INTEGRATION OF Distributed Generation in the Power System

Math H.J. Bollen • Fainan Hassan

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PREFACE

The idea of writing this book first came in February 2008, with its final structure being decided by May 2009 when the main writing work also started. The contents of most chapters were finalized about a year thereafter. In the period of 2.5 years that we worked on this book, there have been a lot of developments in the related area: concerning not only new sources of energy (from biomass to nuclear) but also the power system. For the first time in many years, the power system is on the political agenda, instead of just the electricity production or the electricity market.

Two important concepts of this book, the "hosting capacity" and the use of "risk-based methods" have within the last few months been propagated in important reports by international organizations. The hosting capacity is proposed as a method for quantifying the performance of future electricity networks by both the European energy regulators[1] and by a group of leading European network operators.[2] The latter also recommends the development of risk-based methods for transmission system operation, whereas ENARD,[3] a government-level cooperation within the IEA, makes the same recommendation for the design of distribution networks.

During the last few years, while writing this book, giving presentations about the subject, and listening to other's presentations, we also realized that distributed generation and renewable electricity production are very sensitive areas. It is extremely difficult to keep some middle ground between those in favor and those against the idea. We would, therefore, like to emphasize clearly that this book is not about showing how good or how bad the distributed generation is. This book is about understanding the impact of distributed generation on the power system and about methods for allowing more distributed generation to be integrated into the power system, where the understanding is an essential base.

By writing this book, we hope to help removing some of the technical and nontechnical barriers that the power system poses to a wider use of renewable sources of energy.

June 2011
Math Bollen and Fainan Hassan

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[1] European Regulators Group for Electricity and Gas, Position paper on smart grids, June 10, 2010.

[2] ENTSO-E and EDSO. European electricity grid initiative roadmap and implementation plan, May 25, 2010.

[3] J. Sinclair. ENARD Annex III: Infrastructure asset management. Phase 1 final report, March 2010.

ACKNOWLEDGMENTS

The material presented in this book is obtained from different sources. Most of it is work done by the authors themselves, but with important contributions from others. Although some of the ideas presented in this book are much older, the main philosophical thoughts were triggered when André Even introduced the term “hosting capacity” in 2004 during one of the first meetings of the EU-DEEP project. Discussions with other project partners helped in further refining the concepts.

Important contributions, in different forms, were also made by Johan Lundquist (Götene Elförening), Peter Axelberg, Mats Wahlberg (Skellefteå Kraft Elnät), Waterschap Roer en Overmaas, and Emmanouil Styvaktakis. Also, our colleagues and former colleagues Alstom Grid, Chalmers University of Technology, STRI AB (especially Mats Häger, Carl Öhlén and Yongtao Yang, but also many others), Luleå University of Technology, and the Energy Markets Inspectorate should be mentioned for many interesting discussions, which often triggered new ideas.

Of course, we should not forget our families and friends here, having been forced to forget them too often during the past two years.

CHAPTER 1

INTRODUCTION

The electric power system consists of units for electricity production, devices that make use of the electricity, and a power grid that connects them. The aim of the power grid is to enable the transport of electrical energy from the production to the consumption, while maintaining an acceptable reliability and voltage quality for all customers (producers and consumers), and all this for the lowest possible price. The different companies and organizations involved in this have managed to do an excellent job: the reliability and voltage quality are acceptable or better for most customers, and electricity is overall a cheap commodity. There is still a lot of research and other activities going on to make things even better or to improve the situation at specific locations, including work by the authors of this book, but we have to admit that overall the power system performance is excellent.

A sudden change either on the production side or on the consumption side could endanger the situation we have become so accustomed to. Modern society is very much dependent on the availability of cheap and reliable electricity. Several recent blackouts and price peaks have very much shown this. In this book, we will discuss not only the possible impact on the power system of one such change: the shift from large conventional production units to small and/or renewable electricity production. We will discuss not only the problems but also the solutions. Understanding the problems is essential for being able to choose the right solution.

There are different reasons for introducing new types of production into the power system. The open electricity market that has been introduced in many countries since the early 1990s has made it easier for new players to enter the market. In North America and Europe, it is now possible for almost anybody to produce electricity and export this to the power system. The rules for the actual sales of the electricity vary strongly between countries; even the rules for the connection are different between countries. Enabling the introduction of new electricity production is one of the main reasons for the deregulation of the electricity market. More market players will increase competition; together with an increased production capacity, this will result in reduced prices. The price of electricity produced by large conventional installations (fossil fuel, nuclear, hydro) is, however, too low in most countries for small units to be competitive.

