Pieter Schavemaker | Lou van der Sluis

electrical power system essentials

Second Edition

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Electrical Power System Essentials

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Contents

Preface

In the field of power system analysis, an extensive amount of high-quality literature is available. Most of these textbooks follow more or less the same line and cover the same topics. This book differs from existing materials because the (steady-state) modeling of the power system components is covered in appendices. Therefore, the focus in the chapters itself is not on the modeling, but on the structure, functioning, and organization of the power system. The appendices contribute to the book by offering material that is not an integral part of the main text, but support and enhance it and as such are an integral part of the book. The book contains a large number of problems of which the extensive solutions are presented in a separate chapter.

The following is a short summary of the contents of the chapters and the appendices.

Chapter 1 (Introduction to Power System Analysis)

This first chapter describes the scope of the material and is an introduction to the steady-state analysis of power systems. Questions such as "why AC," "why 50 or 60 Hz," "why sinusoidally shaped AC," "why a three-phase system" are addressed. The basics for a steady-state analysis of balanced three-phase power systems are outlined, such as phasors, single-line diagrams, active power, reactive power, complex power, power factor, and per-unit normalization.

Chapter 2 (The Generation of Electric Energy)

The conversion from a primary source of energy to electrical energy is the topic of Chapter 2. The primary source of energy can be fossil fuels such as gas, oil, and coal or uranium, but can come from renewable sources as well: wind energy, hydropower, solar power, or geothermal power. In order to understand the nature of a thermal power plant, which is still the main source of power in the system, the principles of thermodynamics are briefly discussed. The final conversion from mechanical energy to electrical energy is achieved by the synchronous machine. The coupling of the machine with the grid and the actual power injection is analyzed.

Chapter 3 (The Transmission of Electric Energy)

The transmission and distribution network is formed by the overhead lines, the underground cables, the transformers, and the substations between the points of power injection and power consumption. Various substation concepts are presented, together with substation components and the protection installed. The transformers, overhead transmission lines, underground cables, gas-insulated transmission lines, protective relay operating principles, surge arresters, fuses, and circuit breakers are then considered in more detail. The transformer design, possible phase shift, and specific properties due to the magnetic core are highlighted. As overhead transmission lines are the most visible part of the power system, they are discussed from the point of view of what may be seen and why it is like that. The underground cables are also considered, contrasting them with overhead transmission. The chapter ends with the principles of HVDC transmission.

Chapter 4 (The Utilization of Electric Energy)

The power system is designed and arranged in such a way that demand may be fulfilled: consumers are supplied with the requested amount of active and reactive power at constant frequency and with a constant voltage. A load actually transforms the AC electrical energy into another form of energy. The focus in this chapter is on the various types of loads that transform the AC electrical energy into mechanical energy (synchronous and induction motors), light, heat, DC electrical energy (rectifiers), and chemical energy. After that, the individual loads in the system are clustered and classified as grid users according to three categories: residential loads (mostly single-phase loads), commercial and industrial loads (often three-phase loads), and electric railways (either DC or single-phase AC).

Chapter 5 (Power System Control)

Continuous control actions are necessary in the system for the control of the voltage, to maintain the balance between the amount of generated and consumed electricity, and to keep the system frequency at either 50 or 60 Hz. It is demonstrated that, in transmission networks, there is more or less a "decoupling" between the active power and the voltage angles on one side and the reactive power and voltage magnitudes on the other, which is the basis for the control. The power balance is maintained (primary control), and the system frequency deviation minimized (secondary control), by controlling the active power output of the generators. Voltage is controlled locally either at generator buses by adjusting the generator voltage control or at fixed points in the system where tap-changing transformers, capacitor banks, or other reactive power consumers/producers are connected. Flexible AC transmission systems (FACTS) devices are large power-electronic devices; they are operated in a shunt configuration for reactive power and voltage control, or they are connected in series to control the power flow.

