Analysis of time-varying harmonics in electrical distribution systems

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ANALYSIS OF TIME-VARYING HARMONICS IN
ELECTRICAL DISTRIBUTION SYSTEMS

by

Venkatasubramaniam Banunarayanan

A thesis submitted in partial fulfillment
of the requirements for the degree of

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in

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Department of Electrical and Computer Engineering
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ABSTRACT

This thesis analyzes the time-varying nature of fundamental and harmonic signals in electric power distribution systems. Measurements show that signal variations are neither completely deterministic nor random. As a consequence the deterministic and random parts are analyzed separately. Two methods are employed to extract the deterministic and random parts. One method extracts the deterministic part using regression analysis, and the remaining random part is expected to resemble the normal distribution. A procedure for obtaining the distribution of the peak voltages is presented. In the second method, wavelet transforms is applied to harmonic signal variations. The Discrete Wavelet Transform is used to quantify harmonic changes with time. Experimental data of fundamental and harmonic currents are analyzed both methods and the results presented. The thesis concludes with the potential applications of the proposed techniques.
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Chapter 1

INTRODUCTION

An ideal electrical power system is one in which the voltages and currents are sinusoidal with fixed frequency and voltage magnitudes. However, none of these conditions are fulfilled in practice. Waveform distortion is present in both voltage and current waveforms. These distortions corresponding to deviations from perfect sinusoids are expressed in terms of harmonic components [1]. The causes for the distortion include non-linear electronic devices as well as transients from load switching and intermittent use of appliances.

The analysis of power system harmonic distortion is of prime importance to power engineers. It is known that harmonics have undesirable effects including the degradation of telephone communications caused by induced harmonic noise [1],[2], overloading of power apparatus and systems, maloperation of control and protection equipment and destruction of power factor correction capacitors [1]. Furthermore, industrial processes have begun to rely on more and more control systems involving rectification of alternating voltage. These control equipment employ semiconductors and other nonlinear devices which assume a distortion free sinusoidal supply voltage. Thus the harmonic problem worsens due to the injection of more harmonics into the power system by these equipment.

Harmonic components of both voltages and currents vary continually with respect to time due to continuous switching of various individual loads. Another source that contributes to these variations is the change in system configuration from the switching of power factor correction capacitors, voltage regulators and distribution feeders by the utility company.
There is a wide range of non-linear loads connected to the distribution system which inject harmonic currents in a random fashion as well. Also transients due to induction motors and other equipment cause a change in harmonic currents. In recent years studies of time variation of harmonics indicate that these changes are not deterministic in nature. Therefore, the harmonic components cannot be modeled deterministically. The random nature of the harmonics should also be taken into consideration while analysing harmonic levels.

In the following paragraphs, a brief literature survey on the application of probability and statistical analysis to power system harmonics is presented.

In an effort to predict harmonic levels, Ref. [3] proposed to divide the non-linear loads into four categories, a deterministic number of deterministic currents, a random number of constant currents, a constant number of random currents and a random number of random currents. In most practical cases, however, individual customer loads are often unknown. Kaprelian et al. [4] modeled the real and imaginary components of the harmonic current phasors injected into the network as jointly normal random variables. A complete characterisation of the harmonic components at a single bus was accomplished by using the mean, standard deviation and the correlation coefficient of the real and imaginary parts, while independence among various sources of harmonic current generation was assumed. Reference [5] presents the results of a survey of the harmonic levels on the American Electric Power Distribution System. The authors observed that capacitors contribute to circuit resonance, and recommend including more information about probability of failure from the manufacturers end when supplying power equipment.

Reference [6] reported a seven-day measurement of harmonic current and voltage. The stochastic behavior of the harmonic voltages and currents are characterized with the help of the maximum, minimum and mean levels of harmonics. The authors found that at all of the locations 99% of the time the voltage Total Harmonic Distortion was much smaller than the 5% limit recommended by IEEE Std. 519 [2]. They recommended that a probabilistic approach instead of a deterministic one should be used while accounting for the random variation of harmonics.

A statistical description of grouped domestic electrical load currents from the 60 Hz point of view is made in Ref. [7] where the authors indicated that it is imperative that
an analysis of the behavior of domestic electrical load currents be based on valid data measurement. A sampling interval of 2 minutes was made in an attempt to follow the time variation of the loads, and analysis of the customer current distributions is shown to fit a beta distribution. Reference [8] contains the details of a survey of power system harmonics in a metropolitan area network. Measurements were made at loads in both distribution and transmission circuits, and compliance of the harmonic levels to the IEEE 519 Standard were discussed. The reference found that, despite numerous violations of current THD limits set by the Standard, no voltage harmonics were found above the recommended limits.

Another article which discusses probabilistic representation of harmonics is by Morrison and Clark [9] who used a Monte-Carlo simulation to predict the traction feeder-station currents. The authors fit an elliptic distribution to the harmonic current data using the real and imaginary component variances of the current and the standard deviation ratio. Simulation results were compared to actual measurements obtained from field tests. Probabilistic representations taking into account the variation of harmonic currents provided more detail than deterministic calculations.

The objective of this thesis is to analyze the variation of harmonic voltages and currents over an extended time period, by splitting them into a random component and a deterministic component. Two methods of extracting the deterministic component are presented. The first method described in Chapter 2 extracts the deterministic component by regression analysis. A procedure to determine the distribution of instantaneous peak value of the voltage is also presented as the knowledge of the variation of peak value is useful when estimating insulation stress on power equipment.

The second method of separating the deterministic and random parts is outlined in the Chapter 3. A new technique known as “Wavelet Transform” is applied for analysis of harmonic variations. Wavelet transform is similar to Fourier transform but overcomes some of the disadvantages of Fourier analysis. Wavelets are basically translated and scaled functions obtained from a primary function know as the “mother wavelet”. In its discrete form, the wavelet transform analyses a data sequence by computing its wavelet coefficients. These wavelet coefficients form wavelets which, when combined together, give back the original data sequence. In this thesis, “Haar Wavelet” is used as a mother wavelet due to
its ease of interim computation.