The second reason for introducing new types of production is environmental. Several of the conventional types of production result in emission of carbon dioxide with the much-discussed global warming as a very likely consequence. Changing from conventional production based on fossil fuels, such as coal, gas, and oil, to renewable

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sources, such as sun and wind, will reduce the emission. Nuclear power stations and large hydropower installations do not increase the carbon dioxide emission as much as fossil fuel does, but they do impact the environment in different ways. There is still carbon dioxide emission due to the building and operation even with these sources, but this is much smaller than that with fossil fuel-based production. The radioactive waste from nuclear power stations is a widely discussed subject as well as the potential impact of an unlikely but nonetheless serious accident. Large hydropower production requires large reservoirs, which impact the environment in other ways. To encourage the use of renewable energy sources as an alternative, several countries have created incentive mechanism to make renewable energy more attractive. The main barrier to the wide-scale use of renewable energy is that it is cheaper to use fossil fuel. Economic incentives are needed to make renewable energy more attractive; alternatively, fossil fuel can be made more expensive by means of taxation or, for example, a trading mechanism for emission rights. Some of the incentive schemes have been very successful (Germany, Denmark, and Spain), others were less successful.

The third reason for introducing new production, of any type, is that the margin between the highest consumption and the likely available production is too small. This is obviously an important driving factor in fast-growing economies such as Brazil, South Africa, and India. In North America and Europe too, the margin is getting rather small for some regions or countries. Building large conventional power stations is not always politically acceptable for, among others, environmental reasons. It also requires large investments and can take 10 years or longer to complete. Small-scale generation based on renewable sources of energy does not suffer from these limitations. The total costs may be higher, but as the investments can be spread over many owners, the financing may actually be easier. The right incentive schemes, economically as well as technically, are also needed here. Instead of building more generation, the recent trend, for example, in Northern Europe, is to build more transmission lines. In this way, the production capacity is shared among transmission system operators. Building transmission lines is often cheaper than building new power stations, so this can be a very attractive solution. Another reason for building new lines instead of new production is that in most countries there is no longer a single entity responsible for ensuring that there is sufficient production capacity available. This means that no single entity can order the building of new production. It is, however, the task of the transmission system operator to ensure that there is sufficient transmission capacity available for the open electricity market. The transmission system operator can decide to build new lines to alleviate bottlenecks that limit the functioning of the open market.

Although growth in electricity consumption has been moderate for many years in many countries, there are reasons to expect a change. More efficient use of energy often requires electricity as an intermediate step. Electric cars are the most discussed example; electrified railways and heat pumps are other examples. Even the introduction of incandescent lamps 100 years ago was an improvement in energy efficiency compared to the candles they were replacing.

No matter what the arguments are behind introducing new electricity production, it will have to be integrated into the electric power system. The integration of large production units, or of many small units, will require investments at different voltage levels. The connection of large production units to the transmission or subtransmission system is in itself nothing remarkable and the investments needed are a normal part of transmission system planning. With new types of production, new types of phenomena occur, which require new types of solutions. Small production units are connected to the low- or medium-voltage distribution system, where traditionally only consumption has been connected. The introduction of large numbers of them will require investments not only at the voltage level where the units are connected but also at higher voltage levels. The variation in production from renewable sources introduces new power quality phenomena, typically at lower voltage levels. The shift from large production units connected at higher voltage levels to small units connected at lower voltage levels will also impact the design and operation of subtransmission and transmission networks. The difficulty in predicting the production impacts the operation of the transmission system.

The terminology used to refer to the new types of production differs: “embedded generation,” “distributed generation,” “small-scale generation,” “renewable energy sources” and “distributed energy resources” are some of the terms that are in use. The different terms often refer to different aspects or properties of the new types of generation. There is strong overlap between the terms, but there are some serious differences as well. In this book, we will use the term “distributed generation” to refer to production units connected to the distribution network as well as large production units based on renewable energy sources. The main emphasis in this book will be on production units connected to the distribution network. Large installations connected to the transmission system will be included mainly when discussing transmission system operation in Chapter 8.

In this book, we will describe some of the ways in which the introduction of distributed generation will impact the power system. This book has been very much written from the viewpoint of the power system, but the network owners are not the only stakeholders being considered. The basic principle used throughout the book is that the introduction of new sources of production should not result in unacceptable performance of the power system. This principle should, however, not be used as a barrier to the introduction of distributed generation. Improvements should be made in the network, on the production side and even on the consumption side, to enable the introduction of distributed generation. Several possible improvements will be discussed throughout this book. We will not discuss the difficult issue of who should pay for these investments, but will merely give alternatives from which the most cost-effective one should be chosen.