Chapter 6 (Energy Management Systems)

In the control center, the transmission and distribution of electrical energy are monitored, coordinated, and controlled. The energy management system (EMS) is the interface between the operator and the actual power system. The supervisory control and data acquisition (SCADA) system collects real-time measured data from the system and presents it to the computer screen of the operator, and it sends control signals from the control center to the actual components in the network. The EMS is in fact an extension of the basic functionality of the SCADA system and includes tools for the analysis and the optimal operation of the power system. The state estimator serves as a "filter" for the collected measurement data; it determines the state of the power system that matches best with the available measurements. This is necessary input for other analysis programs in the EMS, such as the load flow or power flow and the optimal power flow. The load flow computation is one of the most important power system computations, giving us insight into the steady-state behavior of the power system. Therefore, besides the well-known Newton–Raphson load flow, a decoupled load flow and the DC load flow are also presented.

Chapter 7 (Electricity Markets)

At a broad conceptual level, there exists such a thing as a "common market model" that provides for both spot market trading coordinated by a grid/market operator and for bilateral contract arrangements scheduled through the same entity. The spot market is based on a two-sided auction model: both the supply and demand bids are sent to the power exchange. Market equilibrium occurs when the economic balance among all participants is satisfied and the benefits for society, called "the social welfare," are at their maximum value. The power system is a large interconnected system, so that multiple market areas are physically interconnected with each other: this facilitates the export of electricity from low-price areas to high-price areas.

Chapter 8 (Future Power Systems)

In this chapter some developments, originating from the complex technological, ecological, sociological, and political playing field and their possible consequences on the power system, are highlighted. A large-scale implementation of electricity generation based on renewable sources, for example, will cause structural changes in the existing distribution and transmission networks. Many of these units are decentralized generation units, rather small-scale units that are connected to the distribution networks often by means of a power-electronic interface. A transition from the current "vertically operated power system" into a "horizontally operated power system" in the future is not unlikely. Energy storage can be applied to level out large power fluctuations when the power is generated by renewable energy sources, driven by intermittent primary energy. The complexity of the system increases because of the use of FACTS devices, power-electronic interfaces, intermittent power production, and so on. Chaotic phenomena are likely to occur in the near future and large system blackouts will probably happen more often.

Appendix A (Maxwell's Laws)

Circuit theory can be regarded as describing a restricted class of solutions of Maxwell's equations. In this appendix, power series approximations will be applied to describe the electromagnetic field. It is shown that the zero- and first-order terms in these approximations (i.e., the quasi-static fields) form the basis for the lumped-circuit theory. By means of the second-order terms, the validity of the lumped-circuit theory at various frequencies can be estimated. It is the electrical size of the structure – its size in terms of the minimum wavelength of interest in the bandwidth over which the model must be valid – that dictates the sophistication and complexity of the required model. A criterion is derived that relates the dimensions of the electromagnetic structure to the smallest wavelength under consideration so that the validity of the lumped-element model can be verified.

Appendix B (Power Transformer Model)

Transformers essentially consist of two coils around an iron core. The iron core increases the magnetic coupling between the two coils and ensures that almost all the magnetic flux created by one coil links the other coil. The central item of this appendix is the mathematical description of the voltage–current relations of the transformer. First, the voltage–current relation of an ideal transformer, including the impedance transformation, is given. After that, a more general description of the transformer by means of magnetically coupled coils is derived. In the next step, the nonideal behavior of the transformer, comprising leakage flux and losses in the windings and in the iron core, is taken into account, and a transformer equivalent circuit is derived. The appendix ends with an overview of single-phase equivalent models of three-phase transformers.

Appendix C (Synchronous Machine Model)

A synchronous generator generates electricity by conversion of mechanical energy into electrical energy. The two basic parts of the synchronous machine are the rotor and the armature or stator. The iron rotor is equipped with a DC-excited winding, which acts as an electromagnet. When the rotor rotates and the rotor winding is excited, a rotating magnetic field is present in the air gap between the rotor and the armature. The armature has a three-phase winding in which the time-varying EMF is generated by the rotating magnetic field. For the analysis of the behavior of the synchronous machine in the power system, a qualitative description alone is not sufficient. The central item of this appendix is the mathematical description of the voltage–current relation of the synchronous generator. Based on the voltage–current relation, a circuit model is developed that is connected to an infinite bus to study the motor and generator behavior.

