * pdiff  / 50.0
        if(ivar .eq. 2) zmag  = zmin   + (jj - 0.5) * zdiff  / 50.0
        if(ivar .eq. 3) xr    = xrmin  + (jj - 0.5) * xrdiff / 50.0
        if(ivar .eq. 4) ccl   = cclmin + (jj - 0.5) * cdiff  / 50.0
```

```
        zang      = atan(xr)
c
c  convert to actual units
c
        rs        = zmag * cos(zang)
        lls       = zmag * sin(zang) / 2.0 / pi / fr * 1.0e+03
c
c  millihenries and microfarads
c
        ls        = lls / 1.0e+03
        cl        = ccl / 1.0e+06
        call bridge
        theta1    = th1 * dr
        theta2    = th2 * dr
        write(1,507)
        write(6,507)
        write(1,501) iflag,thdi,rpl,rl,pspec,pout,rs,lls,ccl
        write(1,506) icount,jcount,kcount,theta1,theta2,rmsc,rmsv
        write(6,501) iflag,thdi,rpl,rl,pspec,pout,rs,lls,ccl
        write(6,506) icount,jcount,kcount,theta1,theta2,rmsc,rmsv
        write(6,*)' iflag,pspec,zmag,xr,ccl = ',iflag,pspec,zmag,xr,ccl
        htabv(jj,1) = pspec
        htabv(jj,2) = zmag
        htabv(jj,3) = xr
        htabv(jj,4) = ccl
        if(iflag .ne. 0) then
          write(1,570) iflag
          write(6,570) iflag
          write(11,570) iflag
          write(12,570) iflag
          read(5,*)
          stop
        endif
  570 format(1x,'stop because iflag = ',i5)
        do 28 k     = 3,nhar3,2
        hmtab(jj,k) = harmg(k)
        hatab(jj,k) = haran(k)
   28   continue
c
c  write the fourier components of current to file fourier
c
        write(2,508) jj,(harmg(j),haran(j),j=1,nhar3,2)
  508   format(i6,8(f15.6,f9.3))
c
   27   continue
      endif
c
c  end mexec if
c
      endif
c
c  for all values of imeth (note, jjmax = 1 for meth 3)
c
   13 do 30  jj   = 1, jjmax
c
   85 if(imeth .ne. 3) then
c
c  methods 1 and 2, vary the individual p, z, xr, c variables. (zmag,xr)
c  variations can be replaced by (r1,l1,r2,l2) variations.
c
        if(ivar .eq. 1 .or. ivar .eq. 5) then
          if(.not.unix) call random(randp)
          if(unix) randp       = ran(iseed)
```

```
          if(jj .eq. 1 .and. iflag .eq. 0) randp = 0.0
          if(jj .eq. 2 .and. iflag .eq. 0) randp = 1.0
          pspec   = pmin   + pdiff * randp
        endif
c
        if(ivar .eq. 2 .or. ivar .eq. 5) then
           if(.not.unix) call random(randz)
           if(unix) randz      = ran(iseed)
           if(jj .eq. 1 .and. iflag .eq. 0) randz = 0.0
           if(jj .eq. 2 .and. iflag .eq. 0) randz = 1.0
           zmag    = zmin   + zdiff * randz
c
c  r1 and l1 variations are linked to the same random variable
c
           r1      = r1min  + r1diff * randz
           l1      = l1min  + l1diff * randz
        endif
c
        if(ivar .eq. 3 .or. ivar .eq. 5) then
          if(.not.unix) call random(randxr)
          if(unix) randxr      = ran(iseed)
          if(jj .eq. 1 .and. iflag .eq. 0) randxr = 0.0
          if(jj .eq. 2 .and. iflag .eq. 0) randxr = 1.0
          xr      = xrmin  + xrdiff * randxr
c
c  r2 and l2 variations are not linked to the same random variable
c
          r2      = r2min  + r2diff * randxr
c
c  if statements are needed on the next two calls to allow
c  zmag,xr variations to match old program values by
c  avoiding an extra random variable call
c
          if(rlvar .and. .not.unix) call random(randxr)
          if(rlvar .and. unix) randxr = ran(iseed)
c
          if(jj .eq. 1 .and. iflag .eq. 0) randxr = 0.0
          if(jj .eq. 2 .and. iflag .eq. 0) randxr = 1.0
          l2      = l2min  + l2diff * randxr
        endif
c
        if(ivar .eq. 4 .or. ivar .eq. 5) then
          if(.not.unix) call random(randc)
          if(unix) randc      = ran(iseed)
          if(jj .eq. 1 .and. iflag .eq. 0) randc = 0.0
          if(jj .eq. 2 .and. iflag .eq. 0) randc = 1.0
          ccl     = cclmin + cdiff * randc
        endif
c
c  vary the harmonic voltages so that the thdv is between 0.00 and 0.10
c
        if(ivar .eq. 6) then
          echeck   = 0.0
          do 42 kk = 3,nhar1,2
          if(.not.unix) call random(randv)
          if(unix) randv = ran(iseed)
          e(kk)    = randv
          echeck   = echeck + e(kk) * e(kk)
   42     continue
          echeck   = sqrt(echeck)
          if(.not.unix) call random(randv)
          if(unix) randv = ran(iseed)
c
```

```
c  the 0.10 in the following statement refers to 10 percent voltage
c
          eratio   = randv * 0.10 / echeck
          echeck   = 0.0
          do 43 kk = 3,nhar1,2
          e(kk)    = e(kk) * eratio
          echeck   = echeck + e(kk) * e(kk)
   43     continue
          echeck   = sqrt(echeck)
c
c  the following 100.0 is percent and has nothing to do with
c  the 10 percent input above
c
          thdv      = echeck * 100.0
c
c  vary the harmonic voltage phase angles between 0 and 360 degrees
c
          do 44 kk  = 3,nhar1,2
          if(.not.unix) call random(randv)
          if(unix) randv = ran(iseed)
          phase(kk) = 2.0 * pi * randv
          e(kk)     = e(1) * e(kk)
   44     continue
          vpeak      = 0.0
          do 46 jdeg = 1,181
          deg        = (jdeg - 1) / dr
          vvv        = 0.0
          do 47 kk   = 1,nhar1,2
          vvv        = vvv + e(kk) / e(1) * sin(kk * deg +
     1    phase(kk))
   47     continue
          vvv        = abs(vvv)
          if(vvv .gt. vpeak) vpeak = vvv
   46     continue
          crest      = vpeak / sqrt(1.0 + thdv * thdv / 1.0e+04)
        endif
      endif
c
c  end of methods 2 and 3 if
c
c ----------------------------------------------------------------------
c
c  the next six statements discretize pspec and scale r2,l2,c with
c  pspec.  they areused only by the july 94 paper to determine building
c  harmonics produced by generic 100w pc loads, and they apply only for
c  imeth = 1.  comment-out if not wanted.
c
c  also, comment them out if you want to do p-only variation (ivar = 1)
c  and do not want to scale r2,l2 at the same time.
c
      if(rlvar .and. imeth .eq. 1) then
        pspec = 100 * int((pspec + 50.1) / 100.0)
        r2    = r2  * 100.0 / pspec
        l2    = l2  * 100.0 / pspec
        ccl   = ccl * pspec / 100.0
      endif
c
c ----------------------------------------------------------------------
c
      if(rlvar .and. imeth .ne. 3) then
        rs        = r1 + r2
        lls       = l1 + l2
        xs        = 2.0 * pi * fr * lls / 1.0e+03
```

