SIGNAL PROCESSING OF POWER QUALITY DISTURBANCES

MATH H. J. BOLLEN

IRENE YU-HUA GU

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To my father and in memory of my mother (from Irene)

CONTENTS

PREFACE

This book originated from a few occasional discussions several years ago between the authors on finding specific signal-processing tools for analyzing voltage disturbances. These simple discussions have led to a number of joined publications, several Masters of Science projects, three Ph.D. projects, and eventually this book. Looking back at this process it seems obvious to us that much can be gained by combining the knowledge in power system and signal processing and bridging the gaps between these two areas.

This book covers two research areas: signal processing and power quality. The intended readers also include two classes: students and researchers with a power engineering background who wish to use signal-processing techniques for power system applications and students and researchers with a signal-processing background who wish to extend their research applications to power system disturbance analysis and diagnostics. This book may also serve as a general reference book for those who work in industry and are engaged in power quality monitoring and innovations. Especially, the more practical chapters (2, 5, 6, and 10) may appeal to many who are currently working in the power quality field.

The first draft of this book originated in 2001 with the current structure taking shape during the summer of 2002. Since then it took another three years for the book to reach the state in which you find it now. The outside world did not stand still during these years and many new things happened in power quality, both in research and in the development of standards. Consequently, we were several times forced to rewrite parts and to add new material. We still feel that the book can be much more enriched but decided to leave it in its current form, considering among others the already large number of pages. We hope that the readers will pick up a few open subjects from the book and continue the work. The conclusion sections in this book contain some suggestions on the remaining issues that need to be resolved in the authors' view.

Finally, we will be very happy to receive feedback from the readers on the contents of this book. Our emails are m.bollen@ieee.org and i.gu@ieee.org. If you find any mistake or unclarity or have any suggestion, please let us know. We cannot guarantee to answer everybody but you can be assured that your message will be read and it will mean a lot to us.

MATH H. J. BOLLEN
IRENE Y. H. GU

Ludvika, Sweden
Gothenburg, Sweden
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The availability of data from real power system measurements has been an important condition for allowing us to write this book. Measurement data and other power system data and information were collected through the years. Even though not all of them were used for the material presented in this book, they all contributed to our further understanding of power quality monitoring and disturbance data analysis. Therefore we would like to thank all those that have contributed their measurement data through the years (in alphabetical order): Peter Axelberg (Unipower); Geert Borloo (Elia); Larry Conrad (Cinergy); Magnus Ericsson (Trinergi); Alistair Ferguson (Scottish Power); Zhengti Gu (Shanghai, China); Per Halvarsson (Trinergi and Dranetz BMI); Mats Häger (STRI); Daniel Karlsson (Sydkraft, currently at Gothia Power); Johan Lundquist (Chalmers, currently at Sycon); Mark McGranaghan (Electrotek, currently at EPRI Solutions); Larry Morgan (Duke Power); Robert Olofsson (Göteborg Energi, currently at Metrum, Sweden); Giovanna Postiglione (University of Naples, currently at FIAT Engineering); Christian Roxenius (Göteborg Energi); Dan Sabin (Electrotek); Ambra Sannino (Chalmers, currently at ABB); Helge Seljeseth (Sintef Energy Research);

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M. H. J. B
I. Y-H. G

CHAPTER 1

INTRODUCTION

This chapter introduces the subjects that will be discussed in more detail in the remainder of this book: power quality events and variations, signal processing of power quality measurements, and electromagnetic compatibility (EMC) standards. This chapter also provides a guide for reading the remaining chapters.

1.1 MODERN VIEW OF POWER SYSTEMS

The overall structure of the electric power system as treated in most textbooks on power systems is as shown in Figure 1.1: The electric power is generated in large power stations at a relatively small number of locations. This power is then transmitted and distributed to the end users, typically simply referred to as "loads." Examples of books explicitly presenting this model are [193, 211, 322].

In all industrialized countries this remains the actual structure of the power system. A countrywide or even continentwide transmission system connects the large generator stations. The transmission system allows the sharing of the resources from the various generator stations over large areas. The transmission system not only has been an important contributing factor to the high reliability of the power supply but also has led to the low price of electricity in industrialized countries and enabled the deregulation of the market in electrical energy.