Actual measurements of harmonic voltages and currents are presented in Chapter 4. The data collected over a period of one week is presented and analyzed according to the conventional methods and the two proposed methods. A brief description of the experimental setup is also given. Finally, potential applications of the work presented are discussed.
Chapter 2

DECOMPOSITION
TECHNIQUE FOR ANALYSIS
OF HARMONIC VARIATIONS

This chapter consists of two main sections: The first section describes a method for decom­posing the recorded harmonic signals into deterministic and random components, which will both be described analytically. The second section describes the statistical characteristics of the peak value of the instantaneous voltage by means of Monte Carlo simulation in combination with an optimization technique. The determination of peak value distribution is important when analyzing insulation stress on power equipment such as transformer windings and capacitor banks.

2.1 Separation of Deterministic and Random Components

Reported field measurements in various parts of power system distribution networks indicate that the harmonic voltages and currents represent a combination and deterministic and
random signals. Large variations occur in current harmonics within minutes. There is a
degree of uncertainty in the fundamental voltage and current due to constant changes in
load demand and network configuration. This uncertainty along with the variable nature
of the operating modes of nonlinear loads result in more randomness when considering
harmonic components. This randomness often amplifies when a nonsinusoidal voltage is
supplied to a nonlinear load. As a consequence, the deterministic analysis and modeling
is not an effective diagnostic tool for power system harmonic problems [10]. The random
nature of harmonics should also be taken while analyzing harmonic quantities.

The variation of power system harmonics are often described by graphs showing the
changes with respect to time, or histograms derived from measured data over a period
of time showing the frequency of occurrence of each value of the harmonic [6]. While
histograms represent the measured data in a much compressed form, they hide information
regarding the time duration of a harmonic component at a certain level - a crucial element
when studying the thermal effects of harmonics. Another hidden element in a histogram
is the deterministic component of the measured quantity. Also, harmonic histograms often
cannot be described by simple analytical functions.

When analyzing the statistical behavior of harmonics, the correlation coefficient between
any two harmonics, or between a harmonic and the fundamental voltage, has to be taken
into consideration. For this reason, it is best to decompose the individual harmonic com­
ponents into a deterministic component and a random component [10]. Mathematically, if
$X$ represents the amplitude of a harmonic component (either current or voltage), then

$$X = X_D(t) + X_R \quad (2.1)$$

where $X_D$ and $X_R$ represent the deterministic and random components, respectively. De­
pending upon the actual pattern of variation of harmonics, polynomial functions of various
orders may be used for curve fitting. Obviously, the higher the order, the better is the
accuracy of the model.

For illustration purposes, the simplest model for the deterministic component is the
least-square line:

\[ X_D(t) = At + B, \]  

(2.2)

where the coefficients \( A \) and \( B \) are determined by the method of least squares.

Given a set of variables \( (x_i, t_i) \), with mean values \( (\bar{x}, \bar{t}) \), the coefficients \( A \) and \( B \) are computed by [10],

\[
A = \frac{SS_{xt}}{SS_{tt}},
\]

(2.3)

\[
B = \bar{x} - A\bar{t},
\]

(2.4)

where

\[
SS_{tt} = \sum (t_i - \bar{t})^2
\]

(2.5)

\[
SS_{xt} = (\sum t_i x_i) - \frac{I}{m} (\sum t_i)(\sum x_i).
\]

(2.6)

The correlation coefficient between \( X_D \) and time \( t \) is defined by

\[
R = \frac{SS_{xt}}{\sqrt{SS_{tt} SS_{xx}}},
\]

(2.7)

Now the random component of the harmonic voltages or currents can be obtained by computing the deviation of the actual values of harmonics from those generated by the least-square method. After the deterministic component is extracted from the measured data, the remaining random component is expected to resemble a normal distribution with zero mean and standard deviation given by,

\[
\sigma_R = \sqrt{\frac{SS_{xx} - BSS_{xt}}{m - 2}},
\]

(2.8)

thus allowing its histogram to be described analytically by a normal distribution.

\[
f(X_R) = \frac{1}{\sqrt{2\pi}\sigma_R} \exp \left[ -\frac{(X_R)^2}{2\sigma_R^2} \right].
\]

(2.9)
The above analysis implies that any harmonic can be represented by means of two components, both of which have explicit analytical expressions. This analysis is useful in determining the probable level of harmonics at a particular time.

2.2 Statistical Description of Instantaneous Peak Voltage

Modern waveform analyzers have the ability to record and store the magnitude and phase angle of each harmonic component. Some even have the capability to plot, from recorded data over a time period, the probability distribution functions of each harmonic component as well as the RMS value and total harmonic distortion. But to the best of knowledge, none of the available instruments provide statistical data on the instantaneous voltage peak value - an important quantity in electrical stress studies. This section describes an algorithm for obtaining the statistical characteristic of the voltage peak value [20].

The expression for the instantaneous voltage is given by

\[ v(t) = \sum_{n=1}^{N} V_n \cos(\omega_n t + \phi_n) \]  

(2.10)

where \( V_n \) is the peak value of the \( n \)-th harmonic component and \( \phi_n \) is the corresponding phase angle with respect to the fundamental. (for the fundamental component, \( \phi_1 = 0 \)).

The peak value at any period \( T \) is defined by

\[ V_{\text{peak}} = \max_{t:0 \rightarrow T/2} v(t). \]  

(2.11)

The instantaneous voltage \( v(t) \) in (2.9) can be rewritten in terms of real and imaginary parts of each harmonic component.

\[ v(t) = \sum_{n=1}^{N} X_n \cos(n\omega t) + \sum_{n=1}^{N} Y_n \sin(n\omega t), \]  

(2.12)

where \( Y_1 = 0 \) and \( X_1 = V_1 \). Recorded measurements indicate that the fundamental voltage often resembles a normal distribution, while scatter plots of various harmonic orders
tend resemble an elliptical distribution. A method to fit an ellipse within a scatter plot is outlined below.