```
        zmag      = sqrt(rs * rs + xs * xs)
        xr        = xs / rs
        else
        r1        = 0.0
        l1        = 0.0
        r2        = 0.0
        l2        = 0.0
      endif
      zang      = atan(xr)
c
c  convert to actual units
c
      rs        = zmag * cos(zang)
      lls       = zmag * sin(zang) / 2.0 / pi / fr * 1.0e+03
c
c  millihenries and microfarads
c
      ls        = lls / 1.0e+03
      cl        = ccl / 1.0e+06
      pavg      = pavg   + pspec
      zavg      = zavg   + zmag
      xravg     = xravg  + xr
      cclavg    = cclavg + ccl
      r1avg     = r1avg  + r1
      l1avg     = l1avg  + l1
      r2avg     = r2avg  + r2
      l2avg     = l2avg  + l2
c
c     rewind 4
c     write(6,*)
      write(1,*)
c     write(6,*) ' trial = ',jj
      write(1,*) ' trial = ',jj
c
c  methods 1 and 3 - use subroutine bridge for every sample
c
      if(imeth .eq. 1 .or. imeth .eq. 3) then
        call bridge
        if(imeth .eq. 3) then
          write(6,507)
          write(6,501) iflag,thdi,rpl,rl,pspec,pout,rs,lls,ccl
          write(6,506) icount,jcount,kcount,theta1,theta2,rmsc,rmsv
c
c  harmonic powers
c
          do 36 j = 1,nhar1,2
          phar    = e(j) * harmg(j) * cos((phase(j) - haran(j)) / dr)
     1     / sqrt2
          write(1,521) j,phar
          write(6,521) j,phar
   36     continue
  521 format(1x,'power for harmonic ',i5,' is ',2f10.3)
        endif
      theta1    = th1 * dr
      theta2    = th2 * dr
      write(1,507)
c     write(6,507)
  507 format(' iflag,thdi,rpl,rl,pspec,pout,rs,lls,ccl'/
     1' icount,jcount,kcount,theta1,theta2,rmsc,rmsv')
      write(1,501) iflag,thdi,rpl,rl,pspec,pout,rs,lls,ccl
      write(1,506) icount,jcount,kcount,theta1,theta2,rmsc,rmsv
c     write(6,501) iflag,thdi,rpl,rl,pspec,pout,rs,lls,ccl
c     write(6,506) icount,jcount,kcount,theta1,theta2,rmsc,rmsv
```

```
  501 format(' summary ',i1,f6.1,1x,f10.1,f10.3,2f8.1,f8.3,f9.3,f10.1)
  506 format(10x,3i5,2f6.1,f10.3,f10.1)
      if(iflag .ne. 0) then
        write(1,570) iflag
        write(6,570) iflag
        write(11,570) iflag
        write(12,570) iflag
        write(6,501) iflag,thdi,rpl,rl,pspec,pout,rs,lls,ccl
        write(6,506) icount,jcount,kcount,theta1,theta2,rmsc,rmsv
        if(imeth .eq. 3) then
c
c  plot the failed case and stop
c
          write(6,*) ' iflag = ',iflag,', plot the failed case and stop'
          rewind 3
c
c  plot the input voltage, load current, fourier series of load current,
c  and dc voltage
c
          do 220  i  = 1,361
c
c for plotting in emx do not use '(i-1)'
c
          if(unix) write(3,504)sup(i),cur(i),hcur(i),vol(i)
          if(.not.unix)
     1             write(3,503) (i - 1),sup(i),cur(i),hcur(i),vol(i)
  220     continue
          stop
          else
          nflags = nflags + 1
          if(nflags .gt. 50) stop
          go to 85
       endif
      endif
c
      else
c
c  method 2 - retreive the fourier series from the table  (does not
c  apply to r1,l1,r2,l2 variations)
c
        iflag  = 0
        icount = 0
        jcount = 0
        kcount = 0
        theta1 = 0.0
        theta2 = 0.0
        rmsc   = 0.0
        rmsv   = 0.0
c
c  50.0 implies 50 equally-spaced values
c
        if(ivar .eq. 1) ipos= int(50.0 * (pspec - pmin)   / pdiff)  +1
        if(ivar .eq. 2) ipos= int(50.0 * (zmag  - zmin)   / zdiff)  +1
        if(ivar .eq. 3) ipos= int(50.0 * (xr    - xrmin)  / xrdiff) +1
        if(ivar .eq. 4) ipos= int(50.0 * (ccl   - cclmin) / cdiff)  +1
        if(ipos .gt. 50) ipos = 50
        do 31 k   = 3,nhar3,2
        harmg(k)  = hmtab(ipos,k)
        haran(k)  = hatab(ipos,k)
   31   continue
        htaba(1)  = htaba(1) + htabv(ipos,1)
        htaba(2)  = htaba(2) + htabv(ipos,2)
        htaba(3)  = htaba(3) + htabv(ipos,3)
```

```
        htaba(4)  = htaba(4) + htabv(ipos,4)
        pout      = htabv(ipos,1)
      endif
c
c  end of method 2 if
c
      if((imeth .eq. 1 .or. imeth .eq. 3) .and. iflag .eq. 0) then
c
c  build the fourier and plot files (first experiment only for
c  plot file)
c
        write(2,508) jj,(harmg(j),haran(j),j=1,nhar3,2)
        if(ivar .eq. 6) then
          write(9,509) jj,thdv,crest,
     1    thdi,(e(j),phase(j)*dr,j=1,nhar1,2)
          write(10,515) jj,pout,zmag,xr,ccl
        endif
  515   format(i6,f10.1,2f10.4,f10.1)
c
c  average the thdv, crest factor, and thdi
c
        nsqsum      = nsqsum + 1
        sqsum1(1)   = sqsum1(1) + thdv
        sqsum1(2)   = sqsum1(2) + crest
        sqsum1(3)   = sqsum1(3) + thdi
c
c  remember the min and max ckt. thdi, fund. volts and thdv at
c  wall outlets.
c
        if(rlvar) then
c
c  calculate the fund. voltage and thdv at the wall outlet
c
          do 406 k = 1,nhar1,2
          vinf  = e(k) * cmplx(cos(phase(k)),sin(phase(k)))
          amag  = harmg(k) / sqrt2
          aang  = haran(k) / dr
          ampr  = amag * cos(aang)
          ampi  = amag * sin(aang)
          amps  = cmplx(ampr,ampi)
          x1    = 2.0 * pi * fr * k * l1 / 1.0e+03
          volts = vinf - amps * cmplx(r1,x1)
          vmag  = cabs(volts)
          if(k .eq. 1) then
            v1mag    = vmag
            dist     = 0.0
            else
            dist     = dist + (vmag / v1mag) ** 2.0
          endif
  406     continue
          dist       = sqrt(dist) * 100.0
          if(jj .eq. 1) then
            thdimn = thdi
            thdimx = thdi
            thdvmn = dist
            thdvmx = dist
            v1min  = v1mag
            v1max  = v1mag
            else
            if(thdi .lt. thdimn) thdimn = thdi
            if(thdi .gt. thdimx) thdimx = thdi
            if(dist .lt. thdvmn) thdvmn = dist
            if(dist .gt. thdvmx) thdvmx = dist
```

```
            if(v1mag .lt. v1min) v1min  = v1mag
            if(v1mag .gt. v1max) v1max  = v1mag
          endif
        endif
c
c  average the voltage magnitudes and angles
c
        do 49 kk    = 3,nhar1,2
        sqsum2(kk,1)= sqsum2(kk,1) + e(kk)
        sqsum2(kk,2)= sqsum2(kk,2) + phase(kk)
   49   continue
c
        if(jj .eq. 1) then
          rewind 3
c
c  plot the input voltage, load current, fourier series of load current,
c  and dc voltage
c
          do 20  i  = 1,361
c
c for plotting in emx do not use '(i-1)'
c
          if(unix) write(3,504)sup(i),cur(i),hcur(i),vol(i)
          if(.not.unix)
     1            write(3,503) (i - 1),sup(i),cur(i),hcur(i),vol(i)
   20     continue
        endif
  504 format(1x,6f12.6)
  503 format(1x,i5,6f12.6)
  509 format(i6,f8.2,f8.4,f8.2,4(f15.6,f9.3))
      endif
c
c  end of method 1 and method 3 if
c
c  for all methods
c
c  sum the fundamental currents
c
      csreal(1,1) = csreal(1,1) + harmg(1) * cos(haran(1) / dr)
      csimag(1,1) = csimag(1,1) + harmg(1) * sin(haran(1) / dr)
      javg        = javg + 1
      do 25 k     = 3,nhar3,2
      harmr       = harmg(k) * cos(haran(k) / dr)
      harmi       = harmg(k) * sin(haran(k) / dr)
c
c  for running totals for all experiments
c
      csreal(k,1)  = csreal(k,1) + harmr
      csimag(k,1)  = csimag(k,1) + harmi
      csmag(k,1)   = csmag(k,1)  + harmg(k)
c
c  for present jjspace experiments
c
      csreal(k,2)  = csreal(k,2) + harmr
      csimag(k,2)  = csimag(k,2) + harmi
      csmag(k,2)   = csmag(k,2)  + harmg(k)
c
      if(javg .eq. jjspac) then
c
c  for running totals for all experiments
c
        diver(k,1) = sqrt(csreal(k,1) * csreal(k,1) + csimag(k,1) *
     1  csimag(k,1)) / csmag(k,1)
```

