Time-Varying Waveform Distortions in Power Systems

Edited by

Paulo F. Ribeiro
Calvin College, Michigan, USA

Celebrating 125 Years
of Engineering the Future

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“No model is a catalogue of ultimate realities, and none is a mere fantasy. Each is a serious attempt to get in all the phenomena known in a given period, and each succeeds in getting in a great many. But also, no less surely, each reflects the prevalent psychology of its age almost as much as it reflects the state of that age’s [scientific] knowledge.”

C. S. Lewis, The Discarded Image, Cambridge University Press, 1964.

“These things are so delicate and numerous that it takes a sense of great delicacy and mathematical precision to perceive them and judge them correctly and accurately: Often it is not possible to set it out analytically, because the necessary principles are not ready to hand, and it would be an endless task to undertake. The thing must also be seen all at once, at a glance, intuitively, and not only as a result of progressive reasoning, at least up to a point.”

Blaise Pascal, 1650

Contents

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Preface

The ever-present time-varying nature of waveform distortions in power systems requires a comprehensive and precise analytical basis that needs to be incorporated into the system studies and analyses. This time-varying behavior, which is due to continuous changes in system configurations and variations of linear and nonlinear load and equipment, presents conceptual and practical challenges. Figure 1 illustrates the nature of the problem by indicating the possible methods of analyzing waveform distortions; connecting the time domain to the frequency domain as a function of its time-varying condition. For example, for steady-state waveforms Fourier analysis is sufficient, whereas when the time-varying conditions prevail, then spectral, probabilistic, evolutionary spectrum and time-frequency techniques are required.

This publication has been in preparation for several years as part of an activity within the IEEE Task Force on Probabilistic Aspects of Harmonics (Harmonics Working Group) which I have had the privilege to convene, and many people have contributed to. During this process our understanding of the problem and the tools available has evolved and we have agreed on a more encompassing perspective of the subject. First we moved away from the strict steady-

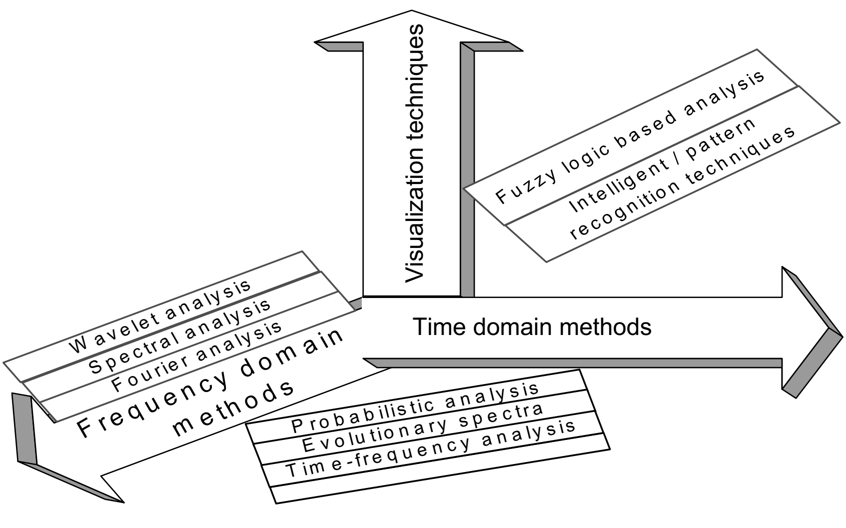

Figure 1 Time-varying distortions – connecting time and frequency domains

state "harmonic distortion" definition to a "waveform distortion" deviation where the time-varying nature (the main challenge of the problem) could be dealt with frequency/spectral, time-frequency, probabilistic, and computational intelligence methods. Second, several new techniques became available or were applied for the first time to power systems problems, and this prompted the editor to seek better understanding and additional contributions.

What seemed a settled issue, that is, that harmonics could only be dealt with as steady-state components and that the time-varying nature of waveforms could only be analyzed by probabilistic methods applied to short interval averages of individual harmonic components or decompositions by windowing techniques, was reconsidered. The new signal processing methods based on time-frequency decomposition such as wavelet transform and multi-rate filter methods presented in Section 6 have allowed us much more precise analyses of the behavior of time-varying waveform distortions and opened up new opportunities for monitoring and investigating power systems phenomena.