### 2.2.1 Elliptical Fitting for Harmonic Scatter Plots

Let the real and imaginary parts $X_n$ and $Y_n$ of a harmonic of order $n$ be distributed with mean and standard deviation $(\mu_x, \sigma_x)$ and $(\mu_y, \sigma_y)$ respectively with a correlation coefficient $\rho_{xy}$. Then the equation which fits an elliptical boundary around the set of data points is [11]:

\[
\frac{1}{1 - \rho^2} \left[ \left( \frac{X_n - \mu_x}{\sigma_x} \right)^2 - 2\rho \left( \frac{X_n - \mu_x}{\sigma_x} \right) \left( \frac{Y_n - \mu_y}{\sigma_y} \right) + \left( \frac{Y_n - \mu_y}{\sigma_y} \right)^2 \right] = 1. \tag{2.13}
\]

The ellipse fitted will be tilted at a certain angle. The degree of tilt of the major and minor axes of the ellipse is proportional to the value of the correlation coefficient $\rho_{xy}$.

### 2.2.2 Numerical Algorithm

A Monte Carlo simulation is proposed to obtain the distribution of the peak voltage value. Random values of the fundamental voltage (scalar) and harmonic voltages (phasors) are generated by using the mixed congruential method described below [12].

Random numbers for a normal distribution (fundamental voltage) are generated by the following equations.

\[
\begin{align*}
x_1 &= \mu + \sigma \sqrt{-2 \ln u_1} \cos(2\pi u_2), \tag{2.14} \\
x_2 &= \mu + \sigma \sqrt{-2 \ln u_1} \sin(2\pi u_2),
\end{align*}
\]

where $\mu$ and $\sigma$ are the mean and standard deviation of the fundamental component respectively, $u_1$ and $u_2$ are a pair of uniform random numbers generated by the mixed congruential method, and $x_1, x_2$ are the random numbers obtained. There might be a correlation between $x_1$ and $x_2$ but, it is not of consequence since only one of the pair of random numbers generated is used for this application.
Uniformly distributed random phasors (harmonic voltages) are generated using the following congruent relationship.

\[ x_i = ax_{i-1} + b \pmod{m}, \]  
\[ y_i = ay_{i-1} + b \pmod{m}, \]  

where \( a \) is the multiplier, \( b \) is the increment, \( m \) is the modulus (\( a, b, m \) are non-negative integers).

The random numbers thus generated have a rectangular, uniform distribution in the interval \([0-1]\). By suitably changing the variables \( a, b \) and \( m \), the distribution of the random numbers can be made to lie between any two values instead of 0 and 1. In this case the variables are adjusted such that the width and length of the rectangle of uniformly distributed random numbers is made to enclose the elliptical boundary of the harmonic data points. An example of such a procedure is shown in the Fig 2.1 below.

![Figure 2.1: Generating a Random Vector Uniformly Distributed Over a Complex Area](image)

After obtaining the rectangular distribution of random numbers, the next step is to
accept only those numbers falling within the ellipse. This is done by checking whether each point corresponding to a pair of random numbers inside the rectangle is also inside the ellipse. The following inequality is used for that purpose.

\[
\frac{1}{1 - \rho_{xy}^2} \left[ \left( \frac{X - \mu_x}{\sigma_x} \right)^2 - 2\rho \left( \frac{X - \mu_x}{\sigma_x} \right) \left( \frac{Y - \mu_y}{\sigma_y} \right) + \left( \frac{Y - \mu_y}{\sigma_y} \right)^2 \right] \leq 1 \quad (2.17)
\]

This elimination process is repeated for each pair of random numbers generated.

Now the stage is set for the calculation of the peak value of the voltage waveform. Since the values of the harmonic components are small, the peak value of the total waveform should occur in the neighborhood of \( \pi/2 \) radians. A simple numerical method that converges to the peak value is as follows:

IF \( v(\omega t = \pi/2 + \epsilon) > v(\omega t) \), then \( \omega t = \omega t + \epsilon \)

ELSE

IF \( v(\omega t = \pi/2 - \epsilon) > v(\omega t) \), then \( \omega t = \omega t - \epsilon \)

Repeat till maximum value is reached.

The above procedure is repeated for each set of random numbers generated. A summary of the complete numerical algorithm is shown in Figure 2.2.
Figure 2.2: Flowchart for Computing Distribution of Peak Voltage

Start

INPUT Mean and Standard Deviation for $V_1$ and $V_n$, $n = 3, 5, 7$

Fit ellipses for harmonic component scatter plots.

Generate random numbers for harmonic phasors inside the ellipse and for $V_1$ modeled as a normal distribution.

Compute Peak Voltage using numerical algorithm for $V_1$ and each $V_n$

End of generated random numbers?

No

Yes

Plot the Peak Value Distribution

Stop
This chapter presents an alternative method for analyzing harmonic voltage and current waveform variations. This method applies wavelet transform to decompose the harmonic components into various levels. The Fourier transform decomposes the signal into an infinite frequency spectrum with no time localization. One of the advantages of Wavelet transform is that it provides time localization.

Wavelet theory is the mathematics associated with building a model for a signal, system, or process with a set of special signals. These special signals are little waves called “wavelets” [14], which can be viewed as a new basis for representing functions, as a technique for time-frequency analysis.

Wavelets were introduced recently by J. Morlet, a French geo-physicist, as a tool for signal analysis in view of applications for the analysis of seismic data. In 1988, Daubechies
constructed orthonormal wavelets with compact support which was inspired by the work of Mallat in applying the wavelets to signal analysis and reconstruction. Wavelets have since been applied in various diverse fields ranging from astronomical image analysis and to analysis of mammalian visual systems.

Wavelet theory represents signals by breaking them down into many interrelated pieces. These pieces are scaled and translated versions of a principal wavelet known as the "mother wavelet". The breakdown of a signal is a process known as wavelet decomposition or wavelet transform. The reverse process involves combining the wavelets back together to reconstruct the original signal and this is known as the inverse wavelet transform. Mathematically, the continuous wavelet transform of a function \( f(x) \), with respect to a mother wavelet \( \psi(x) \) is [14]

\[
W_\psi f(a, b) = |a|^{-\frac{1}{2}} \int f(x) \psi^* \left( \frac{x - b}{a} \right) \, dx,
\]

where \( a \) is the scaling factor and \( b \) is the translation factor.