```
c
c  for present jjspace experiments
c
        diver(k,2) = sqrt(csreal(k,2) * csreal(k,2) + csimag(k,2) *
     1  csimag(k,2)) / csmag(k,2)
c
c  zero the sum for subscripts (k,2) to restart diver(k,2)
c  with each jjspac interval
c
        csreal(k,2) = 0.0
        csimag(k,2) = 0.0
        csmag(k,2)  = 0.0
      endif
   25 continue
      if(javg .eq. jjspac) then
        write(8,520) jj,((diver(k,kk),k=3,nhar3,2),kk=1,2)
c
c  computer screen shows only the running totals for all experiments
c
        write(6,520) jj,((diver(k,kk),k=3,nhar3,2),kk=1,1)
        javg        = 0
      endif
  520 format(1x,i5,28f9.6)
   30 continue
c
c  tests completed, now summarize the results
c
      do 35 k     = 3,nhar3,2
      diver(k,1)  = sqrt(csreal(k,1) * csreal(k,1) + csimag(k,1) *
     1  csimag(k,1)) / csmag(k,1)
   35 continue
      write(8,*)
      write(8,520) jjmax,(diver(k,1),k=3,nhar3,2)
      write(6,520) jjmax,(diver(k,1),k=3,nhar3,2)
      pdum        = pavg   / jjmax / mexec
      zdum        = zavg   / jjmax / mexec
      xrdum       = xravg  / jjmax / mexec
      ccldum      = cclavg / jjmax / mexec
      r1dum       = r1avg  / jjmax / mexec
      l1dum       = l1avg  / jjmax / mexec
      r2dum       = r2avg  / jjmax / mexec
      l2dum       = l2avg  / jjmax / mexec
      write(1,530) pdum,zdum,xrdum,ccldum,r1dum,l1dum,r2dum,l2dum
  530 format(1x,'pavg,zavg,xravg,cclavg = ',4f14.6/
     11x,'r1avg,l1avg,r2avg,l2avg = ',4f14.6)
      write(6,530) pdum,zdum,xrdum,ccldum,r1dum,l1dum,r2dum,l2dum
      write(8,530) pdum,zdum,xrdum,ccldum,r1dum,l1dum,r2dum,l2dum
      if(imeth .eq. 2) then
        htdum1 = htaba(1) / jjmax / mexec
        htdum2 = htaba(2) / jjmax / mexec
        htdum3 = htaba(3) / jjmax / mexec
        htdum4 = htaba(4) / jjmax / mexec
        write(1,*) ' method 2 averages'
        write(8,*) ' method 2 averages'
        write(1,530) htdum1,htdum2,htdum3,htdum4
        write(8,530) htdum1,htdum2,htdum3,htdum4
      endif
      if(ivar .eq. 6) then
        write(9,*) ' averages'
        sqdum1   = sqsum1(1) / nsqsum / mexec
        sqdum2   = sqsum1(2) / nsqsum / mexec
        sqdum3   = sqsum1(3) / nsqsum / mexec
        write(9,509) jjmax,sqdum1,sqdum2,sqdum3,e(1),phase(1) * dr,
```

```
     1  (sqsum2(j,1) / nsqsum / mexec,sqsum2(j,2) / nsqsum / mexec
     2  * dr,j=3,nhar1,2)
      endif
c
c  build the load current spectrum file (peak magnitudes)
c
      write(8,*) ' rms amps per kw follow'
      write(6,*) ' rms amps per kw follow'
      do 80 k = 1,nhar3,2
      aang    = atan2(csimag(k,1),csreal(k,1))
      amag    = sqrt(csreal(k,1) * csreal(k,1) + csimag(k,1) *
     1 csimag(k,1))
      write(12,*) mexec,k,amag,aang * dr
      a(k)      = amag
      aphase(k) = aang
      write(8,522) k,amag / sqrt2 / pavg * mexec
      write(6,522) k,amag / sqrt2 / pavg * mexec
      if(k .eq. 1) then
        amag1   = amag
        dist    = 0.0
        else
        dist    = dist + (amag / amag1) ** 2.0
      endif
  522 format(1x,i5,3pf12.6)
   80 continue
      dist      = sqrt(dist) * 100.0
      write(6,*)  ' thdi at shared bus = ',dist
      write(8,*)  ' thdi at shared bus = ',dist
      write(12,*) ' thdi at shared bus = ',dist
      write(6,*)  ' min,max thdi on indiv. ckts = ',thdimn,', ',thdimx
      write(8,*)  ' min,max thdi on indiv. ckts = ',thdimn,', ',thdimx
      write(12,*) ' min,max thdi on indiv. ckts = ',thdimn,', ',thdimx
      write(6,*) ' nflags = ',nflags
      write(8,*) ' nflags = ',nflags
      write(12,*)' nflags = ',nflags
c
      vrdiff = 0.0
      vidiff = 0.0
      if(mexec .eq. 1) then
        do 312 k = 1,nhar1,2
        vold(k) = e(k) * cmplx(cos(phase(k)),sin(phase(k)))
  312   continue
      endif
      if(rlvar) then
        write(6,*)  ' min,max fund. v at indiv. wall outlets = ',
     1  v1min,', ',v1max
        write(8,*)  ' min,max fund. v at indiv. wall outlets = ',
     1  v1min,', ',v1max
        write(11,*) ' min,max fund. v at indiv. wall outlets = ',
     1  v1min,', ',v1max
        write(6,*)  ' min,max thdv at indiv. wall outlets = ',
     1  thdvmn,', ',thdvmx
        write(8,*)  ' min,max thdv at indiv. wall outlets = ',
     1  thdvmn,', ',thdvmx
        write(11,*) ' min,max thdv at indiv. wall outlets = ',
     1  thdvmn,', ',thdvmx
      endif
      write(11,*) 'voltage update iteration = ',mexec
      do 306 k = 1,nhar1,2
      vinf = cmplx(0.0,0.0)
      if(k .eq. 1) then
        vmag = efund
        vang = afund
```

```
        vinf = efund * cmplx(cos(afund),sin(afund))
      endif
        amag = a(k) / sqrt2
        aang = aphase(k)
        ampr = amag * cos(aang)
        ampi = amag * sin(aang)
        amps = cmplx(ampr,ampi)
        volts = vinf - amps * cmplx(real(ztran),k * aimag(ztran))
        volts = vold(k) + accel * (volts - vold(k))
c
c ---------------------------------------------------------------------
c
c  comment-out the next statement if you want to update the fundamental
c  voltage (i.e., solve a loadflow using a shared transformer
c  impedance)
c
c     if(k .eq. 1) volts = vold(1)
c
c ---------------------------------------------------------------------
c
      if(abs(real(volts - vold(k))) .gt. abs(vrdiff)) then
        vrdiff  = real(volts - vold(k))
        mrdiff  = k
      endif
      if(abs(aimag(volts - vold(k))) .gt. abs(vidiff)) then
        vidiff  = aimag(volts - vold(k))
        midiff  = k
      endif
      vold(k) = volts
        vmag  = cabs(volts)
        vang  = 0.0
        if(vmag .gt. eps6)
     1   vang  = atan2(aimag(volts),real(volts))
        e(k)     = vmag
        phase(k) = vang
c
c  volts written in rms
c
      write(11,*) mexec,k,vmag,vang * dr
      if(k .eq. 1) then
        vmag1    = vmag
        dist     = 0.0
        else
        dist     = dist + (vmag / vmag1) ** 2.0
      endif
  306 continue
      write(6,1000) mexec,mrdiff,vrdiff,midiff,vidiff
      dist       = sqrt(dist) * 100.0
      write(6,*)  ' thdv at shared bus = ',dist
      write(8,*)  ' thdv at shared bus = ',dist
      write(11,*) ' thdv at shared bus = ',dist
      write(11,*)' nflags = ',nflags
c
      write(6,*)
c
c check for convergence (tolerance .03% of fundamental)
c
      if(abs(vrdiff) .lt. e(1) / 3000.0 .and. abs(vidiff)
     1 .lt. e(1) / 3000.0) then
        write(6,1010)
        stop
      endif
 1010 format(/1x,'solution converged')
```