The structure of this book is shown in Figure 1.1. The next two chapters introduce the new sources of production (Chapter 2) and the power system (Chapter 3). Chapters 4–8 discuss the impact of distributed generation on one specific aspect of the power system: from losses through transmission system operation.

As already mentioned, Chapter 2 introduces the different sources of energy behind new types of electricity production. The emphasis is on wind power and solar power, the renewable sources that get most attention these days. These are the two sources that will constitute the main part of the new renewable sources of energy in the near future. However, more “classical” sources such as hydropower will also be discussed. The different sources will be described in terms of their variation

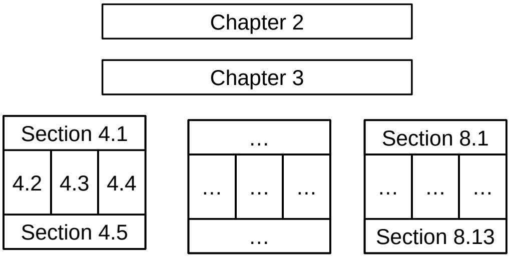

Figure 1.1 Structure of the book: introductory chapters and chapters on specific phenomena.

in production capacity at different timescales, the size of individual units, and the flexibility in choosing locations. These are the properties that play an important role in their integration into the power system.

After a general overview of the power system, Chapter 3 introduces, the "hosting capacity approach." The hosting capacity is the maximum amount of generation that can be integrated into the power system, while still maintaining its performance within acceptable limits. The hosting capacity approach uses the existing power system as a starting point and considers the way in which distributed generation changes the performance of the system when no additional measures are taken. For this, a set of performance indicators is needed. This is a normal procedure in the power quality area, but not yet in other areas of power systems.

Chapters 4–8 discuss in detail various aspects of the integration of distributed generation: the increased risk of overload and increased losses (Chapter 4), increased risk of overvoltages (Chapter 5), increased levels of power quality disturbances (Chapter 6), incorrect operation of the protection (Chapter 7), and the impact on power system stability and operation (Chapter 8).

Chapters 3–8 are structured in the same way, as shown in Figure 1.1. Considering Chapter 5, for example, the first section gives an overview of the impact of increasing amounts of distributed generation on the voltage magnitude as experienced by the end customers. The first section in each chapter is both a summary of the results from the forthcoming sections and an overview of material obtained from the literature. The sections following the first section discuss different details of, in this case, the relation between distributed generation and voltage magnitude. Some of the sections look at the problem from a different perspective or discuss a specific solution. Some of these sections give a general overview, while others go deeper into theoretical models or research results. Most of these sections can be read or studied independent of other sections. The final section of the chapter gives an overview of methods for allowing more distributed generation to be connected without experiencing problems with, in this case, voltage magnitude. The final section of each chapter is again a combination of material from the rest of the chapter and material obtained from the literature. The different solutions presented here include those that are currently referred to as "smart grids." This term has received a huge amount of interest, all the way from fundamental research to politics and newspapers, but it remains unclear what should be included in the term. We will not distinguish here between "smart grid solutions" and "classical solutions," but instead present all the available options.

It is not possible to cover all aspects of the integration of distributed generation in one book. The economic aspects of the different impacts of distributed generation and of the different methods for increasing the hosting capacity are not treated here at all. This is not because economics are not important, they are in fact often the main deciding factor, it is just that we had to stop somewhere. Besides, the economics are very much location and time dependent. The book does not include many detailed simulation studies, but mainly simplified models of the power system and of the distributed generation. There are a number of reasons for this. We would like to propagate the use of such simplified models as a tool to be used during initial discussions; it is our experience that important conclusions can often be drawn from these simplified models. We are also of the opinion that the use of simplified models has a great educational value. The impact of different parameters is much better understood when simplified models rather than detailed simulations are used. Such detailed calculations are, however, needed in many cases before connecting distributed generation to the power system. The structure of the power system is different across the world and the details are very much location dependent. The simplified models of the type presented in this book can be easily adapted to a local situation, whereas simulation studies have to be repeated for each location.

CHAPTER 2

SOURCES OF ENERGY

In this chapter, we will discuss the different sources of energy used for electricity production. We will concentrate on the main renewable sources used for distributed generation—wind power in Section 2.1 and solar power in Section 2.2. Another type of distributed generation, combined heat-and-power (CHP), will be discussed in Section 2.3. We will also discuss the two main sources in use today: hydropower in Section 2.4 and thermal power stations in Section 2.8. Some of the other sources will also be discussed: tidal power in Section 2.5, wave power in Section 2.6, and geothermal power in Section 2.7.