The wavelet transform can be related to the more commonly used Fourier transform. The Fourier models represent functions as weighted sum of exponentials at different frequencies. The Fourier coefficients represent the weights at each different frequency. Similarly, wavelet models represent functions as a weighted sum of scaled and translated mother wavelets. The wavelet transform has a mother wavelet replace the exponential and scaling and translation replace frequency shifting. In a special case where the mother wavelet is \( \psi(x) = e^{jx} \), \( a = \frac{1}{\omega} \), and \( b = 0 \), the wavelet transform becomes the well known Fourier transform:

\[
W_\psi f(a, b) = W_{\psi, f} \left( \frac{1}{\omega}, 0 \right) = \int f(x) e^{-j\omega x} \, dx = F(\omega)
\]

The above illustrates the relationship between wavelet and Fourier transforms. It should be noted that for a given function \( f \), there are many wavelet transforms associated. This is due to the fact that a different wavelet transform is obtained for the same function \( f \) with different mother wavelets. In the Fourier transform, however, only the exponential function is allowed as the analyzing function, leading to the unique Fourier transform. In this chapter, the basic principles of wavelet transforms are outlined, and continuous and discrete
wavelet transforms are defined. Then the properties of wavelet transforms are given. The discrete wavelet transform (DWT) is described in detail and the decomposition procedure of a data sequence using Mallat's algorithm [16] is explained. Lastly, the application of wavelet transforms to the analysis of power system harmonic variations is discussed.

3.1 Basic Principles of Wavelet Transform

Wavelets constitute a family of functions derived from one single function, indexed by two labels: one for position and one for frequency. The continuous wavelet transform is given in Eqn (3.1) where the integral gives the location (in terms of b & at), the rate (in terms of a), and the amount of change of f, with the zoom-in and zoom-out capability. There are two conditions for a function to be a mother wavelet: (a) the function should be oscillatory and, (b) it should have a fast decay to zero. Furthermore, there should be no "d.c." component in the wavelet function. i.e.,

$$\int_{-\infty}^{\infty} \psi(x) \, dx = 0. \quad (3.3)$$

3.1.1 Construction of Wavelets

The first step in the construction of a wavelet is to form the scaling function \( \phi \). For practical purposes, a two-scale relation of the scaling function is described by finite sums. An iterative procedure is used to construct the scaling function. Let \( \phi \) be described by the two scale relation

$$\phi(x) = \sum_{k=0}^{N_\phi} c_k^\phi \phi(2x - k), \quad c_0^\phi, c_{N_\phi}^\phi \neq 0 \quad (3.4)$$

where \( c_k^\phi \) is the wavelet coefficient, and \( N_\phi \) is the number of wavelet coefficients.

Using the above equation it is possible to construct the scaling function using an iterative procedure. For this purpose, the following equation is considered

$$\phi_n(x) = \sum_k c_k \phi_{n-1}(2x - k), \quad n = 1, 2, ..., N_\phi, \quad (3.5)$$

for some suitable initial function \( \phi_0 \). A scaling function \( \phi \) can be obtained by taking the
limit of \( \phi_n \) in the recursive scheme. C. K. Chui [17] suggests using spline functions as the initial function for producing the scaling function.

Once the scaling function is produced, the next step is to construct the wavelet itself. If the two-scale relation of the scaling function in equation (3.5) is used, then the two-scale relation of an orthonormal wavelet is given by

\[
\psi(x) = \sum_{n=-N+1}^{1} -1^n c_{n-1} \phi(2x + n) \tag{3.6}
\]

To generate good wavelets, the wavelet coefficients have to be chosen carefully. A set of wavelet coefficients have to satisfy the following conditions for suitable representation of a signal.

### 3.1.2 Wavelet Conditions

A wavelet given by

\[
W(x) = \sum_{k=0}^{N-1} (-1)^k c_k \phi(2x + k - N + 1) \tag{3.7}
\]

must satisfy the following conditions:

\[
\sum_{k=0}^{N-1} c_k = 2, \tag{3.8}
\]

\[
\sum_{k=0}^{N-1} (-1)^k k^m c_k = 0. \tag{3.9}
\]

Also, in order to achieve accuracy and generate and orthogonal wavelet system,

\[
\sum_{k=0}^{N-1} c_k c_{k+2m} = 0 \quad m \neq 0, \tag{3.10}
\]

\[
\sum_{k=0}^{N-1} c_k^2 = 2 \tag{3.11}
\]
for $m = 1, 2, \ldots, (N/2) - 1$.

### 3.2 The Discrete Wavelet Transform (DWT)

The goal of the wavelet transform is to decompose any arbitrary signal $f(x)$ into a summation of wavelets at different scales. This is achieved by using the Discrete Wavelet Transform as in Equation (3.7), with $N$ as the number of samples, $c_k$ the wavelet coefficient, and $\phi(x)$ the scaling function. The DWT yields a countable set of coefficients in the transform domain. Unlike the Continuous Wavelet Transform, the Discrete Wavelet Transform is defined only for positive scale values.

One of the simplest wavelets is the "Haar Wavelet", having coefficients $c_0 = 1$ and $c_1 = 1$. The expression for the Haar Wavelet is given by

$$
\psi(x) = \begin{cases} 
1 & \text{if } -\frac{1}{2} \leq x < 0 \\
-1 & \text{if } 0 \leq x < \frac{1}{2} \\
0 & \text{elsewhere}
\end{cases}
$$

The shape of the Haar Wavelet is shown Fig (3.1).
Similarly, wavelets with four coefficients are called D4 wavelets named after Ingrid Daubechies who first discussed their properties. Other examples of wavelets include: Mexican hat wavelet, Morlet wavelet, Lemarie-Battle wavelets and the Littlewood-Paley wavelet [17]. The Haar Wavelet is selected for the subject under study for the following reasons:

1) The Haar Wavelet is very simple in construction.
2) No lengthy expressions which are difficult to implement on a computer are present.
3) Some wavelets, due to their structure may introduce noise of their own. This will seriously affect the decomposition and reconstruction of the signal by making it appear with more noise than its content in the original signal. The Haar wavelet, being simple in construction does not introduce any spurious noise.

