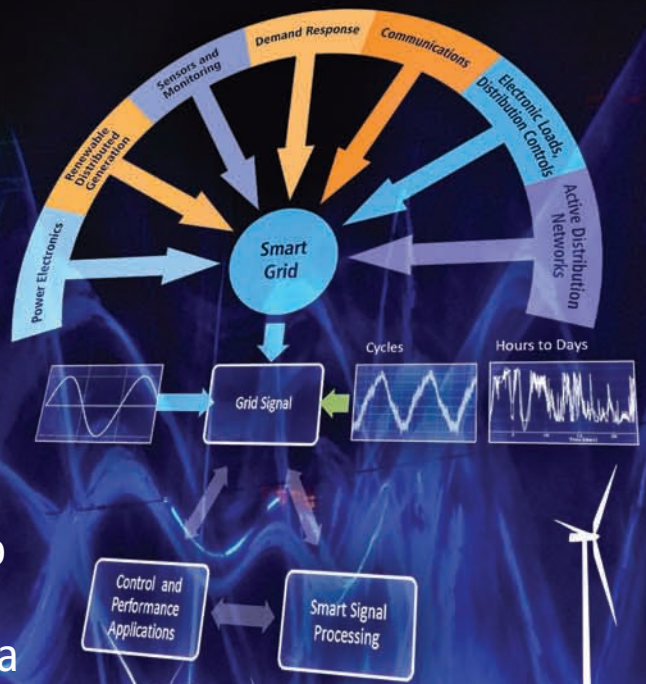


Power Systems Signal Processing for Smart Grids



Paulo Fernando Ribeiro
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**POWER SYSTEMS
SIGNAL PROCESSING
FOR SMART GRIDS**

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Contents

About the Authors	xiii
Preface	xv
Accompanying Websites	xxi
Acknowledgments	xxiii
1 Introduction	1
1.1 Introduction	1
1.2 The Future Grid	2
1.3 Motivation and Objectives	3
1.4 Signal Processing Framework	4
1.5 Conclusions	8
References	10
2 Power Systems and Signal Processing	11
2.1 Introduction	11
2.2 Dynamic Overvoltage	12
2.2.1 Sustained Overvoltage	12
2.2.2 Lightning Surge	13
2.2.3 Switching Surges	15
2.2.4 Switching of Capacitor Banks	17
2.3 Fault Current and DC Component	21
2.4 Voltage Sags and Voltage Swells	25
2.5 Voltage Fluctuations	27
2.6 Voltage and Current Imbalance	29
2.7 Harmonics and Interharmonics	29
2.8 Inrush Current in Power Transformers	42
2.9 Over-Excitation of Transformers	45
2.10 Transients in Instrument Transformers	47
2.10.1 Current Transformer (CT) Saturation (Protection Services)	47
2.10.2 Capacitive Voltage Transformer (CVT) Transients	54
2.11 Ferroresonance	55
2.12 Frequency Variation	56

2.13 Other Kinds of Phenomena and their Signals	56
2.14 Conclusions	57
References	58
3 Transducers and Acquisition Systems	59
3.1 Introduction	59
3.2 Voltage Transformers (VTs)	60
3.3 Capacitor Voltage Transformers	64
3.4 Current Transformers	67
3.5 Non-Conventional Transducers	71
3.5.1 Resistive Voltage Divider	71
3.5.2 Optical Voltage Transducer	72
3.5.3 Rogowski Coil	73
3.5.4 Optical Current Transducer	74
3.6 Analog-to-Digital Conversion Processing	75
3.6.1 Supervision and Control	78
3.6.2 Protection	79
3.6.3 Power Quality	79
3.7 Mathematical Model for Noise	80
3.8 Sampling and the Anti-Aliasing Filtering	81
3.9 Sampling Rate for Power System Application	84
3.10 Smart-Grid Context and Conclusions	84
References	85
4 Discrete Transforms	87
4.1 Introduction	87
4.2 Representation of Periodic Signals using Fourier Series	87
4.2.1 Computation of Series Coefficients	90
4.2.2 The Exponential Fourier Series	92
4.2.3 Relationship between the Exponential and Trigonometric Coefficients	93
4.2.4 Harmonics in Power Systems	95
4.2.5 Properties of a Fourier Series	97
4.3 A Fourier Transform	98
4.3.1 Introduction and Examples	98
4.3.2 Fourier Transform Properties	103
4.4 The Sampling Theorem	104
4.5 The Discrete-Time Fourier Transform	108
4.5.1 DTFT Pairs	109
4.5.2 Properties of DTFT	110
4.6 The Discrete Fourier Transform (DFT)	110
4.6.1 Sampling the Fourier Transform	116
4.6.2 Discrete Fourier Transform Theorems	116
4.7 Recursive DFT	117
4.8 Filtering Interpretation of DFT	120