For each of the sources, we will give a brief overview of the status and the prospects, based on the information available to the authors today, for it to become a major source of electric power. Furthermore, an overview will be given of the properties of the source seen from a power system viewpoint. For the major sources, we will concentrate on the variation in the source with time, which is the main difference between renewable sources like the sun, water, and wind, and the thermal power stations. We will not go into details of the way in which the primary energy is transformed into electricity. For further details, the reader is referred to some of the many books on this subject. An excellent overview of energy consumption and production possibilities for the United Kingdom is given in Ref. 286. The analysis can also be easily applied to other countries and hence the book is highly recommended to those interested in energy supply. Another good overview of the different energy sources is given in Refs. 60, 81 and 389. The latter two give an excellent detailed description of the origin and application of some of the sources. A lot of information on wind energy can be found in Refs. 71 and 292. Both books discuss in detail the whole chain from the aerodynamics to the connection with the grid. For solar power, refer to Ref. 337. Besides, for the power system aspects of wind power and other sources of renewable energy, refer to among others Refs. 5, 56, 157, 167, 200, 232, 296, 392, and 458.

There have been many developments in many countries concerning the future energy sources. The reader should realize, when reading this chapter, that it mainly describes the status as of the first months of 2010. Although we have tried to be as objective as possible, we are quite aware that some parts of this chapter may be outdated within a few years. Hence, the reader is encouraged to also refer to more recent sources of information.

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2.1 WIND POWER

2.1.1 Status

The kinetic energy from the horizontal displacement of air (i.e., wind) is transformed into kinetic energy of the rotation of a turbine by means of a number of blades connected to an axis. This rotational energy is then transformed into electrical energy using an electrical generator. Different technologies have been proposed and used during the years to produce electricity from wind power. Currently, the main technology on the mechanical side is a two-or three-blade turbine with a horizontal axis. Three competing technologies are in use for the transformation into electrical energy and the connection to the power system: the directly connected induction generation; the double-fed induction generator (DFIG) (more correctly named “double-fed asynchronous generator”); and the generator with a power electronics converter.

Wind power is the most visible new source of electrical energy. It started off as small installations connected to the low-or medium-voltage networks. The last several years have seen a huge expansion of wind power in many countries, with the current emphasis being on large wind parks connected to the subtransmission or transmission system. Single wind turbines of 2 MW size have become the typical size and turbines of 5–6 MW are available, although they are not yet widely used. Developments are going fast, so these values could well have become outdated by the time you read this book.

Single wind turbines in Europe are now mainly being connected to medium-voltage networks; but in more and more cases, groups of turbines are connected together into a wind park. Smaller wind parks, 3–10 turbines is a typical range, can still be connected to the medium-voltage network, but the larger ones require connection points at subtransmission or transmission level. Several parks larger than 500 MW are in operation or under construction in the United States, with Texas and California taking the lead. The biggest wind park at the moment is the Horse Hollow Wind Energy Center in Texas. It consists of 291 turbines of 1.5 MW and 130 turbines of 2.3 MW giving it a total capacity of 735 MW. However, even more larger ones are already under construction or planned. For example, a very large wind park is planned near the north Swedish town of Piteå, with 1100 turbines of 2–3 MW each and an expected annual production between 8 and 12 TWh, that is, between 5 and 8% of the total consumption in Sweden. News items about large wind parks appear almost continuously and the wind power production is growing fast in many countries. Several countries have planning targets of 20% electrical energy from wind power by 2020. Some European countries already produce more than 10% of their electrical energy from wind power; Denmark being on top with 20% of its electrical energy produced by wind. Of the large European countries, Germany (with 7% of electricity coming from wind) and Spain (12%) are the main wind power producing countries.

2.1.2 Properties

Wind power shows variations in production capacity over a range of timescales, from less than 1 s through seasonal variations. There remains difference of opinion about which timescale shows the biggest variation. This depends strongly on the application. We will discuss variations at different timescales in this chapter and in some of the other chapters.

The term intermittent generation is often used to refer to the strong variation with time of wind and solar power. What matters to the power system is however not just the variation with time but also the extent to which the variations can be predicted. For the distribution system, it is merely the actual variations that matter; while for the transmission system, it is both the variations and their predictability that are of importance.

The wind speed and thus the wind power production are difficult to predict longer than a few hours ahead of time. Over larger geographical areas, which is what matters at transmission level, predictions of total production become somewhat better. But even here large prediction errors are not uncommon. Details about this is given in Section 8.4.

The accuracy of the prediction is also important for individual turbines and for wind parks to be able to participate in the electricity market. The details of this strongly depend on the local market rules. We will not further discuss this in this book.