```
 1000 format(1x,' mexec,harmonic,vrdiff,harmonic,vidiff = ',
     1 i5,2(i5,f10.4))
c      read(5,*)
c
  301 continue
      stop
      end
c
      subroutine bridge
c
c  subroutine for calculating the current to a single-phase full-wave
c  bridge rectifier load
c
      double precision rmsv,rmsc
      integer tag
      dimension e(25),phase(25),harmg(25),haran(25),sup(361),cur(361),
     1 hcur(361),vol(361),x(100),y(100),del(25)
      real Ls,istart,istep,istop,iloop
      complex b,bi(25),ci(25),di(25),cnst(25),li(25),ki(25),mi(25),s1,
     1 s2,c3(25),c4(25),c(25),s,a1,b1,a2,b2,a3,b3,a4,b4,ha,hb
c
c  nhar1 - highest harmonic of input voltage
c  nhar2 - highest harmonic of bridge current
c  nhar3 - highest harmonic written to current diversity spectrum file
c
      common /bridge1/ rmsv,rmsc,e,phase,harmg,haran,sup,cur,hcur,vol,
     1 rs,ls,pspec,cl,rl,fr,rpl,thdi,iflag,isolt,th1,th2,icount,
     2 jcount,kcount,pout
      common /bridge2/ nhar1,nhar2,nhar3,pi,dr,eps6,sqrt2
      kcount    = 0
      thdi      = 0.0
      w         = 2.0 * pi * fr
      th1       = 40.0 / dr
      if(isolt .eq. 2) Rl = 1.5 * E(1) * E(1) / pspec
      ptol      = pspec / 500.0
      ctol      = 0.0001
      vtol      = 0.001
      if(isolt .eq. 1) amptol = e(1) / rl / 1000.0
      if(isolt .eq. 2) amptol = pspec / e(1) / 1000.0
      voltol    = e(1) / 500.0
      itmax1    = 20
      itmax2    = 3
   95 icount    = 0
      jcount    = 0
      oldth1    = 0.0
      oldth2    = 0.0
      tag       = 0
      iflag     = 0
      atol      = 0.05 / dr
c
c  calculate the constants in the analytical expression from circuit parameters
c

   97 p         = Rs  / (w * Ls)
      q         = 1.0 / (w * Ls)
      r         = 1.0 / (w * Cl)
      t         = 1.0 / (w * Cl * Rl)
      a         = -(p + t) / 2.0
      b         = 0.5 * csqrt(cmplx(-4.0 * q * r + (p - t) * (p - t)))
      s1        = a + b
      s2        = a - b
   96 icount    = icount + 1
      do 70 n   = 1,nhar1,2
```

```
      cnst(n)   = 1.0 / (4 * a * a * n * n + (n * n - a * a + b * b )
     1            **2)
      del(n)    = phase(n) + n * th1
      di(n)     = cnst(n) *((n * n - a * a + b * b - 2 * a * t) * n * n
     1            * sin(del(n)) +(t *(a * a - b * b - n * n) - 2 * a * n
     2            * n) * n * cos(del(n)))
      ci(n)     = cnst(n) *((t *(a * a - b * b - n * n) - 2 * a * n * n)
     1            * sin(del(n)) +(a * a - b * b - n * n + 2 * a * t) * n
     2            * cos(del(n)))
      bi(n)     = cnst(n) *((a * a - b * b) *(a * a - b * b - n * n + 2
     1            * a * t) * sin(del(n)) +((4 * a * a +n * n - a * a + b
     2            * b) * t + 2 * a *(a * a - b * b)) * n * cos(del(n)))
      ki(n)     = cnst(n) * r * ((a * a - b * b) * 2 * a * sin(del(n)) +
     1            (4 * a * a - a * a + b * b + n * n) * n * cos(del(n)))
      li(n)     = cnst(n) * r * ((a * a - b * b - n * n) * sin(del(n)) +
     1            2 * a * n * cos(del(n)))
      mi(n)     = cnst(n) * r * (- 2 * a * n * n * sin(del(n)) + (a * a
     1            - b * b - n * n) * n * cos(del(n)))
 70   continue
c
c  initialization
c

c
c  start calculating th1 & th2
c

c
c  compute theta2 from old theta1
c
      istart     = 15.0
      istop      = 1850.0
      istep      = 10.0
  801 do 5 iloop = istart,istop,istep
      th         = real((iloop - 1) / 10.0 / dr)
c
c  analytical expression for current boundary condition
c
      curr       = 0.0
      do 71 n    = 1,nhar1,2
      curr       = curr + real((sqrt2 * E(n) / (s1 - s2)) * ((cexp
     1             (s1 * th)) *( - q * sin(del(n)) + q * (-ci(n) * s1+bi
     2             (n))) - (cexp(s2 * th)) * (- q * sin(del(n)) + q * (-
     3             ci(n) * s2 + bi(n)))) + (sqrt2 * E(n) * q) *
     4             (ci(n) * cos(n * th) + (di(n) / n) * sin(n * th)))
   71 continue

      if(curr .lt. ctol) then
        if(th .gt. pi) th = pi
        th2      = th
        if(istep .gt. 0.5)then
          istart = iloop - istep
          istop  = iloop + istep
          istep  = istep / 10
          goto 801
        endif
        tag      = tag + 1
        x(tag)   = th1
        y(tag)   = th2
c
c       write(6,*)' th1:',th1,'  , th2:',th2,' from current boundary'
        write(4,*)' th1:',th1,'  , th2:',th2,' from current boundary'
c
```

```
        if(abs(th2 - oldth2) .lt. atol) goto 93
        goto 99
      endif
    5 continue
c
       write(6,*)' did not find th2'
       write(4,*)' did not find th2'
c
       th1       = th1 - 10.0 / dr
       if((th1+eps6) .ge. 0.0) then
         goto 96
      else
        iflag = 7
        return
      endif

c
c  find new theta1 from voltage boundary condition
c

 99   oldth1     = th1
      vstart     = 1
      vstop      = 1800
      vstep      = 10

 914  do 66 vloop = vstart,vstop,vstep
      th1         = (vloop - 1.0) / 10.0 /dr
c
c  analytical expression for voltage(vol) boundary condition
c
      volt        = 0.0
      vol1        = 0.0
      do 73 n     = 1,nhar1,2
      del(n)      = phase(n) + n * th1
      vol1        = vol1 + real((sqrt2 * E(n) / (s1-s2)) * ((cexp
     1              (s1 * th2)) * ((s1 + p) * sin(del(n)) + q * (- li(n)
     2              * s1 + ki(n))) - (cexp(s2 * th2)) * (p * sin(del(
     3              n)) + s2 * sin(del(n)) + q * (- li(n) * s2 + ki(n))
     4              )) + (sqrt2 * E(n) * q) * (li(n) * cos(n * th2
     5              ) + (mi(n) / n) * sin(n * th2)))
      volt       = volt + sqrt2 * E(n) * sin(del(n))
   73 continue
      vol1       = vol1 * exp((th2 - pi) * t) - volt
      if(vol1 .lt. vtol) then
        if(vstep .gt. 0.5) then
          vstart = vloop - 2.0 * vstep
          if(vstart .le. 0.0) vstart = 1.0
          vstop  = vloop + vstep
          vstep  = vstep / 10.0
          goto 914
        endif
c
c        write(6,*)' th1:',th1,'  , th2:',th2,' from voltage boundary'
         write(4,*)' th1:',th1,'  , th2:',th2,' from voltage boundary'
c
        if(abs(th1 - oldth1) .lt. atol) then
         tag    = 0
         goto 93
        endif
        tag      = tag + 1
        x(tag)   = th1
        y(tag)   = th2
        if(tag .ge. 6) then
```