In Haar Wavelet, the scaling function is a constant, i.e.,

\[ \phi(x) = 1 \quad 0 \leq x < 1. \]  

Hence, for Haar Wavelet the DWT is given by,

\[ \sum_{j=0}^{n} \sum_{k=0}^{N} c_{j,k} W(2^j x - k) = \sum_{k=0}^{N} c_{\phi,k} \phi(x - k) \]
where \( c_{\phi,k}, \; k = 0,1,2,\ldots,N, \) is a new set of coefficients. Because of the definition of wavelets, when \( j \) is negative, \( W(2^j x - k) \) can always be expressed as a sum of terms like \( \phi(x - k) \). Therefore, the general result can be written in an alternative form as:

\[
f(x) = \sum_{k=0}^{N} c_{\phi,k}(x - k) + \sum_{j=0}^{n} \sum_{k=0}^{N} c_{j,k}W(2^j x - k).
\] (3.14)

The above wavelet series provides a practical base for signal analysis.

### 3.3 Discrete Wavelet Transform Algorithm

In this section, the Mallat’s Algorithm for decomposition of harmonic variations is explained. This algorithm is known to be very efficient (comparable to FFT) in terms of computation requirements.

Using the general format of the DWT in the previous equation, the wavelet series expansion can be written as [18]

\[
f(x) = a_0 \phi(x) + a_1W(x) + a_2W(2x) + a_3W(2x - 1) + \ldots + a_{2^j+k}W(2^j x - k) + \ldots \tag{3.15}
\]

Where the coefficients \( a_1, a_2, a_3, a_4, \ldots \) give the amplitudes of each of the contributing wavelets to one cycle of the periodic function. The first term in the series contains the scaling function which in the case of a Haar wavelet is a constant. The second term in the series, \( a_1W(x) \) is a wavelet of scale zero; the third and fourth terms \( a_2W(2x) \) and \( a_3W(2x - 1) \) are wavelets of scale one, the third being translated \( \Delta x = \frac{1}{2} \) with respect to the fourth; the next four terms are wavelets of scale 2, and so on for wavelets of increasingly higher scale. The higher the scale, the finer the detail and the more coefficients there are, so that at scale \( j \) there are \( 2^j \) wavelets each spaced \( \Delta x = 2^{-j} \) apart along the x-axis.

The Discrete Wavelet Transform algorithm is a procedure for computing the above equations for the wavelet coefficients when the values of \( f(x) \) is available at equally spaced intervals over \( 0 \leq x < 1 \). When Mallat’s Algorithm is used, generating the scaling function \( \phi(x) \) and then the wavelets \( W(2^j x - k) \) is not required since the wavelet coefficients and
hence the wavelets can be determined directly from the data sequence.

Mallat’s algorithm takes an array of numbers of length $2^n$ where $n$ is an arbitrary integer and computes the function $f(r)$, $r = 1, \ldots, 2^n$. The procedure for implementing the algorithm is given next.

Assuming that the number of wavelet coefficients is 8, the decomposition of a signal $f$ represented by its sampled values is given by the formula:

$$f = a_0 + M_3 M_2 G_2 [a_1] + M_3 G_2 [a_2 + a_3]^T + G_3 [a_4 + a_5 + a_6 + a_7]^T,$$

(3.16)

where

$$a_0 = \frac{1}{2} L_1 \frac{1}{2} L_2 \frac{1}{2} L_3 f,$$
$$a_1 = \frac{1}{2} H_1 \frac{1}{2} L_2 \frac{1}{2} L_3 f,$$
$$[a_2 \ a_3]^T = \frac{1}{2} H_2 \frac{1}{2} L_3 f,$$
$$[a_4 \ a_5 \ a_6 \ a_7]^T = \frac{1}{2} H_3 f,$$

The matrices $L$ and $H$ above are defined below for a wavelet with 2 coefficients $(c_0, c_1)$.

$$L_1 = [c_0 \ c_1],$$

$$L_2 = \begin{bmatrix} c_0 & c_1 \\ c_0 & c_1 \end{bmatrix},$$

$$L_3 = \begin{bmatrix} c_0 & c_1 \\ c_0 & c_1 \\ c_0 & c_1 \end{bmatrix},$$

Similarly,
By formulating these matrices, the wavelet coefficients $a_0$,...,$a_n$ can be calculated. The matrices $M$ and $G$ which serve to reconstruct the original function are given by

$$M = L^T,$$  \hspace{1cm} (3.17)

and

$$G = H^T.$$  \hspace{1cm} (3.18)

The order of the matrices above are

$$G_r = G(2^r \times 2^{r-1})$$

$$H_r = H(2^{r-1} \times 2^r)$$

$$L_r = L(2^{r-1} \times 2^r)$$

$$M_r = M(2^r \times 2^{r-1})$$

where $r = 1, 2, 2^1, 2^2, ..., 2^n$. This algorithm can be used to decompose and reconstruct any signal represented by its sampled data sequence.
3.4 Application of Wavelets to Harmonic Variations

An application of wavelets in the field of power system harmonics is analysed in this report. To the best of knowledge, only one paper by Ribeiro [19] discusses in broad terms, possible applications of wavelet analysis in different areas of power systems.

Wavelets for analyzing harmonic distortions are chosen for the following reasons: 1) Power system harmonics are continuously varying. 2) The pattern of variation of harmonics repeats itself each weekday. 3) The harmonic signals contain random components 4) Erratic changes of harmonic signals can be observed in more detail.