The amount of energy that can be extracted from the wind is not everywhere the same: some locations are more windy than others. What matters for this are the properties of the wind speed over a longer period of time. The average wind speed is an important factor; however, as we will see later, the distribution of the wind speed also matters. The amount of energy that can be produced per year by a wind turbine strongly depends on the location of this wind turbine. The most favorable areas are coastal areas (like the European west coast or the north coast of Africa) and large flat areas (like the American Midwest or Inner Mongolia in China). Mountaintops also often provide good wind conditions. The wind conditions in built-up areas, such as towns or industrial areas, are often not very good, because the buildings are obstacles to wind, taking away energy from the wind and turning it into turbulence. Only the horizontal movement, not the turbulence, is transformed into electrical energy by the wind turbine. Also, in most cases, it is not possible to get permission to build wind power installations close to buildings. As a result, the wind power is often located at a significant distance from the consumption: tens to hundreds of kilometers is not uncommon. Some of the future plans, like for Inner Mongolia, would result in wind power being located thousands of kilometers away from the consumption areas.

Europe is in a rather good position in this sense because the areas with the best wind conditions (mainly around the North Sea), are not too far from the main consumption areas. The fact that the North Sea is very shallow also makes it relatively easy to build large wind parks there.

2.1.3 Variations in Wind Speed

One of the most discussed properties of wind power is its so-called “intermittent” character—the wind speed and thus the power production vary strongly with time over a range of timescales. The variability of the wind is often presented as a power spectrum. This is discussed among others in Ref. 389, according to which the wind speed variance spectrum shows 5-day variations probably related to major weather patterns, daily variations becoming less with altitude, and variations in the range between 10 s and 1 min. The so-called "spectral gap" is present (in the example shown in Ref. 389) between 2 h and 3 min. It is said to be confirmed by many measurements that such a gap appears at almost all locations. It provided a clear distinction between large-scale motion (at timescales above 2 h) and small-scale motion (at timescales less than 10 min).

As stated in Ref. 386, the wind power production "varies very little in the time frame of seconds, more in the time frame of minutes and most in the time frame of hours." Typical standard deviations are as follows:

- 0.1% at 1 s timescale,
- 3% at 10 min timescale, and
- 10% at 1 h timescale.

The analysis of wind speed records from Brookhaven, New York ([418], quoted in Ref. 71 and many others), in the 1950s showed a power spectrum with three distinctive peaks:

- "turbulence peak" between 30 s and 3 min,
- "diurnal peak" around 12 h, and
- "synoptic peak" between 2 and 10 days.

The measurements showed that there is very little energy in the region between 10 min and 2 h. This region is often referred to as the "spectral gap." The presence of this has been confirmed by measurements performed at other locations, for example, Ref. 169 and is widely mentioned in the literature. From a power system operation viewpoint, this is good news. The turbulence peak is a local phenomenon and will average out when many turbines are connected over a wider geographical area. The result is that wind power production will be in general rather constant for timescales up to a few hours. From this it should not be concluded that there are no changes in this range of timescales. For transmission system planning and operation, it is often the worst-case situations that matter. The fact that they are rare does not always matter. We will come back to this topic in Chapter 8. Not all measurements do however show the presence of the spectral gap, nor the diurnal or synoptic peak. This may depend on local conditions, which will especially impact the turbulence part of the spectrum. Measurements presented in Ref. 15 show, for example, that the output power from two wind parks (with 6 and 10 turbines) follows the so-called "Kolmogorov spectrum" (proportional to frequency to the power of $-5/3$) over the time range of 30 s–2.6 days.

It should also be noted here that the "power spectrum" in this context is not the spectrum of the power production but (for a deterministic signal) the square of the magnitude of the spectrum (Fourier series) of the wind speed. For a stochastic signal, the power spectral density is the Fourier transform of the autocovariance function [30].

Turbulence, leading to power fluctuations in the timescale from less than 1 min to about 1 h, is discussed in detail in, among others, Refs. 71 and 292. A distinction thereby has to be made between "turbulence" and "gusts." Turbulence is a continuous phenomenon, present all the time, whereas a wind gust is an occasional high value of the wind speed superimposed upon the turbulent wind. Readers familiar with power quality will recognize the similarity in the distinction between “power quality variations” and “power quality events” (see Section 3.4.1 for more about variations and events).

Turbulence is a complicated process, which is very difficult if not impossible to quantify. It depends not only on local geographical features (like hills and rivers) but also on the presence of trees and buildings. Also, vertical movement of the air due to heating of the earth surface by the sun results in turbulence. As turbulence is a surface-related phenomenon, it will reduce with increasing height. The higher a wind turbine, the less affected by turbulence. In terms of the power density spectrum, the turbulence peak diminishes with increasing height. The shift from individual small turbines to wind parks consisting of large turbines implies that turbulence has become less of an issue for the power system. It remains an issue for the mechanical design of the turbine, but this is beyond the scope of this book.