4.8.1	<i>Frequency Response of DFT Filter</i>	123
4.8.2	<i>Asynchronous Sampling</i>	124
4.9	The z -Transform	126
4.9.1	<i>Rational z-Transforms</i>	128
4.9.2	<i>Stability of Rational Transfer Function</i>	131
4.9.3	<i>Some Common z-Transform Pairs</i>	131
4.9.4	<i>z-Transform Properties</i>	133
4.10	Conclusions	133
	References	133
5	Basic Power Systems Signal Processing	135
5.1	Introduction	135
5.2	Linear and Time-Invariant Systems	135
5.2.1	<i>Frequency Response of LTI System</i>	138
5.2.2	<i>Linear Phase FIR Filter</i>	140
5.3	Basic Digital System and Power System Applications	142
5.3.1	<i>Moving Average Systems: Application</i>	142
5.3.2	<i>RMS Estimation</i>	144
5.3.3	<i>Trapezoidal Integration and Bilinear Transform</i>	146
5.3.4	<i>Differentiators Filters: Application</i>	148
5.3.5	<i>Simple Differentiator</i>	151
5.4	Parametric Filters in Power System Applications	153
5.4.1	<i>Filter Specification</i>	154
5.4.2	<i>First-Order Low-Pass Filter</i>	155
5.4.3	<i>First-Order High-Pass Filter</i>	155
5.4.4	<i>Bandstop IIR Digital Filter (The Notch Filter)</i>	156
5.4.5	<i>Total Harmonic Distortion in Time Domain (THD)</i>	159
5.4.6	<i>Signal Decomposition using a Notch Filter</i>	161
5.5	Parametric Notch FIR Filters	161
5.6	Filter Design using MATLAB [®] (FIR and IIR)	163
5.7	Sine and Cosine FIR Filters	163
5.8	Smart-Grid Context and Conclusions	165
	References	166
6	Multirate Systems and Sampling Alterations	167
6.1	Introduction	167
6.2	Basic Blocks for Sampling Rate Alteration	167
6.2.1	<i>Frequency Domain Interpretation</i>	168
6.2.2	<i>Up-Sampling in Frequency Domain</i>	169
6.2.3	<i>Down-Sampling in Frequency Domain</i>	169
6.3	The Interpolator	170
6.3.1	<i>The Input–Output Relation for the Interpolator</i>	172
6.3.2	<i>Multirate System as a Time-Varying System and Nobles Identities</i>	172
6.4	The Decimator	174

6.4.1	<i>Introduction</i>	174
6.4.2	<i>The Input–Output Relation for the Decimator</i>	174
6.5	Fractional Sampling Rate Alteration	175
6.5.1	<i>Resampling Using MATLAB[®]</i>	175
6.6	Real-Time Sampling Rate Alteration	176
6.6.1	<i>Spline Interpolation</i>	177
6.6.2	<i>Cubic B-Spline Interpolation</i>	180
6.7	Conclusions	184
	References	184
7	Estimation of Electrical Parameters	185
7.1	Introduction	185
7.2	Estimation Theory	185
7.3	Least-Squares Estimator (LSE)	187
7.3.1	<i>Linear Least-Squares</i>	188
7.4	Frequency Estimation	191
7.4.1	<i>Frequency Estimation Based on Zero Crossing (IEC61000-4-30)</i>	192
7.4.2	<i>Short-Term Frequency Estimator Based on Zero Crossing</i>	195
7.4.3	<i>Frequency Estimation Based on Phasor Rotation</i>	198
7.4.4	<i>Varying the DFT Window Size</i>	200
7.4.5	<i>Frequency Estimation Based on LSE</i>	201
7.4.6	<i>IIR Notch Filter</i>	203
7.4.7	<i>Small Coefficient and/or Small Arithmetic Errors</i>	203
7.5	Phasor Estimation	205
7.5.1	<i>Introduction</i>	205
7.5.2	<i>The PLL Structure</i>	207
7.5.3	<i>Kalman Filter Estimation</i>	209
7.5.4	<i>Example of Phasor Estimation using Kalman Filter</i>	211
7.6	Phasor Estimation in Presence of DC Component	212
7.6.1	<i>Mathematical Model for the Signal in Presence of DC Decaying</i>	213
7.6.2	<i>Mimic Method</i>	214
7.6.3	<i>Least-Squares Estimator</i>	215
7.6.4	<i>Improved DTFT Estimation Method</i>	216
7.7	Conclusions	224
	References	224
8	Spectral Estimation	227
8.1	Introduction	227
8.2	Spectrum Estimation	227
8.2.1	<i>Understanding Spectral Leakage</i>	229
8.2.2	<i>Interpolation in Frequency Domain: Single-Tone Signal</i>	232
8.3	Windows	236
8.3.1	<i>Frequency-Domain Windowing</i>	236
8.4	Interpolation in Frequency Domain: Multitone Signal	240