The text reviews the nature, analytical concepts, special situations and problems associated with the time-varying nature of waveform distortions and associated harmonics, and suggests solutions and ways to deal more effectively with the problem.

The text covers time-varying harmonics produced by different sources from single-phase appliances to Multi-Mega Watt power electronics converters. Also, analytical aspects related to background distortion, harmonic summation and harmonic impedance are discussed. The time-varying and time-frequency aspects are considered in the establishment of an integrated approach to deal with waveform distortions, which need to be carefully applied lest the new sophisticated techniques convolute rather than solve the difficulties.

Professor C.S. Lewis[1] once said:

> "To use the microscope, yet not to focus or clean it, is foolishness. You are passing from uncorrected illusions to positively invited illusions. Here, as elsewhere, untrained eyes or a bad instrument produce both errors: they create phantasmal objects as well as miss real ones."

Paraphrasing this to signal processing applied to waveform distortions, one could say:

> "To use advanced signal processing techniques, and yet not to tune them to the adequate phenomenon, scale, resolution, etc., is foolishness. You are passing from inconsequential information to affirmative mistakes. Here, as elsewhere, ignorant guessing or inattentive signal processing analysis produces both errors: they create illusional results as well as miss the real / desired information"

Thus, one needs to use these techniques with much engineering sensitivity and mathematical precision to avoid producing sophisticated but phantasmal results.

Figure 2 is an attempt to illustrate the big picture of how stationary, nonstationary and spatial nonstationary signals can be analyzed. The engineer or researcher needs to utilize them with both engineering intuition and analytical perceptiveness in order to make full use of the techniques' potential.

We expect that the information here will contribute to a better understanding of time-varying waveform distortions and will allow a better understanding of power systems behavior under time-varying conditions.

I would like to acknowledge the invaluable contributions and encouragement of all the authors and members of the IEEE TF on Probabilistic Aspects of Harmonics who provided the

[1]C.S. Lewis, Studies in Medieval and Renaissance Literature, Cambridge University Press, 1966.

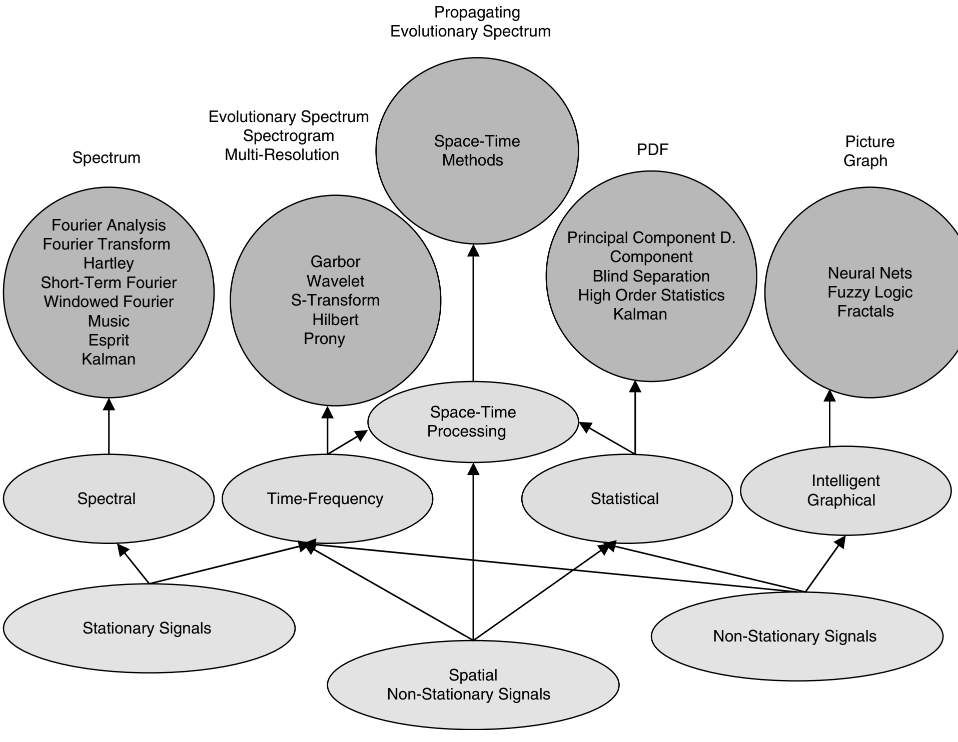

Figure 2 Overall perspective of the signal nature and corresponding analytical methods for analysis