```
          tag    = 0
          if(abs(x(1) - x(5)) .lt. atol .and. abs(y(1) - y(5)) .lt.
     1      atol) then
            if(x(5) .gt. x(6)) then
              th1 = x(6)
            else
              th1 = x(5)
            endif
            if(y(5) .gt. y(4)) then
              th2 = y(5)
              else
              th2 = y(4)
            endif
            write(6,*) ' convergence from tag, th1 = ',th1,', th2 = ',
     1        th2
            write(4,*) ' convergence from tag, th1 = ',th1,', th2 = ',
     1        th2

            iflag = 5
            tag   = 0
            goto 93
          endif
        endif
        if(icount .gt. itmax1) then
          if(jcount .gt. itmax2) then
c
c  error - unable to find a solution
c
          endif
          jcount = jcount + 1
          if(jcount .gt. itmax2) then
            iflag = 1
            return
          endif

          atol   = atol + 0.05 / dr
c
          write(6,*)' atol',atol
          write(4,*)' atol',atol
c
          icount = 0
        endif
      oldth2    = th2
      goto 96
      endif
   66 continue
c
c  unsuccessful in finding a solution for this starting value of
c  theta1.  adjust theta1 and retry.
c
      th1        = oldth1 + 10.0 / dr
c
      write(6,*) ' starting value of theta1 increased by 10 degrees'
      write(4,*) ' starting value of theta1 increased by 10 degrees'

c
      if(th1 .gt. pi) then
        iflag    = 2
        return
      endif
      icount     = 0
c
      write(6,*)th1
```

```
      write(4,*)th1
c
      goto 97
   93 if(th1 .lt. 0.0 .or. th1 .gt. pi .or. th2 .lt. 0.0 .or.
     1 th2 .gt. pi) then
        iflag    = 6
        return
      endif
c     write(6,*)' ITERATION CONVERGED'
c     write(6,*)' th1:',th1,'    ','th2:',th2
      write(4,*)' ITERATION CONVERGED'
      write(4,*)' th1:',th1,'    ','th2:',th2
c
c  theta1 & theta2 obtained; start calculating current and voltage
c
c  calculate cur(input current) at each degree for one cycle
c
c  initialization
c

      do 7 i    = 1 , 361
      cur(i)    = 0.0
      hcur(i)   = 0.0
      vol(i)    = 0.0
      sup(i)    = 0.0
    7 continue
c
c  compute current during conduction period (current is zero on other time)
c

       theta1   = th1 * dr
       theta2   = th2 * dr
       do 8 i   = 1,361
       iang     = i - 1
       if(real(iang) .lt. theta1) goto 8
       if(real(iang) .gt. (theta1 + theta2)) goto 901
       th       = (iang - theta1) / dr
       amps     = 0.0
c
c  analytical expression of current during conduction period
c
      do 74 n  = 1 , nhar1 , 2
      amps     = amps + real((sqrt2 * E(n) / (s1-s2)) *
     1            ((cexp(s1 * th)) * (- q * sin(del(n)) + q * (-ci(n) *
     2            s1 + bi(n))) - (cexp(s2 * th)) * (- q * sin(del(n)) +
     3            q * (- ci(n) * s2 + bi(n)))) + (sqrt2 * E(n) * q
     4            ) * (ci(n) * cos(n * th) + (di(n) / n) * sin(n * th)))
   74 continue
      if(iang .ge. int(theta1 + 1) .and. iang .le. int(theta1 +
     1 theta2 - 1) .and. (amps + amptol) .lt. 0.0) iflag = 8
      cur(i)    = amps
      if(i .eq. 361) cur(1)    = amps
      ipos      = i + 180
      if(ipos .gt. 361) ipos   = ipos - 360
      cur(ipos) = -amps
      if(ipos .eq. 361) cur(1) = -amps
    8 continue
c
c  calculate output dc voltage
c
c  first, the dc voltage at the end of the charging period
c
  901 vfinal    = 0.0
```

```
      th        = theta2 / dr
      do 902 n  = 1,nhar1,2
      vfinal    = vfinal + real((sqrt2 * E(n) / (s1 - s2)) *
     1            ((cexp(s1 * th)) * ((s1 + p) * sin(del(n)) + q * (- li
     2            (n) * s1 + ki(n))) - (cexp(s2 * th)) * (p * sin(del(n)
     3            ) + s2 * sin(del(n)) + q * (- li(n) * s2 + ki(n)))) +
     4            (sqrt2 * E(n) * q) * (li(n) * cos(n * th) + (mi
     5            (n) / n) * sin(n * th)))
  902 continue
      do 9 i   = 1,181
      volts    = 0.0
      iang     = int(theta1) + i
      if(iang .gt. int(theta1 + theta2)) go to 700
c
c  capacitor charging mode
c
      th       = (iang - theta1) / dr
      do 75 n  = 1 , nhar1 , 2
      volts    = volts + real((sqrt2 * E(n) / (s1 - s2)) *
     1            ((cexp(s1 * th)) * ((s1 + p) * sin(del(n)) + q * (- li
     2            (n) * s1 + ki(n))) - (cexp(s2 * th)) * (p * sin(del(n)
     3            ) + s2 * sin(del(n)) + q * (- li(n) * s2 + ki(n)))) +
     4            (sqrt2 * E(n) * q) * (li(n) * cos(n * th) + (mi
     5            (n) / n) * sin(n * th)))
   75 continue
      go to 710
c
c  capacitor discharging mode
c
  700 th        = (iang - theta1 - theta2) / dr
      volts     = vfinal * exp(-th * t)
c
c  put the voltage in the appropriate location
c
  710 ipos      = iang + 1
      i180      = ipos + 180
      vol(ipos) = volts
      if(ipos .eq. 361) vol(1) = volts
      if(i180 .gt. 361) i180   = i180 - 360
      vol(i180) = volts
      if(i180 .eq. 361) vol(1) = volts
    9 continue
c
c  calculate harmonic components
c  calculate the constants in the analytical expression of harmonic components
c
c  the analytical expression is of three parts; all three parts are alike
c  but have different constant values. so a subroutine(har) is used to
c  calculate the identical parts
c

      do 701 n  = 1 , nhar1 , 2
      c3(n)     = (E(n) * q / (sqrt2 * b)) *(- sin(del(n)) - ci(n)
     1            * a - ci(n) * b + bi(n))
      c4(n)     = (E(n) * q / (sqrt2 * b)) * (sin(del(n)) + ci(n)
     1            * a - ci(n) * b - bi(n))
  701 continue
C  CALCULATE UP TO nhar2

      do 11 k  = 1 , nhar2 , 2
      do 702 n = 1 , nhar1 , 2
      c(n)     = c3(n)
  702 continue
```

```
      s          = a+b
      call har(k , th2 , c , s , ha ,hb)

      a1         = ha
      b1         = hb
      do 705  n = 1 , nhar1 , 2
      c(n)       = c4(n)
  705 continue
      s          = a-b

      call har(k , th2 , c , s , ha ,hb)

       a2        = ha
       b2        = hb

c
c  seperate expressions for the fundamentals of third & fourth parts
c
      a3         = 0.0
      b3         = 0.0
      a4         = 0.0
      b4         = 0.0

      do 706  n = 1, nhar1 , 2
      if(k .eq. n) then
      a3         = a3 + E(n) * q * sqrt2 * (di(n) / (2.0 * n * n *
     1             pi)) * (1.0 - cos(2.0 * n * th2))

      b3         = b3 + E(n) * q * sqrt2 * (di(n) / (2.0 * n * pi
     1             )) * (2.0 * th2 - (1.0 / n) * sin(2.0 * n * th2))

      a4         = a4 + E(n) * q * sqrt2 * (ci(n) / (2.0 * pi))*
     1             (2.0 * th2 + (1.0 / n) * sin(2.0 * n * th2))

      b4         = b4 + E(n) * q * sqrt2 * (ci(n) / (2.0 * n * pi)
     1             ) * (1.0 - cos(2.0 * n * th2))

       else
       a3        = a3 + E(n) * q * sqrt2 * (- di(n) / (n * pi)) *
     1             ((cos(k * th2 + n * th2)) / (n + k) + (cos(- k * th2 +
     2             n * th2)) / (n - k) - (2.0 * n / (n * n - k * k)))