8.5	Interharmonics	243
8.5.1	<i>Typical Interhamonic Sources</i>	246
8.5.2	<i>The IEC Standard 61000-4-7</i>	247
8.6	Interharmonic Detection and Estimation Based on IEC Standard	250
8.7	Parametric Methods for Spectral Estimation	254
8.7.1	<i>Prony Method</i>	254
8.7.2	<i>Signal and Noise Subspace Techniques</i>	262
8.8	Conclusions	269
	References	270
9	Time-Frequency Signal Decomposition	271
9.1	Introduction	271
9.2	Short-Time Fourier Transform	274
9.2.1	<i>Filter Banks Interpretation</i>	274
9.2.2	<i>Choosing the Window: Uncertainty Principle</i>	276
9.2.3	<i>The Time-Frequency Grid</i>	279
9.3	Sliding Window DFT	280
9.3.1	<i>Sliding Window DFT: Modified Structure</i>	282
9.3.2	<i>Power System Application</i>	282
9.4	Filter Banks	284
9.4.1	<i>Two-Channel Quadrature-Mirror Filter Bank</i>	288
9.4.2	<i>An Alias-Free Realization</i>	290
9.4.3	<i>A PR Condition</i>	290
9.4.4	<i>Finding the Filters from $P(z)$</i>	292
9.4.5	<i>General Filter Banks</i>	294
9.4.6	<i>Harmonic Decomposition Using PR Filter Banks</i>	295
9.4.7	<i>The Sampling Frequency</i>	298
9.4.8	<i>Extracting Even Harmonics</i>	298
9.4.9	<i>The Synthesis Filter Banks</i>	300
9.5	Wavelet	300
9.5.1	<i>Continuous Wavelet Transform</i>	301
9.5.2	<i>The Inverse Continuous Wavelet Transform</i>	305
9.5.3	<i>Discrete Wavelet Transform (DWT)</i>	305
9.5.4	<i>The Inverse Discrete Wavelet Transform</i>	308
9.5.5	<i>Discrete-Time Wavelet Transform</i>	308
9.5.6	<i>Design Issues in Wavelet Transform</i>	313
9.5.7	<i>Power System Application of Wavelet Transform</i>	316
9.5.8	<i>Real-Time Wavelet Implementation</i>	318
9.6	Conclusions	319
	References	319
10	Pattern Recognition	321
10.1	Introduction	321
10.2	The Basics of Pattern Recognition	322
10.2.1	<i>Datasets</i>	323
10.2.2	<i>Supervised and Unsupervised Learning</i>	323

10.3	Bayes Decision Theory	323
10.4	Feature Extraction on the Power Signal	324
	10.4.1 <i>Effective Value (RMS)</i>	324
	10.4.2 <i>Discrete Fourier Transform</i>	325
	10.4.3 <i>Wavelet Transform</i>	325
	10.4.4 <i>Cumulants of Higher-Order Statistics</i>	325
	10.4.5 <i>Principal Component Analysis</i>	326
	10.4.6 <i>Normalization</i>	327
	10.4.7 <i>Feature Selection</i>	328
10.5	Classifiers	329
	10.5.1 <i>Minimum Distance Classifiers</i>	329
	10.5.2 <i>Nearest Neighbor Classifier</i>	329
	10.5.3 <i>The Perceptron</i>	330
	10.5.4 <i>Least-Squares Methods</i>	334
	10.5.5 <i>Multilayer Perceptron</i>	337
	10.5.6 <i>Support Vector Machines</i>	342
10.6	System Evaluation	348
	10.6.1 <i>Estimation of the Classification Error Probability</i>	349
	10.6.2 <i>Limited-Size Dataset</i>	350
10.7	Pattern Recognition Examples in Power Systems	350
	10.7.1 <i>Power Quality Disturbance Classification</i>	350
	10.7.2 <i>Load Forecasting in Electric Power Systems</i>	351
	10.7.3 <i>Power System Security Assessment</i>	353
10.8	Conclusions	353
	References	353
11	Detection	355
	11.1 Introduction	355
	11.2 Why Signal Detection for Electric Power Systems?	355
	11.3 Detection Theory Basics	356
	11.3.1 <i>Detection on the Bayesian Framework</i>	356
	11.3.2 <i>Newman-Pearson Criterion</i>	357
	11.3.3 <i>Receiving Operating Characteristics</i>	358
	11.3.4 <i>Deterministic Signal Detection in White Gaussian Noise</i>	358
	11.3.5 <i>Deterministic Signals with Unknown Parameters</i>	363
	11.4 Detection of Disturbances in Power Systems	368
	11.4.1 <i>The Power System Signal</i>	368
	11.4.2 <i>Optimal Detection</i>	369
	11.4.3 <i>Feature Extraction</i>	370
	11.4.4 <i>Commonly Used Detection Algorithms</i>	370
	11.5 Examples	371
	11.5.1 <i>Transmission Lines Protection</i>	371
	11.5.2 <i>Detection Algorithms Based on Estimation</i>	373
	11.5.3 <i>Saturation Detection in Current Transformers</i>	377
	11.6 Smart-Grid Context and Conclusions	380
	References	381