Distribution networks transport the electrical energy from the transmission substations to the various loads. Distribution networks are typically operated radially and power transport is from the transmission substation to the end users. This

Signal Processing of Power Quality Disturbances. By Math H. J. Bollen and Irene Yu-Hua Gu

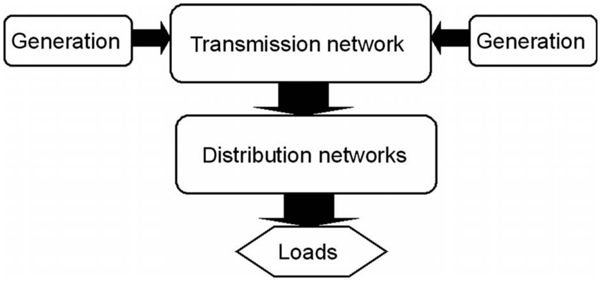

Figure 1.1 Classical structure of power system.

allows for easy methods of protection and operation. The disadvantage is that each component failure will lead to an interruption for some end users.

There are no absolute criteria to distinguish between distribution and transmission networks. Some countries use the term *subtransmission networks* or an equivalent term to refer to the networks around big cities that have a transmission system structure (heavily meshed) but with a power transport more or less in one direction. Discussion of this terminology is however far outside the scope of this book.

Due to several developments during the last several years, the model in Figure 1.1 no longer fully holds. Even though technically the changes are not yet very big, a new way of thinking has emerged which requires a new way of looking at the power system:

- The deregulation of the electricity industry means that the electric power system can no longer be treated as one entity. Generation is in most countries completely deregulated or intended to be deregulated. Also transmission and distribution are often split into separate companies. Each company is economically independent, even where it is electrically an integral part of a much larger system.
- The need for environmentally friendly energy has led to the introduction of smaller generator units. This so-called embedded generation or distributed generation is often connected no longer to the transmission system but to the distribution system. Also economic driving forces, especially with combined heat and power, may result in the building of smaller generation units.
- Higher demands on reliability and quality mean that the network operator has to listen much closer to the demands of individual customers.

A more modern way of looking at the power system resulting from these developments is shown in Figure 1.2. The electric power network no longer transports energy from generators to end users but instead enables the exchange of energy between customers. Note that these customers are the customers of the network (company), not only the end users of the electricity.

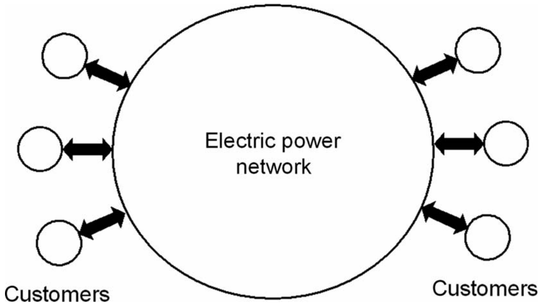

Figure 1.2 Modern view of power system.

The actual structure of the power system is still very much as in Figure 1.1, but many recent developments require thinking in the structure of Figure 1.2. The power network in Figure 1.2 could be a transmission network, a distribution network, an industrial network, or any other network owned by a single company. For a transmission network, the customers are, for example, generator stations, distribution networks, large industrial customers (who would be generating or consuming electricity at different times, based on, e.g., the price of electricity at that moment), and other transmission networks. For a distribution network, the customers are currently mainly end users that only consume electricity, but also the transmission network and smaller generator stations are customers. Note that all customers are equal, even though some may be producing energy while others are consuming it. The aim of the network is only to transport the electrical energy, or in economic terms, to enable transactions between customers. An example of a transmission and a distribution network with their customers is shown in Figure 1.3.