The level of turbulence is quantified by the so-called “turbulence intensity.” To obtain this, the wind speed is sampled with a high sampling frequency (one sample per second or higher) over an interval between 10 min and 1 h. The turbulence intensity is the ratio of the standard deviation to the average over this interval. According to Ref. 292, the turbulence intensity is typically between 0.1 and 0.4, with the highest values obtained during low wind speed. However, some of the standard models for turbulence ([71], Section 2.6.3) recommend the use of a turbulence intensity independent of the wind speed. Reference 292 also states that the Gaussian distribution is an appropriate one to describe turbulence. The distinction between turbulence and gusts is very important here: the probability of a wind gust exceeding a certain value is not found from the Gaussian distribution for turbulence. Of more interest from a power system viewpoint is the spectrum of the turbulence, that is, which frequencies occur most commonly among the fluctuations in wind speed. Several such spectra are shown in Section 2.6.4 of Ref. 71, with their peak between 1 and 10 min. The 50% value of the turbulence peak is between 10 s and 1 h. As mentioned before, the actual spectrum strongly depends on location and time, for example, depending on the wind direction. When the turbulence peak exceeds beyond 1 h, the above-mentioned spectral gap will disappear and the turbulence peak will go over into the diurnal and synoptic peaks.

From a power system viewpoint, what matters are not the variations in wind speed but the variations in power production. The power production is a nonlinear function of the wind speed; variations in wind speed have the strongest impact on the power production when the wind is between (about) 5 and 10 m per second (see Section 2.1.7). Further, the interest is not in the relative variations in power production (in percent) but in the absolute variations (in kilowatt). It is the absolute variations that cause variations in voltage magnitude, that result for example in the kind of fluctuations in light intensity that give complaints from nearby customers about light flicker. More about this in Section 6.2.

2.1.4 Variations in Production Capacity

In this section, we will discuss the variations in production capacity for wind power over a range of timescales, starting at the shortest timescales. The current way of operating wind power implies that variations in production capacity in almost all cases result in the same variations in actual production. In other words, the production is always equal to the capacity. It is possible to reduce the amount of production below the capacity, but that would result in “spilled wind.” Any reduction in wind power production will have to be compensated by other sources, in most cases fossil fuel.

At the shortest timescale, seconds and lower, the production of an individual turbine varies mainly due to the impact of the tower on the flow of air around the turbine. This has been studied in detail because the fluctuations in power production cause variations in voltage magnitude that could result in observable variations in light intensity of certain types of lighting. We will discuss this further in Section 6.2. Another source of power fluctuations at the shortest timescale is the fact that the wind speed is higher at higher altitudes. When a blade is pointed upward, it will catch more energy from the wind than when it is pointed downward; the total amount of energy for the three blades will depend on their position. Also, mechanical oscillations in the turbine and the tower as well as the gearbox cause some fast variations in power. All this holds for individual turbines. For large wind parks and for larger regions, these variations will add randomly and become less and less important. Using power electronics techniques and a small amount of storage, variations at a timescale of seconds can be limited even for individual turbines. Energy storage can be present in the form of capacitors connected to a DC bus or by letting the rotational speed of the turbines vary somewhat.

At a longer timescale (minutes), turbulence is the main cause of variations in produced power. The level of turbulence strongly depends on local conditions (landscape as well as weather) and is very difficult to predict. Recommended values for turbulence given in standards and in the literature are mainly used as input in the mechanical design of the installation. In practice, the level of turbulence is not constant at all even at a single location.

A measurement of the power fluctuations for a 600 kW turbine with full power converter, over two different periods of 1 h, is shown in Figure 2.1. Active power values were obtained every second. The two 1 h periods were about 20 h apart. The level of turbulence varies a lot between these two 1 h periods.

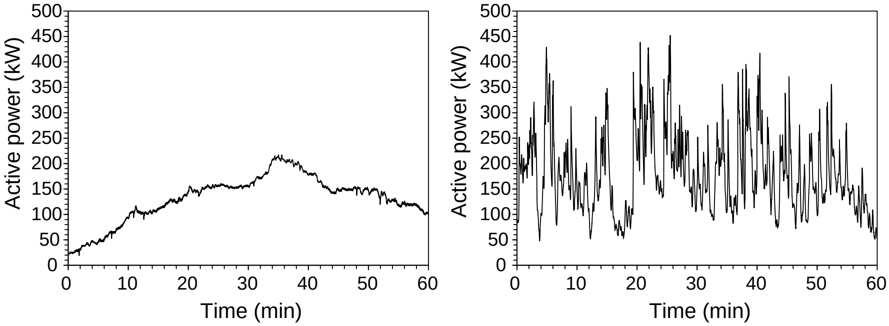

Figure 2.1 Active power fluctuations for the same turbine at the same location during two different 1 h periods.