       b3        = b3 + E(n) * q * sqrt2 * (di(n) / (n * pi)) * ((
     1             sin(- k * th2 + n * th2)) / (n - k) - (sin(k * th2 +
     2             n * th2)) / (n + k))

      a4         = a4 + E(n) * q * sqrt2 * (ci(n) / pi) * ((sin(k *
     1             th2 + n * th2)) / (n + k) + (sin(- k * th2 + n * th2))
     2             / (n - k))

      b4         = b4 + E(n) * q * sqrt2 * (ci(n)/pi) * ((cos(- k *
     1             th2 + n * th2)) / (n - k) -  (cos(k * th2 + n * th2))
     2             / (n + k) - ((2.0 * k) / (n * n - k * k)))

      endif
  706 continue
      ak         = real(a4 + a3 + a2 + a1)
      bk         = real(b4 + b3 + b2 + b1)

c
c  calculating the magnitude and angle for each harmonic
c
```

```
      harmg(k)  = sqrt(ak * ak + bk * bk)
      haran(k)  = atan2(ak , bk) - th1 * k
   11 continue
c
c  calculating thdi
c
C
      thdi      = 0.0
      do 24   j = 3 , nhar2 , 2
      thdi      = thdi + harmg(j) * harmg(j)
   24 continue
      thdi      = ((sqrt(thdi)) / harmg(1)) * 100.0

c
c  calculate cur(current adding all harmonics)
c
      do 21  i  = 1 , 180
      th        = real((i - 1) / dr)
      do 13  k  = 1 , nhar2 , 2
      hcur(i)   = hcur(i) + harmg(k) * sin(k * th + haran(k))
   13 continue
      hcur(180 + i) = - hcur(i)
   21 continue
      hcur(361) = hcur(1)
c
c  making haran(j) wrt input voltage sine wave
c

       do 27  k = 1 , nhar2 , 2
       haran(k) = dr * haran(k)
       nn       = int(haran(k) / 360.0)
       haran(k) = haran(k) - nn * 360.0
   27  continue
       rmsc     = 0.0
       rmsv     = 0.0
       do 49  i = 2 , 361
       rmsv     = rmsv + ((vol(i - 1) * vol(i - 1) + vol(i) * vol(i)) /
     1            2.0)
       rmsc     = rmsc + ((cur(i - 1) * cur(i - 1) + cur(i) * cur(i))/
     1            2.0)
   49 continue
      rmsv      = sqrt(rmsv / 360.0)
      rmsc      = sqrt(rmsc / 360.0)
      ploss     = Rs * rmsc * rmsc
      pout      = (rmsv * rmsv) / Rl
      pin       = ploss + pout
      oldth1    = 0.0
      oldth2    = 0.0
      if(ploss .gt. pout) then
        iflag   = 4
        return
      endif
      kcount    = kcount + 1
      if(isolt .eq. 1) pspec = pout
c
c     write(6,*)' kcount = ',kcount,', pspec,pout = ',pspec,pout
      write(4,*)' kcount = ',kcount,', pspec,pout = ',pspec,pout
c     write(6,*)
      write(4,*)
c
      if(abs(pout - pspec) .gt. ptol) then
        if(kcount .gt. itmax1) then
          iflag = 3
```

```
          return
        endif
        Rl = rmsv * rmsv / pspec
        goto 95
      endif
c
c  calculate the input voltage
c
      do 14 i  = 1,361
      th       = (i - 1) / dr
      do 15 j  = 1,nhar1,2
      sup(i)   = sup(i) + E(j) * sin(j * th + phase(j))
   15 continue
      sup(i)   = sup(i) * sqrt2
   14 continue
c
c  estimate the peak-to-peak ripple
c
      rpl = 100.0 / (2.0 * fr * rl * cl)
c
c  check if there is conduction restart
c
      imin     = int(theta1  + theta2) + 1
      imax     = int(theta1) + 179
      do 76 i  = imin,imax
      if(abs(sup(i)) - vol(i) .gt. voltol) then
        iflag  = 9
        return
      endif
   76 continue
      end

c
c  subroutine to calculate the jarmonic component of is
c


      subroutine har( k , th2 , c , s , ha , hb)
      complex c(25) , s , ha , hb
      common /bridge2/ nhar1,nhar2,nhar3,pi,dr,eps6,sqrt2

c
c  expression for b(k)
c
      ha        = 0.0
      hb        = 0.0
      do 10  n  = 1 , nhar1, 2
      hb        = hb + (2.0 * c(n) / (pi * (s * s + k * k))) * ((
     1            cexp(s * th2)) * (s * sin(k * th2) - k * cos(k * th2)
     2            ) + k)


c
c  expression for a(k)
c

      ha        = ha +(2.0 * c(n) / (pi * (s * s + k * k))) *
     1            ((cexp(s * th2)) * (s * cos(k * th2) + k * sin(k * th2
     2            )) - s)
   10 continue
      return
      end
c
```

```
c  dummy subroutine seed needed when using unix
c
c     subroutine seed(idum)
c     integer*2 idum
c     return
c     end
c
c  dummy functions ran and secnds needed when using fl32
c
      function ran(idum)
      ran = 0.0
      return
      end
      function secnds(adum)
      secnds = 0.0
      return
      end
```

B
APPENDIX B

Overview

Program TRIAC calculates the harmonic components of the input current of a phase-controlled rectifier most commonly used as light dimmers in incandescent lighting. The analytical model of the circuit are based on the derivations provided in Chapter 2. The program is capable of performing a one-shot simulation as well as a Monte Carlo simulation for calculating the diversity factor of a group of loads operating at a different power or lumen level. The load model for the incandescent light is based on the equations provided in Chapter 2. The input parameters are line inductance, fundamental supply voltage, full load power, and operating power/lumen level in percentage of full load power/lumen. All the input data are read from the screen and the output and plot data are dumped into files. Following is a list of input prompts for screen based data acquisition:

Screen-Based Data Input Format for Program TRIAC

The words in *italic* denote the actual screen messages and words in **bold** denote input data options.

enter 1 for a one-shot simulation and 2 for diversity

Input **1** for solving a single circuit under known operating condition and **2** for performing a Monte Carlo simulation for calculating the current harmonics diversity factor for a group of load operating at random power/lumen level. An uniform distribution of power/lumen is used for random number generation.

enter line inductance (ls) in mh

For incandescent lighting loads the line inductance is negligible and a small number such as **1.0E-06** is to be provided.

press 1 for constant resistance load

press 2 for lighting load

For lighting load (input **2**), the load resistance varies with power level of the lamp and the equation 2.13 is used to update load resistance corresponding to a particular power level.

For one-shot simulation (**method 1**) and for lighting load (input **2**)

press 1 to enter output POWER in (0 – 100%)

press 2 to enter output LUMEN in (0 – 100%)

Equation 3.3 is used to convert output lumen level to output power.

For Monte Carlo simulation (**method 2**):

enter total numbers of trials and spacing

For example if there are 60 loads in a group and a 300 shot Monte Carlo simulation is to performed then **total number of trials** will be **18000** and the **spacing** will be **60**.

For constant resistance load (**input 1**)

enter the minimum and maximum range of uniform power variation in (0 – 100%)

For lighting load (**input 2**)

enter the minimum and maximum range of uniform lumen variation in (0 – 100%)

Output Files for Program TRIAC

Several output files are created by the program. A brief description of the output files follows:

Summary.div: For each call to the 'subroutine triac', that actually calculates the line current harmonic spectrum, the summary file contains the data for the circuit parameter, calculated THDI, start and stop angle for input current pulse, output dc power, and input power for each harmonic.

Fourier.div: This file contains the fourier spectrum of the input line current. The magnitude is given in peak values and the phase angle in degrees.

Plot.div:This file contains the time domain data of line current from the circuit equation and reconstructed from the harmonic spectrum for one complete cycle, discretized at 1 degree interval.

Div.div: This file contains the current harmonic diversity numbers for each individual odd harmonic upto the 15th.

Listing of Program TRIAC