motivation and insightful feedback, and in particular, Yahia Bagzouz, Alex Emanuel, Alfredo Testa, Roberto Langella, Tom Ortmeyer, Carlos Duque and Paulo Silveira, for helping to make this publication more intelligible and, hopefully, useful to the Power Sector. This text is intended to assist those who deal with harmonics and want to understand more clearly the time-varying nature and mechanisms of distortion generation, ways to analyze them, and design systems that are more cost/performance effective. I would also like to make a special mention to Dr. Robert Morrison who became one of the foremost influential researchers in this subject, and to Denis Howroyd, the developer of the first harmonic penetration program, who challenged me in the early eighties to seek more adequate tools for dealing with time-varying harmonics.

I would also like to thank Calvin College, Florida State University, New Mexico State University, USA, and the Federal University of Juiz de Fora, Brazil, for providing valuable time for preparing and editing this text.

Finally, I would like to thank my wife for her encouragement, support, and resignation for cancelling some of our kayak trips to work on this demanding but enjoyable effort.

Paulo F. Ribeiro
Grand Rapids, Michigan, USA

Website Information

Along with the publication of this book, a website has been created containing MATLAB® files for additional waveforms of typical non-linear loads which could be signal processed by different techniques for further understanding. Also two MATLAB based time-varying harmonic decomposition techniques will be available at the site for waveform processing. The website can be reached at:

www.laptel.ufjf.br

password: signals

Readers are welcome to send additional waveforms to the editor at pfribeiro@ieee.org to be included in the database.

Additional information and samples can be found in Appendix B: Sample of waveforms and decompositions.

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Part I

GENERAL CONCEPTS AND DEFINITIONS

This part covers general and introductory concepts. Chapter 1 presents an overview of probabilistic aspects of harmonics where initial models were restricted to the analysis of instantaneous values of voltages and currents. Direct analytical methods were originally applied with many simplifications. Attempts to use phasor representation of current also used direct mathematical analysis and simple distributions of amplitude and phase angle. Direct simulation was applied to test the assumptions used. When power systems measurement became more powerful the real distributions were measured for some loads and this enabled a significant increase in the accuracy of observations. The limitations to the application of harmonic analysis in general, and the issues that determine whether full spectral analysis should be used, are discussed. The chapter also reviews existing methods associated with harmonic measurement of nonstationary voltages and currents waveform, characterization of recorded data, harmonic summation and cancelation in systems with multiple nonlinear loads and probabilistic harmonic power flow.

Chapter 2 attempts to integrate spectral analysis and probability distribution concepts, for a better understanding of the nature of time-varying harmonics and possibly as a more precise way to treat time-varying harmonics and validate harmonic summation studies. Similarities between spectral analysis and probability distribution functions are considered and discussed.

Chapter 3 explores the basic definitions of harmonics (Fourier/spectral analysis) of periodic and nonperiodic functions, that is, discrete and continuous range of frequencies. Definitions of typical harmonics and transients phenomena are proposed.

Chapter 4 deals with the correct definitions that characterize the flow of electric power/energy under probabilistic conditions.

Finally, Chapter 5 presents Joseph Fourier's heat transfer experiment through the use of finite element analysis. An iron ring is modeled and transient thermal analysis is performed to reproduce the data Fourier obtained experimentally. Simulated data give a clear view of how Fourier first thought of representing temperature distribution in a ring as a combination of sinusoidal functions and how this experiment gave information about how harmonics content is modified in time. The use of new signal processing methods, based on time–frequency decomposition, further illustrates Joseph Fourier's physical intuition to visualize the time varying components long before the mathematical foundation was developed.