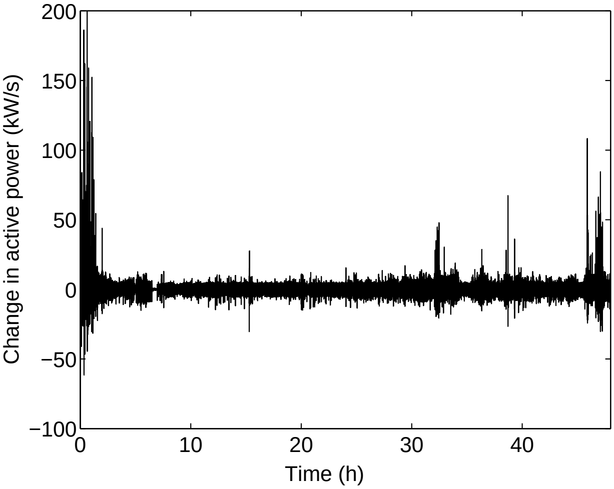

Figure 2.2 Second-by-second change in active power for a 600-kW wind turbine during a 48 h period.

Strictly speaking, note that these figures do not present the turbulence as turbulence is a property of the wind speed. There is, however, no equivalent parameter in use on the power system side of the turbine to quantify the variations in production at this timescale. One option would be to use the ratio between standard deviation and average over a period of 10 min–1 h, in the same way as the definition of turbulence intensity for the wind speed. Closer to existing methods for quantifying voltage quality would be to define the "very short variations" in active and reactive powers in the same way as the very short variations in voltage magnitude [44, 48]. We will discuss this further in Chapter 6.

From the measured values of active power for the 600 kW turbine, the second-by-second variations in power are calculated. The curve in Figure 2.2 is calculated as the difference between two consecutive 1 s averages. Most of the time two consecutive values do not differ more than 20 kW; however, extreme values up to 200 kW can be seen. The fast changes occur only during certain periods, and the largest changes are positive (i.e., a fast rise in power).

The active power produced by the 600 kW turbine during a 48 h period is shown in Figure 2.3. Figure 2.3a shows the measured 1 s averages. From these the 10 min averages have been calculated, shown in Figure 2.3b. The 10 min average shows a much smoother curve; this indicates that the majority of the variations occur at a timescale of less than 10 min.

The standard deviation of the amount of power produced by a 600 kW turbine has been calculated over each 10 min interval (from 600 1 s values). The resulting standard deviation as a function of time is shown in Figure 2.4. Both the absolute value of the standard deviation (in kilowatt) and the value relative to the average power over the same 10 min interval (in percent) are shown. The relative value is up to 50% most of the time. During some periods, the relative standard deviation is very high; this is due to the low values of the average production and does not indicate

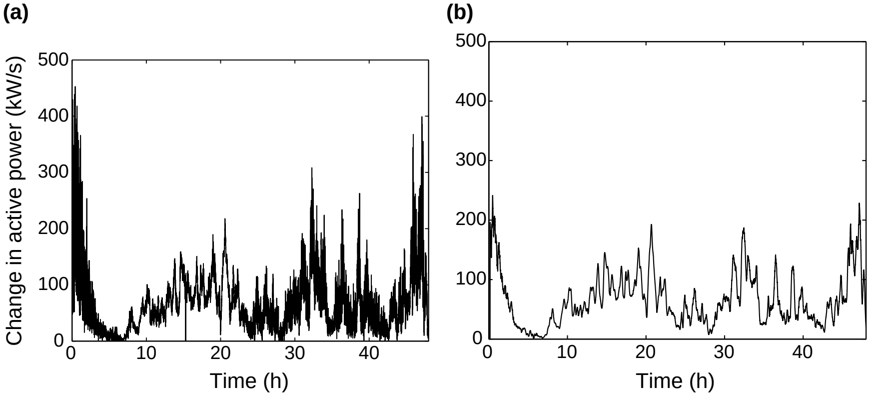

Figure 2.3 1 s (a) and 10 min (b) averages of the active power production for a 600 kW wind turbine during a 48 h period.

any actual high level of variations. As was mentioned before, what matters to the power system is the absolute level of variations. For this measurement, the standard deviation is at most about 100 kW, which is less than 20% of the rating of the turbine.