The aim of applying wavelet transforms to power system harmonics is to split the harmonic component data into several parts. Each part represents a specific behavior of the particular harmonic under analysis. The splitting of a harmonic component is accomplished using Mallat’s algorithm explained in the previous section. The procedure is as follows: Assume that the set of data points representing the time variation of harmonic (e.g., the fifth harmonic) for a specified period of time, is a number equal to an integral power of 2. Once the different wavelet levels are obtained, they are analyzed and singular variations in harmonics are observed according to the requirements. Experimental results obtained by applying the wavelet transform to power system harmonics are described in detail in the next chapter.
Chapter 4

APPLICATION & EXPERIMENTAL RESULTS

This chapter presents the results of an analysis of harmonic data gathered by measuring the line-to-neutral voltage waveform supplied to a large building for a period of one week. The quantities measured were the fundamental, third, fifth and seventh harmonic voltage magnitudes and their phase angles. In addition, the building load current in one phase was observed and recorded for a period of 24 hours. The measurements took place at the Thomas T. Beam Engineering building at University of Nevada, Las Vegas. The time duration between successive measurements was selected to be one minute. The description of the apparatus used for these measurements are presented. This is followed by the measured data and analysis.

4.1 Experimental Setup

The harmonic voltage and current measurements were taken with the Dranetz Precision Power and Harmonic Analyzer. This instrument was interfaced with a SUN Sparcstation (using the RS232C interface cable) for the harmonic voltage measurements and with a 486 Personal Computer for harmonic current measurements. A brief description of each device
used follows.

4.1.1 Harmonic Analyzer

The Dranetz harmonic analyzer is a unique microprocessor-based dual channel precision instrument designed to perform complex voltage, current, phase, power measurements on periodic waveforms in the range of 1 Hz through 500kHz. The instrument rapidly determines the characteristics of each periodic input as well as the characteristics of one input with respect to the other. Employing Fast Fourier Transform analysis techniques, the analyzer measures the fundamental, and each harmonic up to the 50th, with accuracies of up to ±0.04% (magnitude) and 0.03° (phase).

Pre-programmed with a wide range of harmonic, phase and power parameters, characteristics such as $V_{RMS}$, phase angle, complex ratio, real power, power factor, volt amps, voltamps reactive, harmonic phase and total harmonic distortion may be immediately recalled from the analyzer.

The dual channel inputs to the analyzer are gain controlled by respective voltage amplifiers. The frequencies of two inputs must be identical. Twelve voltage ranges, extending from 1 millivolt full scale up to 300 volts full scale are provided for each channel. The isolated voltage and current inputs enable operation to 500V (full scale) and 5A (full scale). The operator may select either a fixed range or an auto-range mode that automatically selects the correct range of each channel.

The outputs of the two amplifiers are sampled in associated sample-and-hold amplifiers. Both channels are sampled simultaneously. Each sampled analog signal is then digitized by an A/D converter and stored in memory for use in the calculation part of the operating cycle. Since the sampling rate is synchronous with the input frequency, a phase-locked loop is used to track the input frequency. The loop automatically tracks the input frequency over the range of 1 Hz to 500 kHz.
Some specifications relevant to the measured data include the following:

Input Impedance : 1 Megohm in parallel with approximately 100 pf.

The input capacity of both channels is matched within ±2pf.

Full Scale RMS Voltage Ranges : 1, 3, 10, 100, 300 volts and 1, 3, 10, 30, 100, 300 millivolts.

Frequency Range : 1 Hz to 500 kHz (400kHz for 256 S/M)

Samples per Measurement (S/M) : 16, 64 or 256.

Measurements per Reading (M/R) : 1, 4, 16, 64.

Harmonics Measured : Upto the 7th for S/M = 16.

Up to the 31st for S/M = 64.

Up to the 50th for S/M = 256.

RMS Volts or Amperes (CH1 and CH2) : Total, fundamental and individual harmonics.

Harmonics can displayed in % of fundamental.

Phase between channels : $\theta$ - Phase (CH2) - Phase (CH1)

Fundamental and Harmonics.

Power : Total, fundamental and individual harmonics.

Maximum Output Reading Rate:

Printer : 1.5 per second

Display and/or RS232 Output : 4 per second

IEEE-488 Option : 5 per second
Printer rate : 2 lines/sec

Typical Calculation Times:

16 S/M : 0.15 sec
64 S/M : 0.5 sec
256 S/M : 3.5 sec

Maximum Current : 5A continuous (10A peak)
Maximum Voltage : 500V RMS continuous (700V peak)

4.1.2 RS232 Interface

The RS232C Interface Port, standard with all analyzers, allows one to direct analyzer data to an RS232C compatible peripheral. The unit is completely baud-rate selectable. Turning off the printer and using the analyzer with a high baud rate peripheral allows one to achieve significantly higher rates of operation.

In the experiment conducted, the Analyzer is interfaced using the RS232C to a Sparc-station for the harmonic voltage measurement and to a Personal Computer for the harmonic current measurements. The Interface cable pinouts are shown below.

For Modem Connection:
Pin 1 - Protective Ground (Chassis)
Pin 2 - Data to Remote
Pin 3 - Data from Remote
Pin 4 - Request to send, output always true
Pin 5 - Clear to send, Input for control
Pin 6 - Data Set Ready, Input not used
4.1.3 SparcStation/PC

The Sparcstation used for harmonic voltage measurements is a SUN Sparcstation 1, with a SUN 4/60 central processing unit with a local memory capacity of 14MB. The workstation treats the analyzer as a device connected to it at a specified input port, reads data and stores it in a file. Then a program was written to separate the necessary harmonic and fundamental voltage components from the file. The quantities measured were the total harmonic distortion, fundamental voltage, third, fifth and seventh harmonic components together with their phase angles with respect to the fundamental.

The PC used for harmonic current measurements was a "MICHADA" with an Intel 80486 Main processor. It has a Base memory of 640 KB and 256 KB cache memory. The extended memory size is 3328 KB and the CPU clock frequency is 33 MHz. The PC is equipped with two serial and one parallel ports.

The RS232C cable is connected to one of the serial ports and measurements are triggered on the analyzer. The "KERMIT" facility installed on the PC is used to read and store the data in a file. Again a program is written to separate the harmonic components needed. The total harmonic distortion, fundamental current and voltage components and the odd order harmonic currents up to the thirteenth was measured.