1

Probabilistic aspects of time-varying harmonics

R. E. Morrison, Y. Baghzouz, P. F. Ribeiro and C. A. Duque

1.1 Introduction

This chapter presents an overview of the motivation, importance and previous development of the text. This chapter considers the early development of probabilistic methods to model power system harmonic distortion. Initial models were restricted to the analysis of instantaneous values of current. Direct analytical methods were originally applied with many simplifications. Initial attempts to use phasor representation of current also used direct mathematical analysis and simple distributions of amplitude and phase angle. Direct simulation was applied to test assumptions used. When power systems measurement systems became sufficiently powerful the real distributions were measured for some loads and this enabled a significant increase of accuracy. However, there is still a lack of knowledge of the distributions that might be used to model converter harmonic currents. The chapter concludes by considering the limitations to the application of harmonic analysis.

The application of probabilistic methods for analyzing power system harmonic distortion commenced in the late 1960s. Initially, direct mathematical analysis was applied based on instantaneous values of current from individual harmonic components [1]. Methods were devised to calculate the probability density function (pdf) of one total harmonic current generated by a number of loads, given the pdfs for the individual load currents. One of the first attempts to use phasor notation was applied by Rowe [2] in 1974. He considered the addition

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of a series of currents modeled as phasors with random amplitude and random phase angle. Further, the assumption was made that the amplitude of each harmonic current was variable with uniform probability density from zero to a peak value and the phase angle of each current was variable from 0 to 2π. Rowe's analysis was limited to the derivation of the properties of the summation current from a group of distorted loads connected at one node.

Properties of the summation current were obtained by simplifying the analysis by means of the Rayleigh distribution. Unfortunately once such simplifications are applied, flexibility on modeling is not retained and the ability to model a bus bar containing a small number of loads is lost. However, Rowe was able to show that the highest expected value of current due to a group of loads could be predicted from the Equation (1.1):

$$I_s = K(I1^2 + I2^2 + I3^2 + \cdots)^{1/2} \tag{1.1}$$

where I_s is the summation current from individual load currents ($I1$, $I2$, $I3$, etc.) and K is close to 1.5.

Equation (1.1) indicates that the highest expected value of summation current was not related to the arithmetic sum of all the individual harmonic current amplitudes. This factor was a major step forward. Also, by introducing the concept of the highest expected current it was noted that this would be less than the highest possible value of current, namely, the arithmetic sum. It was necessary to define the highest expected current as the lowest value which would be exceeded for a negligible part of the time. Negligible was taken to be 1%. To calculate this value, the 99th percentile was frequently referred to.

The early analysis depended on assumed probability distributions as well as variable ranges. Subsequently, some of the actual probability density functions were measured [3] and found to differ from the assumed pdfs stated above. Simulations were arranged to derive the cumulative distribution function (cdf) of the summation current for low-order harmonic current components. The estimated cdfs were then compared with the measured cdfs with reasonable agreement as shown in Figure 1.1.

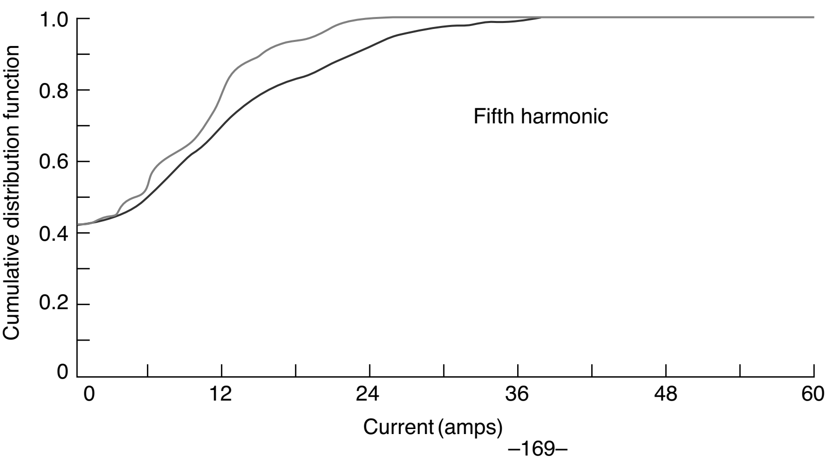

Figure 1.1 Measured (lower curve) and simulated (upper curve) cdf of fifth harmonic current at a 25kV AC traction substation