The technical aim of the electric power networks in Figures 1.2 and 1.3 becomes one of allowing the transport of electrical energy between the different customers,

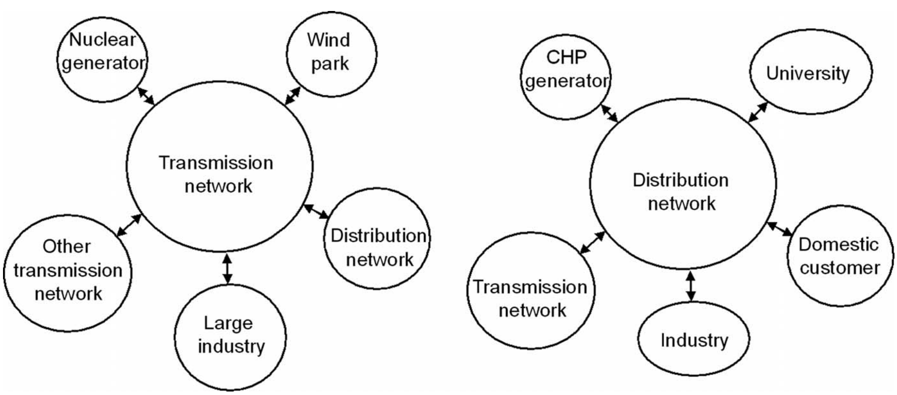

Figure 1.3 Customers of a transmission network (left) and a distribution network (right).

guaranteeing an acceptable voltage, and allowing the currents taken by the customers. As we will see in Section 1.2.2 power quality concerns the interaction between the network and its customers. This interaction takes place through voltages and currents. The various power quality disturbances, such as harmonic distortion, of course also appear at any other location in the power system. But disturbances only become an issue at the interface between a network and its customers or at the equipment terminals.

The model in Figure 1.2 should also be used when considering the integration of renewable or other environmentally friendly sources of energy into the power system. The power system is no longer the boundary condition that limits, for example, the amount of wind power that can be produced at a certain location. Instead the network's task becomes to enable the transport of the amount of wind power that is produced and to provide a voltage such that the wind park can operate properly. It will be clear to the reader that the final solution will be found in cooperation between the customer (the owner of the wind park) and the network operator considering various technical and economic constraints.

Concerning the electricity market, the model in Figure 1.2 is the obvious one: The customers (generators and consumers) trade electricity via the power network. The term *power pool* explains rather well how electricity traders look at the power network. The network places constraints on the free market. A much discussed one is the limited ability of the network to transport energy, for example, between the different European countries. Note that under this model lack of generation capacity is not a network problem but a deficiency of the market.

1.2 POWER QUALITY

1.2.1 Interest in Power Quality

The enormous increase in the amount of activity in the power quality area can be observed immediately from Figure 1.4. This figure gives the number of papers in the INSPEC database [174] that use the term *power quality* in the title, the abstract, or the list of keywords. Especially since 1995 interest in power quality appears to have increased enormously. This means not that there were no papers on power quality issues before 1990 but that since then the term power quality has become used much more often.

There are different reasons for this enormous increase in the interest in power quality. The main reasons are as follows:

- Equipment has become less tolerant of voltage quality disturbances, production processes have become less tolerant of incorrect operation of equipment, and companies have become less tolerant of production stoppages. Note that in many discussions only the first problem is mentioned, whereas the latter two may be at least equally important. All this leads to much higher costs than before being associated with even a very short duration disturbance. The

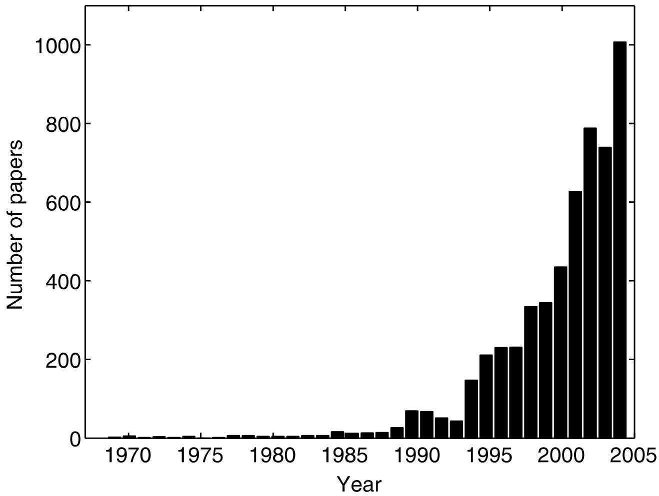

Figure 1.4 Use of term power quality, 1968–2004.

main perpetrators are (long and short) interruptions and voltage dips, with the emphasis in discussions and in the literature being on voltage dips and short interruptions. High-frequency transients do occasionally receive attention as causes of equipment malfunction but are generally not well exposed in the literature.