Measurements of variations in power production at a timescale of seconds to minutes typically require dedicated equipment and are hard to obtain. Performing such measurements over a longer period (for example, 1 year) would also result in large amounts of data. Hourly measurements are more common because they are typically used for metering purposes. In some countries, the electricity market is based on 15 or 30 min intervals, which would typically require measurements of the average production to be available over these intervals.

As an example, Figure 2.5 shows the hourly average power produced by an 850 kW wind turbine located in the middle of Sweden over a period of about 4 months (January–April 2005). Not only does the power vary significantly, it also is

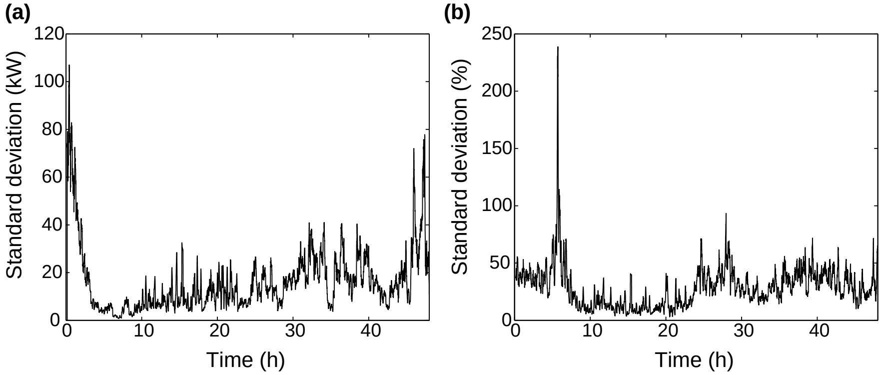

Figure 2.4 Standard deviation of the power production per 10 min interval for a 600 kW turbine during a 48 h period. (a) Absolute values. (b) Relative values.

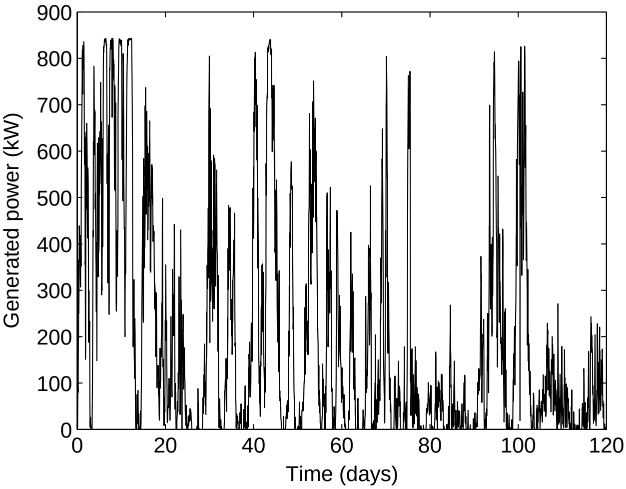

Figure 2.5 Power produced by a wind turbine during a 4-month period.

close to zero a large part of the time. The maximum power production, for which the installation is dimensioned, is reached only during a small fraction of the time.

The variation in production can be presented by using the probability distribution function, as shown in Figure 2.6. This function is obtained from the 1 h averages obtained over a 4.5-year period. The power production was zero during about 14% of the time and less than 100 MW during about 50% of the time. Low production during a significant amount of time is a general phenomenon observed with all wind power installations. This is strongly related to the distribution of the wind speed as will be

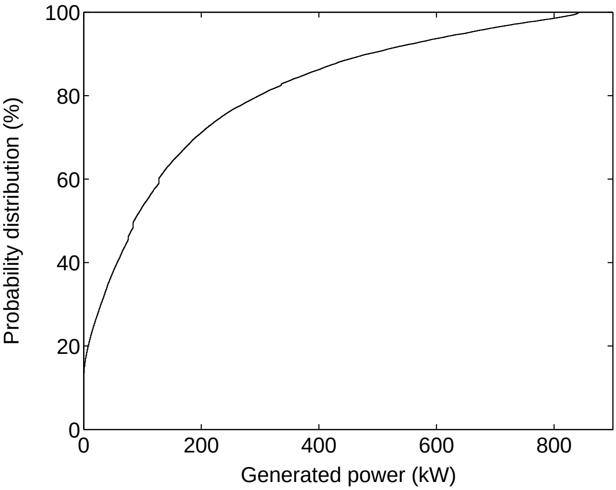

Figure 2.6 Probability distribution function of the hourly power produced by a 850 kW wind turbine over a 4.5-year period.