12	Wavelets Applied to Power Fluctuations	383
12.1	Introduction	383
12.2	Basic Theory	384
12.3	Application of Wavelets for Time-Varying Generation and Load Profiles	385
12.3.1	<i>Fluctuation Analyses with FFT</i>	385
12.3.2	<i>Methodology</i>	386
12.3.3	<i>Load Fluctuations</i>	387
12.3.4	<i>Wind Farm Generation Fluctuations</i>	389
12.3.5	<i>Smart Microgrid</i>	390
12.4	Conclusions	392
	References	392
13	Time-Varying Harmonic and Asymmetry Unbalances	395
13.1	Introduction	395
13.2	Sequence Component Computation	396
13.3	Time-Varying Unbalance and Harmonic Frequencies	397
13.4	Computation of Time-Varying Unbalances and Asymmetries at Harmonic Frequencies	398
13.5	Examples	401
13.5.1	<i>Inrush Current</i>	401
13.5.2	<i>Voltage Sag</i>	404
13.5.3	<i>Unbalance in Converters</i>	407
13.6	Conclusions	410
	References	411
	Index	413

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Preface

This book has grown out of a cooperation between friends who have a common interest, expertise and passion for power systems (PS) and signal processing (SP). It has evolved as a consequence of SP projects applied to power quality (PQ) and power systems in general.

The rapid growth of computational power associated with the cross-fertilization of applications and use of SP for analysis and diagnosis of system performance has led to unprecedented development of new methods, theories and models.

The authors have come to appreciate the potential for much wider applications of SP, prompted in particular by the modernization of electric power systems via the current and comprehensive developments associated with the implementation of smart grid (SG) technologies.

The increasing complexity of the electric grid requires intensive and comprehensive signal monitoring followed by the necessary signal processing for characterizing, identifying, diagnosing and protecting and also for a more accurate investigation of the nature of certain phenomena and events. SP can also be used for predicting and anticipating system behavior.

For electrical engineering SP is a vital tool for clarifying, separating, decomposing and revealing different aspects and dimensions of the complex physical reality of the operation of electrical systems, in which different phenomena are usually intricately and intrinsically aggregated and not trivially resolved.

SP can be qualified by the analytical aspects of the electrical systems, and can help to expose and characterize the diversity, unity, meaning and intrinsic purpose of electrical parameters, system phenomena and events.

As the electric grid becomes more complex, modeling and simulation become less capable of capturing the influence of the multitude of independent and intertwined components within the network. SP deals with the actual system and not with modeling abstraction or reduction (although it may be used in connection with simulations), so may clarify aspects of the whole through a multiplicity of analytical tools. Consequently, SP allows the engineer to detect and measure the behavior and true nature of the electric grid.

Today, the vast majority of analog signals are converted to digital signals. In the context of electrical systems, this conversion is carried out by numerous secondary smart digital devices that perform the tasks of controlling, metering, protecting, supervising or communicating with other components of the system. Moreover, the quality of such smart devices is enhanced by their ability to perform digital signal processing (DSP).

The term DSP is used to describe the mathematics, algorithms and techniques used to manipulate signals after they have been converted into a convenient digital form in order to