- Equipment produces more current disturbances than it used to do. Both low- and high-power equipment is more and more powered by simple power electronic converters which produce a broad spectrum of distortion. There are indications that the harmonic distortion in the power system is rising, but no conclusive results are available due to the lack of large-scale surveys.
- The deregulation (liberalization, privatization) of the electricity industry has led to an increased need for quality indicators. Customers are demanding, and getting, more information on the voltage quality they can expect. Some issues of the interaction between deregulation and power quality are discussed in [9, 25].
- Embedded generation and renewable sources of energy create new power quality problems, such as voltage variations, flicker, and waveform distortion [325]. Most interfaces with renewable sources of energy are sensitive to voltage disturbances, especially voltage dips. However, such interfaces may be used to mitigate some of the existing power quality disturbances [204]. The relation between power quality and embedded generation is discussed among others in [178, Chapter 5; 99, Chapter 9; 118, Chapter 11]. An important upcoming issue is the immunity of embedded generation and large wind parks to voltage dips and other wide-scale disturbances. The resulting loss of generation as a result of a fault in the transmission system becomes a system security (stability) issue with high penetration of embedded generation.

- Also energy-efficient equipment is an important source of power quality disturbances. Adjustable-speed drives and energy-saving lamps are both important sources of waveform distortion and are also sensitive to certain types of power quality disturbances. When these power quality problems become a barrier for the large-scale introduction of environmentally friendly sources and end-user equipment, power quality becomes an environmental issue with much wider consequences than the currently merely economic issues.

1.2.2 Definition of Power Quality

Various sources give different and sometimes conflicting definitions of power quality. The Institute of Electrical and Electronics Engineers (IEEE) dictionary [159, page 807] states that "power quality is the concept of powering and grounding sensitive equipment in a matter that is suitable to the operation of that equipment." One could, for example, infer from this definition that harmonic current distortion is only a power quality issue if it affects sensitive equipment. Another limitation of this definition is that the concept cannot be applied anywhere else than toward equipment performance.

The International Electrotechnical Commission (IEC) definition of power quality, as in IEC 61000-4-30 [158, page 15], is as follows: "Characteristics of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters." This definition of power quality is related not to the performance of equipment but to the possibility of measuring and quantifying the performance of the power system.

The definition used in this book is the same as in [33]: Power quality is the combination of voltage quality and current quality. *Voltage quality* is concerned with deviations of the actual voltage from the ideal voltage. *Current quality* is the equivalent definition for the current. A discussion on what is ideal voltage could take many pages, a similar discussion on the current even more. A simple and straightforward solution is to define the ideal voltage as a sinusoidal voltage waveform with constant amplitude and constant frequency, where both amplitude and frequency are equal to their nominal value. The ideal current is also of constant amplitude and frequency, but additionally the current frequency and phase are the same as the frequency and phase of the voltage. Any deviation of voltage or current from the ideal is a *power quality disturbance*. A disturbance can be a voltage disturbance or a current disturbance, but it is often not possible to distinguish between the two. Any change in current gives a change in voltage and the other way around. Where we use a distinction between voltage and current disturbances, we use the cause as a criterion to distinguish between them: Voltage disturbances originate in the power network and potentially affect the customers, whereas current disturbances originate with a customer and potentially affect the network. Again this classification is due to fail: Starting a large induction motor leads to an overcurrent. Seen from the network this is clearly a current disturbance. However, the resulting voltage dip is a voltage disturbance for a neighboring customer. For the network operator this is a current disturbance, whereas it is a voltage disturbance for the neighboring customer. The fact that one underlying event (the motor start in this case) leads to different disturbances for different customers or at different locations is very common for power quality issues. This still often leads to confusing discussions and confirms the need for a new view of power systems, as mentioned in Section 1.1.