```
c
c  triac.for
c
c  computes the fourier coefficients of the current waveform of
c  a phase-controlled triac circuit.  Supply voltage sinusoidal
c  and inductance included in calculation.
c  a one-shot simulation or a monte-carlo simulation assuming uniform
c  distribution of load power or lumen intensity can be performed
c
      real harmg(25),haran(25),cur(361),hcur(361),ls
      common /dimmer1/ nhar2,nhar3,sqrt2,pi,dr,fr,rl,e,alpha,harmg,
     1                 haran,rmsc, thdi, pout ,pspec,pload,perr,
     2                 beta,theta,w,ls,z,irl
c
c  nhar2 - highest harmonic of triac current
c  nhar3 - highest harmonic written to current diversity spectrum file
c  fr    - system frequency
c

      nhar2     = 25
      nhar3     = 15
      fr        = 60.0
      eps6      = 1.0e-06
      pi        = 4.0 * atan(1.0)
      w         = 2 * pi * fr
      dr        = 180.0 / pi
      sqrt2     = sqrt(2.0)
      perr      = 0.005
      iflag     = 0
```

```
c
c  open output files
c  summary.div -- summary of results
c  fourier.div -- frequency spectrum of line line current
c  plot.div    -- plot file containing the data points in space
c              -- delimited format
c  div.div     -- diversity numbers for harmonics 3 through 15
      open(unit=1,file='summary.div')
      open(unit=2,file='fourier.div')
      open(unit=3,file='plot.div')
      open(unit=4,file='div.div')
      write(1,300)
      write(2,300)
      write(3,300)
      write(4,300)
 300  format(1x)
      rewind 1
      rewind 2
      rewind 3
      rewind 4
c
c  random number generating function
c
      call gettim(is1,is2,is3,is4)
      call seed(is4)

c
c  input and poutput statements
c


 90   write(6,*)'enter 1 for a one-shot simulation and 2 for diversity'
      read(5,*,err=90)imeth
      if(imeth .ne. 1 .and. imeth .ne. 2) then
        write(6,*)'Invalid entry : try again'
        write(6,*)
        goto 90
      endif

      write(*,*)
      write(6,*)'enter line inductance (ls) in mh'
      write(6,*)
      read(5,*,err =26)ls
      ls        = ls * 1.E-3

      write(6,*)'press 1 for constant resistance load'
      write(6,*)'press 2 for lighting load'
      read(*,*)irl
c
c  for imeth = 2 ; diversity calculation
c
      if (imeth . eq. 2) then
         ebase     = 120.00
         e         = ebase
         pbase     = 100.00
         pload     = pbase
         rl        = (e * e / pload)
         z         = sqrt(rl * rl + w * w * ls * ls)
         theta     = atan2(w * ls , rl)
         call diversity
         stop
      endif
c
```

```
c  for imeth = 1 ; one-shot simulation
c
      write(6,*)
 25   write(6,*)'enter the fundamental voltage magnitude (volts - rms)'
      read(5,*,err =25)e
      write(6,*)'ok, ',e,' volts, with phase angle = 0'
 26   write(6,*)

 15   write(6,*)'Enter full load power(pload)'
      read(5,*,err=15)pload
      write(6,*)

      if (irl .eq. 2) then
          write(6,*)
          write(6,*)'press 1 to enter output POWER in (0 - 100%)'
          write(6,*)'press 2 to enter output LUMEN in (0 - 100%)'
          read(5,*)ipl

          write(6,*)'Enter output lumen/power in %'
          read(5,*)pspec

          if(ipl .eq. 1)then
               pspec = pspec * pload / 100.0
          else
               pspec = ((pspec / 100.0) ** .47059) * pload
          endif
      else
          write(6,*)'enter output power in %'
          read(5,*)pspec
         pspec = pspec * pload / 100.0
      endif

      if(pload .lt. pspec)then
        write(6,*)'Invalid output power : try again'
        write(6,*)
        goto 15
      endif

      write(5,*)' ok, load power = ',pload,' watts, and'
     1,' output power = ',pspec,' watts  '
c
c  calculate load resistance 'rl', impedance 'z', and angle 'theta'
c

      if (irl .eq. 1) then
        rl  = e * e / pload
      else
        rl  = (e * e / pload) * ((pspec / pload) ** .25)
      endif
      z         = sqrt(rl * rl + w * w * ls * ls)
      theta     = atan2(w * ls , rl)

c
c  calculate the fourier components of input light current of light dimmer
c
c
      call dimmer

c
c  write the fourier components of currnt to file fourier
c
      do 20 k = 1, nhar2, 2
      write(2,*)k, harmg(k) / harmg(1) * 100.0 ,'%',haran(k) * dr,'deg'
```

```
 20   continue

c
c  Write the sumary file
c
      write(6,*)
      write(6,*)' Fundamental voltage (rms,voltss) = ',e
      write(6,*)' Fundamental current (rms,amps)   =',harmg(1) / sqrt2
      write(6,*)' THD current (%)                  =',thdi
      write(6,*)' Output power (watts)             =',pout
      write(6,*)' Load resistance (ohms)           =',rl
      write(6,*)' Delay Angle (Alpha)              =',alpha * dr
      write(6,*)' Extinction Angle (beta)          =',beta * dr
      write(1,*)
      write(1,*)' Fundamental voltage (rms,voltss) = ',e
      write(1,*)' Fundamental current (rms,amps)   =',harmg(1) / sqrt2
      write(1,*)' THD current (%)                  =',thdi
      write(1,*)' Output power (watts)             =',pout
      write(1,*)' Load resistance (ohms)           =',rl
      write(1,*)' Delay Angle (Alpha)              =',alpha * dr
      write(1,*)' Extinction Angle (beta)          =',beta * dr
c
c  Build the plot file
c
      do 29 i   = 1 , 361
        cur(i)  = 0.0
        hcur(i) = 0.0
 29   continue
      do 30   i = 1 , 361 , 1
        th        = real((i - 1) / dr)
        if(th .lt. alpha) goto 30
        if(th .gt. beta)  goto 39
        if(rl / ls / w .gt. 20.0)then
          cur(i)  = sqrt2 * e / rl * sin(th)
        else
          cur(i)  = (sqrt2 * e / z) *  (sin(th - theta) - exp((-rl /ls)
     1              * (th / w - alpha /w)) * sin(alpha - theta))
        endif

      do 35   j = 1 , nhar2 , 2
      hcur(i)   = hcur(i) + harmg(j) * sin(j * th + haran(j))
 35   continue

      ipos      = i + 180
      if(ipos .gt. 361) ipos  = ipos -360
      cur(ipos)  = - cur(i)
      hcur(ipos) = - hcur(i)
      if(ipos .eq. 361) then
        cur(1)  = -cur(i)
        hcur(1) = -hcur(i)
      endif
 30   continue
 39   do 40   i = 1, 361
      write(3,*) (i - 1), cur(i), cur(i), hcur(i), hcur(i)
 40   continue
      stop
      end

c
c
c  subroutine dimmer uses the bisection technique to solve for delay
c  angle (alpha) given a specified outo\put power
c
```

```
      subroutine dimmer

      real harmg(25), haran(25),ls
      common /dimmer1/ nhar2,nhar3,sqrt2,pi,dr,fr,rl,e,alpha,harmg,
     1                 haran,rmsc, thdi, pout ,pspec,pload,perr,
     2                 beta,theta,w,ls,z,irl
c
c  initial guess of alpha
c
      alpha     = (1 - pspec / pload ) * 180.00 / dr
 100  call triac1

c
c  start bisection technique for alpha convergence
c
      if (pout .gt. pspec) then
        goto 120
      else
      alpha     = alpha - 10.0 /dr
      goto 100
      endif

 120  alpstr    = alpha * dr
      alpstp    = 360.00
      alpinc    = 10.00

 125  do 130 angle = alpstr , alpstp, alpinc
         alpha  = angle / dr
         call triac1
         if (pout .lt. pspec) then
            if (abs(pout - pspec) / pspec .lt. perr) return
            alpstr  = angle - alpinc
            alpstp  = angle
            alpinc  = alpinc / 10.0
            if (alpinc .lt. .00001) then
            write(6,*)'power not converging'
            stop
            endif
            goto 125
         endif
 130  continue
        return
        end

c
c
c  subroutine triac1 calculates the fourier component of line current
c  for a particular value of delay angle (alpha)
c
      subroutine triac1
      real harmg(25), haran(25), ls
      common /dimmer1/ nhar2,nhar3,sqrt2,pi,dr,fr,rl,e,alpha,harmg,
     1                 haran,rmsc, thdi, pout ,pspec,pload,perr,
     2                 beta,theta,w,ls,z,irl

      ijump     = 0
      if(rl / ls / w .gt. 20.00) then
        ijump   = 1
        beta    = pi
        goto 140
        endif
c
```