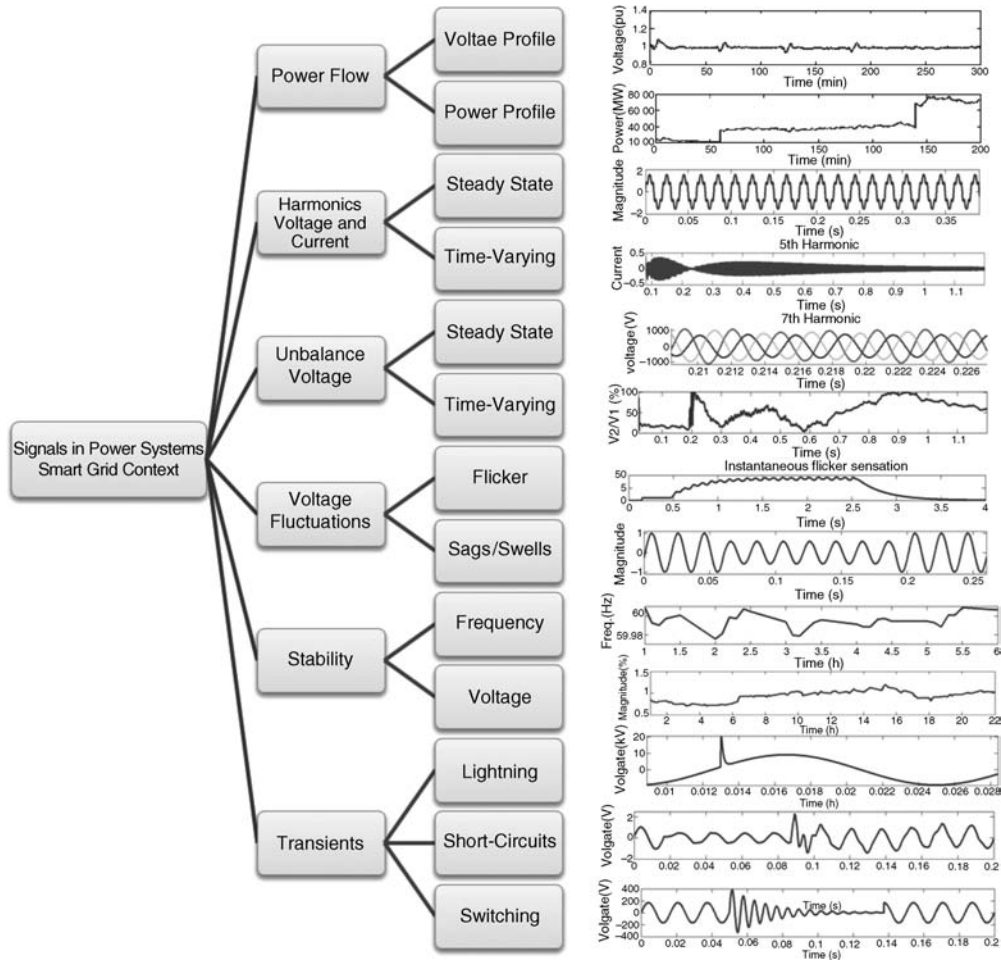


Figure 1 Power systems signals in the context of smart grids.

address a wide variety of needs such as the enhancement of visual images, recognition and generation of speech and compression of data for storage and transmission [1].

The aim of this book is to further promote the use of DSP within power systems, and to expand its application in the context of smart grids. Various techniques are presented, discussed and applied to typical and expected system conditions. Figure 1 illustrates a sample of the gamma of waveforms of typical power systems signals in a context of traditional and smart-grid power system environments.

Chapter 1 describes the motivation for the use of signal processing in different applications of power systems in the context of the smart grids of the future. A wide variety of digital measurements and data analysis techniques required to deliver diagnostic solutions and correlations is provided.

Chapter 2 provides a comprehensive list of power system events and phenomena in terms of time-varying voltage and current signals, characterizing these in terms of magnitude, phase

and waveform. It will become apparent that many signals can be represented by a mathematical expression (e.g. exponential DC, faults, waveform distortions).

Chapter 3 describes the different aspects as related to voltage transformers, current transformers, analog filters and analog to digital converters. These components are sources of noise and errors, and impose speed constraints. Due to the lack of information about acquisition systems for electric power signals, this chapter addresses a few of the important demands that are generally neglected in common signal processing literature.

Chapter 4 covers discrete transforms essential in the analysis and synthesis of power systems signal processing. The chapter describes the discrete-time Fourier transform (DTFT), discrete Fourier transform (DFT) and z-transform, as well as a summary of the continuous transforms. Although these transforms are widely treated in several textbooks, the focus of the authors is on specific and common power systems applications.

Chapter 5 covers basic aspects of power system signal processing. These include digital signal operators (delay, adders, multipliers), digital signal operations (modulation, filtering, correlation and convolution), finite impulse response filters and infinite impulse response filters. Several power systems applications are used to illustrate these concepts.

Chapter 6 covers the multirate and sampling frequency alterations, a common time-variant method used in power systems to change the sampling frequency or to analyze a signal. Such an example is using filter banks or wavelet transform. (Filter banks and wavelet transform are covered in Chapter 9, but the digital principles for the implementation of these structures are presented in Chapter 6.) Offline and real-time frequency alterations for power systems application are also discussed.

In Chapter 7 the focus is on algorithms that are capable of estimating parameters such as phasor, frequency, RMS (root mean square), harmonics and transients (decaying exponential) for real-time and offline applications. The basic concepts of estimation theory are presented, including the Cramer–Rao lower bound (CRLB), the MVU estimator, BLUE and LSE estimators. The smart-grid environment is one of higher-complexity electrical signals, which need to be properly and accurately measured.

Chapter 8 covers the basic concepts of spectrum analysis and parametric and non-parametric spectrum estimations. Common errors in parametric estimation are covered, including aliasing, scalloping loss and spectrum leakage. Among the parametric methods discussed are the Prony, Pisarenko, MUSIC and ESPRIT methods.

Chapter 9 introduces a unified view of time-frequency decomposition based on filter banks and wavelet transforms for power system applications. The short-time Fourier transform (STFT) is presented, and the basic principle of filter banks theory and its connection with wavelets is discussed. The basic theory of the wavelet and relevant signal processing techniques are described. Guidance on how to choose the mother wavelet for power system applications is provided.

Chapter 10 covers pattern recognition as an essential enabling tool for the operation and control of the upcoming electric smart-grid environment. The chapter highlights the main aspects and necessary steps required for providing necessary tools to operate the grid of the future.

Chapter 11 presents the basic aspects of detection theory using the Bayesian framework and discusses the deterministic signal detection for white Gaussian noise.