4.2 Recorded Data

Figures 4.1 through 4.8 show the recorded variation of fundamental $3^{rd}$, $5^{th}$, and $7^{th}$ harmonic voltage and voltage total harmonic distortion over the one week period. It is observed that the fundamental voltage has a distinct deterministic component with a daily cycle. The third, fifth and seventh harmonic voltages are repetitive and also varies over the week as seen in the plots. The deterministic component of the harmonic components is not as clear except for the $7^{th}$ harmonic voltage magnitude. Also, the fundamental voltage variation is
variation is within a very narrow range (3 volts), whereas the harmonic voltage magnitudes vary over a much wider range with a large number of random spikes.

The following table shows the statistical data of the measured harmonic voltages.

<table>
<thead>
<tr>
<th></th>
<th>Min.</th>
<th>Max.</th>
<th>Mean</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1$ (V)</td>
<td>114.29</td>
<td>120.97</td>
<td>117.697</td>
<td>1.2608</td>
</tr>
<tr>
<td>$V_3$ (V)</td>
<td>0.863</td>
<td>2.146</td>
<td>1.447</td>
<td>0.1484</td>
</tr>
<tr>
<td>$V_{3\phi}$ (deg)</td>
<td>-169.36</td>
<td>-119.88</td>
<td>-148.41</td>
<td>4.9546</td>
</tr>
<tr>
<td>$V_5$ (V)</td>
<td>0.670</td>
<td>1.940</td>
<td>1.228</td>
<td>0.2059</td>
</tr>
<tr>
<td>$V_{5\phi}$ (deg)</td>
<td>-114.74</td>
<td>-64.849</td>
<td>-92.783</td>
<td>7.2404</td>
</tr>
<tr>
<td>$V_7$ (V)</td>
<td>1.134</td>
<td>2.600</td>
<td>1.877</td>
<td>0.219</td>
</tr>
<tr>
<td>$V_{7\phi}$ (deg)</td>
<td>-154.61</td>
<td>-91.548</td>
<td>-121.453</td>
<td>9.359</td>
</tr>
<tr>
<td>THD (%)</td>
<td>1.778</td>
<td>3.265</td>
<td>2.283</td>
<td>0.172</td>
</tr>
</tbody>
</table>

Figure 4.1: Variation of Fundamental Voltage with Time
Figure 4.2: Variation of Third Harmonic Voltage with Time

Figure 4.3: Variation of Third Harmonic Phase with Time

Figure 4.4: Variation of Fifth Harmonic Voltage with Time
Figure 4.5: Variation of Fifth Harmonic Phase with Time

Figure 4.6: Variation of Seventh Harmonic Voltage with Time

Figure 4.7: Variation of Seventh Harmonic Phase with Time
Figures 4.9 - 4.17 show the fundamental, $3^{rd} - 13^{th}$ harmonic current magnitudes and current total harmonic distortion. The fundamental and harmonic currents are very low (50% of normal) except the fifth harmonic in the morning and rise to their maximum levels in the afternoon. Also, as the harmonic order increases so does the randomness in the variation pattern. Only the $3^{rd}$ harmonic current follows the fundamental current variations closely. The fundamental voltage measured at the building's power supply for calculation of power supplied, is also shown. Using a power factor of 0.9, the load demand is computed and plotted. It is observed that the voltage decreases as the load demand increases, due to the voltage drops along the power lines and cables.
Figure 4.10: Time Variation of Third Harmonic Current

Figure 4.11: Time Variation of Fifth Harmonic Current

Figure 4.12: Time Variation of Seventh Harmonic Current
Figure 4.13: Time Variation of Ninth Harmonic Current

Figure 4.14: Time Variation of Eleventh Harmonic Current

Figure 4.15: Time Variation of Thirteenth Harmonic Current
Figure 4.16: Time Variation of Current Total Harmonic Distortion

Figure 4.17: Time Variation of Fundamental Voltage

Figure 4.18: Time Variation of Power Demand
4.3 Frequency of Occurrence (Histograms)

The conventional way to represent the variations in fundamental and harmonic components in compressed form is a plot of histograms, derived from the recorded data by plotting the recorded values of the quantity to be analyzed versus the frequency of occurrence of each value. These histograms show the distribution of frequency of occurrence which when normalized, represent the probability density function of the quantity under consideration. The histograms have a disadvantage since time information is totally lost. The amplitude of a signal at a certain moment is not known.

Histograms corresponding to Figures 4.1, 4.2, 4.4 and 4.6 are shown in Figures 4.19 through 4.22 respectively. It is noted that the histogram for the fundamental voltage is irregularly shaped, whereas the histograms for the harmonic components can be modeled as a normal distribution. The standard normal distribution is plotted over the histograms for comparison. It is also observed from Figure 4.23 that the modeling of the harmonics as a normal distribution is valid only if one week's recorded data is used. The model will not be applicable when considering one day's recorded data. This is evident from the comparison of one day's and one week's plot of the fifth harmonic voltage magnitude in Fig 4.23.
Figure 4.20: Third Harmonic Voltage Distribution

Figure 4.21: Fifth Harmonic Voltage Distribution

Figure 4.22: Seventh Harmonic Voltage Distribution
4.4 Decomposition of Individual Harmonic Components

To overcome the problem with the histograms described in the previous section, the deterministic part of the fundamental voltage was extracted using a sawtooth approximation. Figure 4.23 shows the sawtooth waveform fitted to the fundamental voltage magnitude plot from one week's recorded data.

The procedure for fitting the sawtooth waveform is as follows: First, a straight line was fitted to one day's recorded data by observing the maximum and minimum values for each section of the plot. For example, if \((x_1, y_1)\) and \((x_2, y_2)\) are the minimum and maximum values of a section of the plot, then the corresponding equation of the straight line is:

\[
Y = y_1 + m(x - x_1),
\]

(4.1)

where

\[
m = \frac{y_2 - y_1}{x_2 - x_1}.
\]

(4.2)

Next, this straight line is repeated seven times for fitting one week's recorded data. The resultant sawtooth waveform provides a good approximation for the deterministic part of the fundamental voltage. The deviation of the actual fundamental voltage values from the corresponding sawtooth waveform values is shown in Figure 4.24 resembling a normal
distribution. Thus the fundamental voltage magnitude recordings can be separated into two parts as shown.