```
c  determine beta from the current equation using bisection method
c


 120  betstr    = 170.00
      if(betstr .lt. alpha * dr)betstr = pi * dr
      betstp    = 360.00
      betinc    = 10.00

 125  do 130 angle  = betstr , betstp , betinc
         ang     = angle / dr
         c3      = (rl / ls) * (ang /w - alpha /w)
         if(c3 .gt. 20) c3 = 20.0
         curr    = ( sqrt2 * e / z) * (sin(ang - theta) - exp(-c3)
     1              * sin (alpha - theta))
         if (curr.lt. 0.0) then
            if(betinc .lt. .1) then
              beta = ang
              goto 135
            endif
            betstr = angle - betinc
            if(betstr .lt. alpha * dr)betstr = pi * dr
            betstp = angle
            betinc = betinc / 10.0
            goto 125
         endif
 130   continue
       beta = pi

c  define the constants c1 and  c2
c
 135  c1        = rl * alpha / ls / w
      if(c1 .gt. 20 ) c1 = 20.0
      c2        = rl * beta / ls / w
      if (c2 .gt.20) c2 = 20.00

 140  do 10 k   = 1 , nhar2 , 2
      if(k .eq. 1)then
        a1      = (sqrt2 * e / pi / z ) * ((beta - alpha) * cos(theta)
     1             - 0.5 * (sin(2 * beta - theta) - sin(2 * alpha -
     2             theta)))
        b1      = (sqrt2 * e / pi / z ) * ((-beta + alpha) * sin(theta)
     1            + 0.5 * (-cos(2 * beta - theta) + cos(2 * alpha -
     2            theta)))
      else
        a1      = (sqrt2 * e / pi / z) * (-sin((1 + k) * beta - theta) /
     1            (1 + k) + sin((1 - k) * beta - theta) / (1 - k) + sin
     2            ((1 + k) * alpha - theta) / (1 + k) - sin((1 - k) *
     3            alpha - theta) / (1 - k) )
        b1      = (sqrt2 * e / pi / z) * (-cos((1 + k) * beta - theta) /
     1            (1 + k) - cos((1 - k) * beta - theta) / (1 - k) + cos
     2            ((1 + k) * alpha - theta) / (1 + k) + cos((1 - k) *
     3            alpha - theta) / (1 - k) )
      endif
      a2        = 0.0
      b2        = 0.0
      if(ijump .eq. 1) goto 145

      a2        = exp(c1) *  sin (theta - alpha) * (2 * sqrt2 * e * w /
     1            pi / z) * (exp(-c1) * (rl / ls * sin(k * alpha) + k *
     2            w * cos (k * alpha)) - exp(-c2) * (rl /ls * sin(k *
     3            beta) + k * w * cos(k * beta))) / ((rl /ls) ** 2 + (k
     4            * w) ** 2)
```

```
      b2        = exp(c1) *  sin (theta - alpha) * (2 * sqrt2 * e * w /
     1            pi / z) * (exp(-c2) * (-rl / ls * cos(k * beta) + k *
     2            w * sin (k * beta)) - exp(-c1) * (-rl /ls * cos(k *
     3            alpha) + k * w * sin(k * alpha))) / ((rl /ls) ** 2 +
     4            (k * w) ** 2)
 145  ak        = a1 + a2
      bk        = b1 + b2
      harmg(k)  = sqrt(ak * ak + bk * bk)
      haran(k)  = atan2(bk,ak)
 10   continue
c
c  calculate the output power 'pout', RMS current 'rmsc', and THDI, 'thdi'
c

      rmsc      = 0.0
      thdi      = 0.0
      do 25   j = 3 , nhar2 , 2
      thdi      = thdi + harmg(j) * harmg(j)
 25   continue
      rmsc      = sqrt((harmg(1) * harmg(1) + thdi) / 2.0)
      thdi      = ((sqrt(thdi)) / harmg(1)) * 100.0
      pout      = rl * rmsc * rmsc

      return
      end

c
c
c  subroutine diversity calculates the diversity factor of current
c  harmonics for uniform power variation
c

            subroutine diversity

      real harmg(25), haran(25),div(49),algadd(49),veccos(49),
     1     vecsin(49),vecadd(49),ls
      common /dimmer1/ nhar2,nhar3,sqrt2,pi,dr,fr,rl,e,alpha,harmg,
     1                 haran,rmsc, thdi, pout ,pspec,pload,perr,
     2                 beta,theta,w,ls,z,irl

c
c  input output statements for diversity calculation
c
      write(6,*)
 95   write(6,*)'enter total number of trials and spacing?'
      read(5,*,err=95)jjmax,jjspac

      if(jjmax .lt. jjspac)then
        write(6,*)'Invalid entry : Try again'
        write(6,*)
        goto 95
      endif
      icount    = jjspac


 90   if(irl .eq. 1) then
         write(6,*)'enter the minimum and maximum range of uniform'
         write(6,*)'POWER variation in  (0 - 100 %)'
      else
         write(6,*)'enter the minimum and maximum range of uniform'
         write(6,*)'LUMEN variation in  (0 - 100 %)'
      endif
      read(5,*,err=90) pmin, pmax
```

```
      if(pmin .gt. pmax .or. pmin .gt. 100 .or. pmax .gt. 100) then
        write (6,*)'Invalid Entry : Try again '
        write(6,*)
        goto 90
      endif
      write(6,*)

      write(6,220)irl,int(pmin), int(pmax)
      write(6,*)
      write(6,210)
      if(irl .eq. 2) then
         write(4,*)'IVAR = 1 : LUMEN variation'
      else
         write(4,*)'IVAR  = 2 : POWER variation'
      endif
      write(4,*)
      write(4,220)irl,int(pmin) , int(pmax)
      write(4,*)
      write(4,210)

 210  format('   Harm #   1     3     5     7     9    11    13    15')
 220  format('   Uniform variation of IVAR =',i2,'(',i3,'% - ',i3,'% )')
      write(6,*)
      write(4,*)

      pmin      = pmin / 100.0
      pmax      = pmax / 100.0

          do 50 k = 1 , nhar3 , 2
            algadd(k)  = 0.0
            veccos(k)  = 0.0
            vecsin(k)  = 0.0
            vecadd(k)  = 0.0
 50      continue

      pavg      = 0.0
      do 10 n = 1, jjmax
         call random(randp)

         pspec  = pmin + (pmax - pmin) * randp

          if(irl .eq. 2 ) then
           pspec = (pspec ** .47059) * pload
           rl        = (e * e / pload) * ((pspec / pload) ** .25)
           z         = sqrt(rl * rl + w * w * ls * ls)
           theta     = atan2(w * ls , rl)
          else
            pspec = pspec * pload
          endif

         pavg   = pavg + pspec
         call dimmer
             do 20 j = 1 , nhar3 , 2
                algadd(j) = algadd(j) + harmg(j)
                veccos(j) = veccos(j) + harmg(j) * cos(haran(j))
                vecsin(j) = vecsin(j)+harmg(j) * sin(haran(j))
 20         continue
       if(n . eq. icount) then

         do 30 j = 1 , nhar3 , 2
            vecadd(j)=sqrt(veccos(j)*veccos(j)+ vecsin(j)*vecsin(j))
             div(j)=vecadd(j)/algadd(j)
```

```
 30      continue
c
c  write diversity file
c
         write(6,200)n,(div(j), j = 1 , nhar3 , 2)
         write(4,200)n,(div(j), j = 1 , nhar3 , 2)

 200     format(1x, i5, 2x, 8f6.3)

         icount = jjspac + icount
         if(icount . gt. jjmax) goto 40
       endif
 10    continue

 40    pavg     = pavg / jjmax / pload * 100.00
       write(6,*)
       write(6,230)int(pavg)
       write(4,*)
       write(4,230)int(pavg)
 230   format ('   Average power = ',i3,' %')
       return

       end
```

Target:
End-Use Power Quality Mitigation Systems

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EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com