Chapter 12 discusses the application of wavelet analysis to determine fluctuation patterns in generation and load profiles. This is achieved by the filtering of its wavelet components based

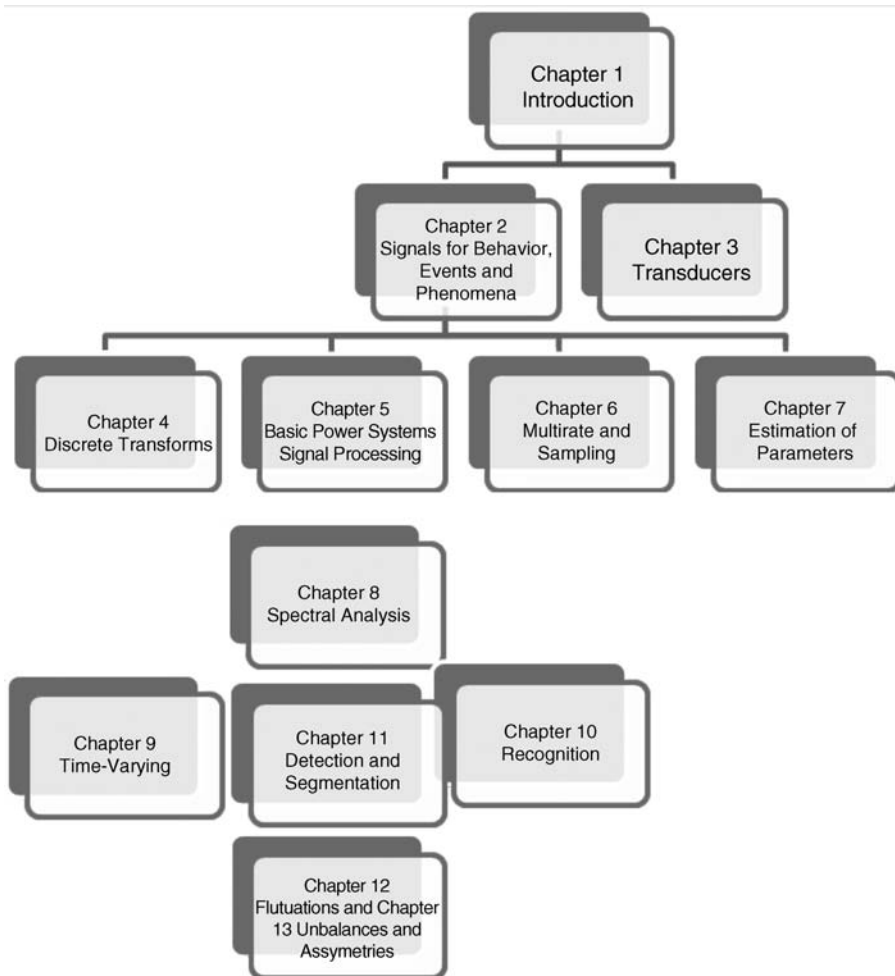


Figure 2 Structure of the book.

on their RMS values, from which it is possible to identify the most-relevant scaling factors. The procedure reveals fluctuation patterns which cannot be visualized via frequency decomposition methods.

Chapter 13 describes an application in which the evaluation of unbalances and asymmetries in power systems can be facilitated by the use of a time-varying decomposition method based on SW-DFT. The time-varying harmonics and their positive-, negative- and zero-sequence components are calculated for each frequency.

Figure 2 depicts the structure of the book.

Finally, some philosophical considerations with regards to the utilization and reception of this book (or any other book) is adapted below from the writings of British author C. S. Lewis:

‘A scientific or engineering work such as this can be either *received* or *used*. When we *receive* it, we exercise our senses and imagination and various other powers according to a pattern suggested by the authors. When we *use* it we treat it as an assistance for our own activities. . . . *Using* is inferior to *receiving* because, in science and engineering, *using* merely facilitates, relieves or palliates our research/applications; it does not add to it.’ [2]

The authors hope that the reader will both use and receive this book as a valuable and thought-provoking guide and tool.

References

1. Smith, S.W. (1997) *The Scientist and Engineer’s Guide to Digital Signal Processing*, California Technical Publishing.
2. Lewis, C.S. (1961) *An Experiment in Criticism*, Cambridge University Press.

Accompanying Websites

To accompany this book, two websites have been set up containing MATLAB[®] files for additional waveforms of typical non-linear loads; these can be signal-processed by different techniques for further understanding. Two MATLAB[®]-based time-varying harmonic decomposition techniques are also available on site for waveform processing.

Please visit <http://www.ufjf.br/pscope-eng/digital-signal-processing-to-smart-grids/>

Password: dspsgird

Or http://www.wiley.com/go/signal_processing

Readers are welcome to send additional waveforms for signals and MATLAB[®] scripts to be included in the database to Professor Paulo Fernando Ribeiro at pfribeiro@ieee.org.