The advantage of this decomposition method is that both the deterministic and the random components can be expressed by simple expressions as opposed to the expressions obtained by theoretical means.

![Figure 4.24: Fitting of Sawtooth Waveform to Fundamental Voltage](image1)

![Figure 4.25: Random Component of Fundamental Voltage](image2)
4.5 Distribution of Instantaneous Peak Voltage

The peak voltage value distribution is determined using the simulation method explained in the Chapter 2. The fundamental voltage is assumed to be normally distributed. The graph of the fundamental voltage plotted from normally distributed random numbers is shown in Figure 4.26. The scatter plots of the real and imaginary parts of the third, fifth and seventh harmonic are shown in Figures 4.27, 4.28 and 4.29 along with the ellipse fitted on the scatter points. It is observed that some of the actual values lie outside the fitted ellipse. This may cause some differences to appear between the actual and simulated peak value distributions since it is assumed that the scatter plots are uniformly distributed inside the ellipse for simulation purposes.

The actual and simulated peak value distributions are shown in Figure 4.30. It is observed that the simulated peak value distribution is a good approximation of the actual peak value variation. Some noticeable difference observed between the shapes of simulated and actual peak value distribution may be due to slight errors in fitting the ellipses in the scatter plots.

![Figure 4.26: Distribution of Random Values of Fundamental Voltage](image-url)
Figure 4.27: Scatter Plot of the Third Harmonic Voltage with Fitted Ellipse

Figure 4.28: Scatter Plot of the Fifth Harmonic Voltage with Fitted Ellipse
Figure 4.29: Scatter Plot of the Seventh Harmonic Voltage with Fitted Ellipse

Figure 4.30: Actual and Simulated Peak Voltage Value Distribution
4.6 Wavelet Transform Method

The fundamental component of the current measured in Figure 4.9 is used to illustrate the application of Wavelet transform. A Haar Wavelet and Mallat's algorithm are applied and the different wavelet levels are shown in the succeeding figures. The different stages in reconstruction of the original waveform is shown in Figure 4.32 by plotting the original and reconstructed waveforms at each level of addition. From the plots of the ten wavelet levels, it is observed that the frequency of variation of the current increases as wavelet level increases. The wavelet transform acts as a filter separating the more frequent random variations from the less frequent ones.
Wavelet Level 8

Wavelet Level 9

Wavelet Level 10

Figure 4.31: Wavelet Levels for Fundamental Current
Addition of Wavelet Levels 0 and -1

Addition of Wavelet Levels -1,0 and 1

Addition of Wavelet Levels -1,0,1 and 2
Addition of Wavelet Levels -1,0,1,2 and 3

Addition of Wavelet Levels -1,0,1,2,3 and 4

Figure 4.32: Steps in Reconstruction of Original Waveform

Figure 4.33: Actual and Reconstructed Current Waveforms
4.7 Applications

One of the potential applications of the decomposition techniques presented in Chapters 2 and 3 can be found in the design of passive and active harmonic filters for reducing or eliminating harmonic signals in the power distribution system. Another application may be in the implementation of standards for limiting voltage and current harmonic levels in power systems [2]. It is known that assigning limits on the magnitudes of harmonics is not an easy task. The distribution of harmonics over the system for a time period and the extent to which any power system will sustain a certain level of harmonics while remaining reliable, should be known. The method of obtaining the first piece of information required namely, the distribution of harmonics using probabilistic and statistical analysis on measured data can be quite useful in this regard.

The optimal value of capacitance for power factor correction capacitors depend upon the amplitude of the harmonic voltages. The capacitance is calculated under the assumption that the harmonic voltages are a constant. However as often seen in the measured data, harmonic voltages are continually varying thus reducing the performance of power factor correction capacitors. A static var compensator will be the ideal solution for optimal power factor correction where the value of capacitance at any point in time will depend on the magnitude of harmonic voltage at that instant. The analysis of the previous chapters will serve as useful techniques to design control strategies for static var compensators.

The proposed procedure for harmonic variation analysis will also be useful in estimating line losses. Instead of a fixed value of harmonic current, the harmonic current distribution can be used to obtain a more accurate estimate of the line losses. Furthermore, the method of obtaining the peak value distribution of voltage described in Section 2.2 can be utilized in distribution systems where the statistical parameters (mean, standard deviation and correlation coefficient) are known, without the detailed knowledge of the actual distribution of harmonics in the network.

The method of decomposition of a harmonic component into different wavelet levels, each representing a different pattern present in the original signal, is useful when a complete analysis of a particular harmonic with regard to its pattern of variations is desired. Higher wavelet levels depict the variations that occur in a small duration (spikes); whereas, lower
wavelet levels represent the deterministic part of the harmonic within each period. This decomposition is useful when analysing the spikes that occur in harmonics. These spikes can be damaging to sensitive equipment and can be observed and analysed using wavelets.
Chapter 5

CONCLUSION

Field measurements show that fundamental and harmonic components of voltages and currents found in power distribution systems are time-variant. These signal variations, which are due to on/off switching of various electrical loads and network reconfiguration, are neither deterministic nor random.

The work presented in this thesis proposes two methods for analyzing time variation of harmonic signals in eclectic power distribution systems: The first method separates the signal into a deterministic component and a random component. The deterministic component, extracted from the recorded signal by regression analysis, is expressed by a polynomial function of time. The remaining random component can be accurately described by a normal distribution function with a mean value of zero. A statistical description of the instantaneous voltage peak value is also presented.

The second method considered for describing signal variation uses wavelet theory to decompose the signal into wavelets. An overview of this relatively new theory including wavelet construction from scaling functions, selection of 'mother wavelets', and Mallat's algorithm (a fast Discrete Wavelet Transform), is presented.

The two signal decomposition methods are then applied to a one-week recording of supply voltage and load current variations of the Thomas T. Beam Engineering Complex at UNLV. The measured data contains the changes in the fundamental (60 Hz), 3rd, 5th and 7th harmonic components of the voltage and current signals.
The signal decomposition techniques presented will likely have potential applications in harmonic filter design, power factor correction and reactive power control, power quality assessment and standards.
Bibliography