This difficulty of distinguishing between voltage and current disturbances is one of the reasons the term power quality is generally used. The term voltage quality is reserved for cases where only the voltage at a certain location is considered. The term current quality is sometimes used to describe the performance of power-electronic converters connected to the power network.

Our definition of power quality includes more disturbances than those that are normally considered part of power quality: for example, frequency variations and non-unity power factor. The technical aspects of power quality and power quality disturbances are not new at all. From the earliest days of electricity supply, power system design involved maintaining the voltage at the load terminals and ensuring the resulting load currents would not endanger the operation of the system. The main difference with modern-day power quality issues is that customers, network operators, and equipment all have changed. The basic engineering issues remain the same, but the tools have changed enormously. Power-electronic-based (low-power and high-power) equipment is behind many of the timely power quality problems. Power-electronic-based equipment is also promoted as an important mitigation tool for various power quality problems. The introduction of cheap and fast computers enables the automatic measurement and processing of large amounts of measurement data, thus enabling an accurate quantification of the power quality. Those same computers are also an essential part in power-electronic-based mitigation equipment and in many devices sensitive to power quality disturbances.

A large number of alternative definitions of power quality are in use. Some of these are worth mentioning either because they express the opinion of an influential organization or because they present an interesting angle.

Our definition considers every disturbance as a power quality issue. A commonly used alternative is to distinguish between *continuity* (or *reliability*) and *quality*. Continuity includes interruptions; quality covers all other disturbances. Short interruptions are sometimes seen as part of continuity, sometimes as part of quality. Following this line of reasoning, one may even consider voltage dips as a reliability issue, which it is from a customer viewpoint. It is interesting to note that several important early papers on voltage dips were sponsored by the reliability subcommittee of the IEEE Industrial Applications Society [e.g., 30, 75, 73].

The Council of European Energy Regulators [77, page 3] uses the term *quality of service in electricity supply* which considers three dimensions:

- *Commercial quality* concerns the relationship between the network company and the customer.
- *Continuity of supply* concerns long and short interruptions.

- *Voltage quality* is defined through enumeration. It includes the following disturbances: "frequency, voltage magnitude and its variation, voltage dips, temporary and transient overvoltages, and harmonic distortion."

It is interesting that "current quality" is nowhere explicitly mentioned. Obviously current quality is implicitly considered where it affects the voltage quality. The point of view here is again that adverse current quality is only a concern where it affects the voltage quality.

A report by the Union of the Electricity Industry (Eurelectric) [226, page 2] states that the two primary components of supply quality are as follows:

- *Continuity*: freedom from interruptions.
- *Voltage quality*: the degree to which the voltage is maintained at all times within a specific range.

Voltage quality, according to [226], has to do with "several mostly short-term and/or frequency related ways in which the supply voltage can vary in such a way as to constitute a particular obstacle to the proper functioning of some utilization equipment." The concept of voltage quality, according to this definition, is especially related to the operation of end-use equipment. Disturbances that do not affect equipment would not be part of voltage quality. Since at the measurement stage it is often not possible to know if a disturbances will affect equipment, such a definition is not practical.

Another interesting distinction is between *system quality* and *service quality*. System quality addresses the performance of a whole system, for example, the average number of short-circuit faults per kilometer of circuit. This is not a value which directly affects the customer, but as faults lead to dips and interruptions, it can certainly be considered as a quality indicator. A regulator could decide to limit the average number of faults per kilometer per circuit as a way of reducing the dip frequency. Service quality addresses the voltage quality for one individual customer or for a group of customers. In this case the number of dips per year would be a service quality indicator. Like any definition in the power quality area, here there are also uncertainties. The average number of dips per year for all customers connected to the network could be seen as a service quality indicator even though it does not refer to any specific customer. The 95% value of the number of dips per year, on the other hand, could be referred to as a system quality indicator. We will come back to this distinction when discussing site indices and system indices in Chapters 5 and 10.

Reference [260] refers in this context to *aggregate system service quality* and *individual customer service quality*. Reference [77] refers to the quality-of-supply and the quality-of-system approach of regulation. Under the *quality-of-supply approach* the quality would be guaranteed for every individual customer, whereas under the *quality-of-system approach* only the performance of the whole system would be guaranteed. An example of the quality-of-supply approach is to pay