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1

Introduction

1.1 Introduction

A power system is one of the most complex systems that have been made by man. It is an interconnected system consisting of generation units, substations, transmission, distribution lines and loads (consumers). Additionally, these encompass a vast array of other equipment such as synchronous machines, power transformers, instrument transformers, capacitor banks, power electronic devices, induction motors and so on. In this context the smart grid has contributed even further to this complex situation, of which a better understanding is required. Given these conditions, signal processing is becoming an essential assessment tool to enable the engineer and researcher to understand, plan, design and operate the complex and smart electronic grid of the future.

Signal processing is used in many different applications and is becoming an important class of tools for electric power system analysis. This is partly due to a readily available vast arsenal of digital measurements that are needed for the understanding, correlation, diagnosis and development of key solutions to this complex context of smart grids.

Measurements retrieved from numerous locations can be used for data analysis and can be applied to a variety of issues such as:

- voltage control
- power quality and reliability
- power system and equipment diagnostics
- power system control
- power system protection.

This book focuses on electrical signals associated with power system analysis in terms of characterization and diagnostics, or where signal-processing techniques can be useful such as for the analysis of possible concerns about individual loads and/or state of the system.

A large variety of equipment can be used to capture and characterize system variations. These include monitors, digital fault recorders, digital relays, various power system controllers and other intelligent electronic devices (IEDs). Furthermore, power system conditions and events require signal processing techniques for the analysis of its recorded signals. This book

promotes attentiveness to issues in the signal processing community. It will provide an overview of these techniques for the understanding and promotion of solutions to its concerns.

1.2 The Future Grid

The future of the developed, developing and emerging countries in a global economy will rely even more on the availability and transport of electrical energy. It is believed that in the near future the global consumption of electrical energy will grow to unprecedented levels. Additionally, security and sustainability have become major priorities both for industry and society.

The deployment of sustainable/renewable energy sources is crucial for a healthy relationship between man and his environment. These changes are driven by a number of developments in society, where the transition to a more sustainable society is a priority. Moreover, the availability of various new technologies and the deregulation of the electric industry may have an additional impact on future developments.

The sustainable and low-carbon imprinting of a society and problematical energy storage requires an integrated power grid which will play a central role in the achievement of energy-efficiency targets and savings. However, the large-scale incorporation of renewable energy production and novel forms of consumption will substantially increase the complexity of its electricity distribution system. The urgency requirement of this complex smart energy grid is evident from the extensive research and development in this area.

An overall picture of this new complex infrastructure is shown in Figure 1.1, where the smart grid of the future can be seen as a merging of the power system and control information technologies.

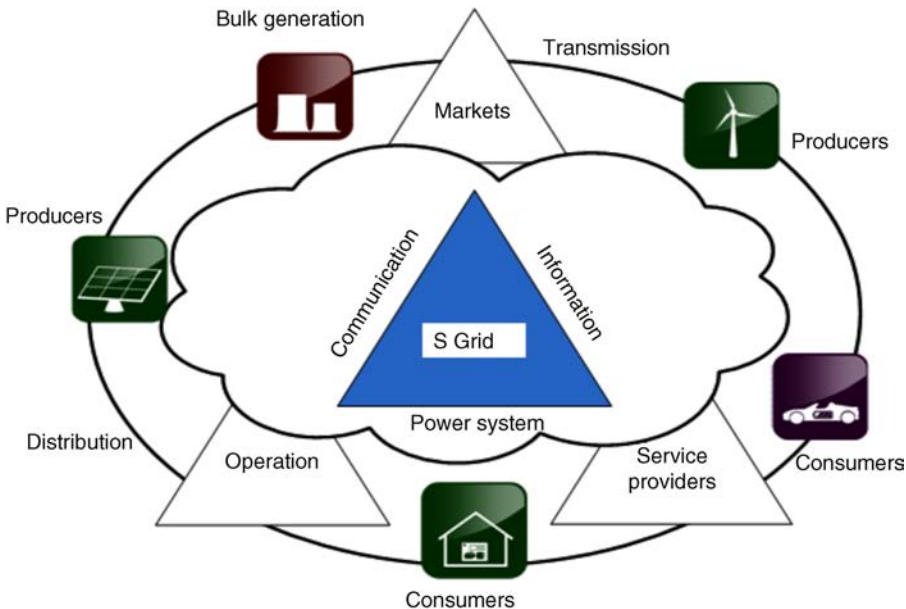


Figure 1.1 The grid of the future.

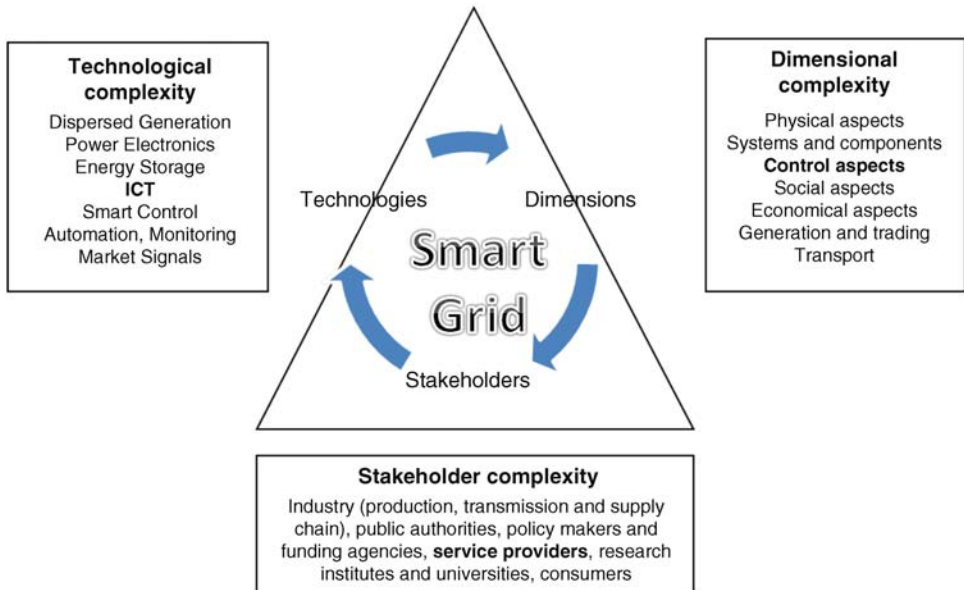


Figure 1.2 The complexity of the smart grid: technologies, stakeholders, dimensions.

The complexity of a smart grid (illustrated in Figure 1.2) might be classified as:

- dimensional complexity
- technological complexity
- stakeholder complexity.

The science and art of designing technological systems within a complex societal environment is a challenging job. In order to produce systems that are synchronized with all the different normative moments of each complexity, new projects must take into account the abovementioned evolving reality. In philosophical terms, a simultaneous realization of different laws and norms is required, where dimensional, technological and stakeholder issues with conflicting objectives and interests need to be accommodated in a well-integrated manner.

In this context, signal processing emerges as one of the most important and effective tools for investigating the operation of such a system.

1.3 Motivation and Objectives

In topics such as power quality, research has traditionally been motivated by the need to supply acceptable voltage quality to end-user loads where voltage, current and frequency deviations in the power system are normal concerns of a systems operator.

The characterization of the incompatibilities caused by these deviations requires an understanding of the phenomena themselves. Listed among the possible aspects to be

investigated are the need for efficient representation of the voltage and current variations and the signal processing to understand how equipment behaves. There is also a need for continuous monitoring that can capture deviations, events and variations and the correlation with equipment performance, decomposition, modeling, parametric estimation and identification algorithms.

This book aims at utilizing more widely and effectively the signal processing tools for electrical power and energy engineering systems analysis. The text uses an integrated approach to the application of signal processing in power systems by means of the critical analysis of the methodologies recently developed or in innovative ways. The main techniques are critically illustrated, compared and applied to a variety of power systems signals.

Both traditional and advanced signal processing tools for monitoring and control of power systems are considered. To meet future requirements, methods and techniques shall be engaged to explore the full range of signals that derive from the complex interaction between suppliers, consumers and network operators. The book is not only intended to convey the theoretical concepts, but also to demonstrate the application.

How do engineers in the research and development of electrical grids cope with this increased complexity? It is impossible for an engineer to take the full complexity of these systems into account? During the design process, focus is generally on one or two aspects, one or two components or systems or the perspective of one or two parties involved. In other words, the complex system is reduced to a simplified, neatly arranged subsystem in order to design a new component, to study its performance and to optimize its stability. Through the years this has proven to be a very practical approach as long as the system does not experience major changes, allowing engineering judgment to be used in the simplification process. Unfortunately, a direct consequence of this is that it is not the whole system that is considered: only a reduced system.

In research and development, reduction is unavoidable. Engineers and researchers therefore have to be aware that they study and design in the context of reduced realities. As a consequence, they have to question themselves continuously whether they are missing any relevant dimensions. In practice, engineers cannot easily handle all the technical and non-technical dimensions of an electrical system due to the enormous complexity of smart grids and the requirements of all parties involved, including the requirements of governments and powerful stakeholders. As a consequence it is easy to miss relevant dimensions, to overlook important interactions between technical systems, to neglect the interests of certain parties and to lose a great amount of information. The interaction between multitudes of participants produces very complex signals that must be monitored and processed in order to determine the state of and developments around devices and systems, as depicted in Figure 1.3.

1.4 Signal Processing Framework

The condition of the grid can be fully assessed through the measurement and analysis of signals at different points in the system. Figure 1.4 illustrates the basic concept of signals and parameters that can be processed and derived in steps. First, three-phase signals are decomposed into time-varying harmonics and these are then processed by symmetrical components. The result provides the engineer with a unique tool to visualize the nature of time-varying imbalances and asymmetries in power systems.