Appendix D (Induction Machine Model)

The induction machine is an alternating current machine that is very well suited to be used as a motor when it is directly supplied from the grid. The stator of the induction machine has a three-phase winding; the rotor is equipped with a short-circuited rotor winding. When the rotor speed is different from the speed of the rotating magnetic field generated by the stator windings, we describe the rotor speed as being asynchronous, in which case the short-circuited rotor windings are exposed to a varying magnetic field that induces an EMF and currents in the short-circuited rotor windings. The induced rotor currents and the rotating stator field result in an electromagnetic torque that attempts to pull the rotor in the direction of the rotating stator field. The central item of this appendix is the mathematical description of the voltage–current relation and the torque–current relations of the induction machine. Based on the voltage–current relation, a circuit model is developed.

Appendix E (The Representation of Lines and Cables)

When we speak of electricity, we think of current flowing through the conductors of overhead transmission lines and underground cables on its way from generator to load. This approach is valid because the physical dimensions of the power system are generally small compared to the wavelength of the currents and voltages in steady-state analysis. This enables us to apply Kirchhoff's voltage and current laws and use lumped elements in our modeling of overhead transmission lines and underground cables. We can distinguish four parameters for a transmission line: the series resistance (due to the resistivity of the conductor), the inductance (due to the magnetic field surrounding the conductors), the capacitance (due to the electric field between the conductors), and the shunt conductance (due to leakage currents in the insulation). Three different models are derived, which, depending on the line length, can be applied in power system analysis.

In the process of writing this book, we sometimes felt like working on a film script: we put the focus on selected topics and zoomed in or out whenever necessary, as there is always a delicate balance between the thing that you want to make clear and the depth of the explanation to reach this goal. We hope that we have reached our final goal and that this book provides you with a coherent and logical introduction to the interesting world of electrical power systems!

While writing this book we gratefully made use of the lecture notes that have been used over the years at the Delft University of Technology and the Eindhoven University of Technology in the Netherlands. The appendices on the modeling of the transformer, the synchronous machine, and the induction machine are based on the excellent Dutch textbook of Dr. Martin

Hoeijmakers on the conversion of electrical energy. We are very grateful for the careful reading of the manuscript by Prof. Emeritus Koos Schot, Robert van Amerongen, and Jan Heijdeman. We would like to thank Ton Kokkelink and Rene Beune, both from TenneT TSO B.V., for their valuable comments on Chapters 5 and 7, respectively. We appreciate the contribution to the problems and their solutions of Romain Thomas, and Dr. Laura Ramirez Elizondo.

The companion website for the book is http://www.wiley.com/go/powersystem, where PowerPoint slides for classroom use can be downloaded.

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Spring 2017

List of Abbreviations

AC	alternating current
ACE	area control error
ACSR	aluminum conductor steel reinforced
ATC	available transmission capacity
AVR	automatic voltage regulator
BES	battery energy storage
CAES	compressed air energy storage
CHP	combined heat and power
CO_2	carbon dioxide
CT	current transformer
DAM	day-ahead market
DC	direct current
DG	decentralized generation, distributed generation, dispersed generation
EMF	electromotive force
EMS	energy management system
ENTSO-E	European network of transmission system operators for electricity
FACTS	flexible AC transmission systems
GIL	gas-insulated transmission line
GTO	gate turnoff thyristor
HVDC	high-voltage DC
ID	intraday
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGBT	insulated gate bipolar transistor
IPP	independent power producer
ISO	independent system operator
LCC	line commutated converter
LED	light-emitting diode
LFC	load frequency control

LL	line-to-line
LN	line-to-neutral
LTI	linear time-invariant
MCP	market clearing price
MCV	market clearing volume
NEC	net export curve
OTC	over the counter
pu	per unit
PV	photovoltaic
PWM	pulse-width modulation
PX	power exchange
RMS	root mean square
SCADA	supervisory control and data acquisition
SF_6	sulfur hexafluoride
SIPL	switching impulse protective level
SMES	superconducting magnetic energy storage
SSSC	static synchronous series compensator
STATCOM	static synchronous compensator
SVC	static var compensator
TCR	thyristor-controlled reactor
TCSC	thyristor-controlled series capacitor
TSC	thyristor-switched capacitor
TSO	transmission system operator
UCTE	Union for the Coordination of Transmission of Electricity
UPFC	unified power flow controller
VSC	voltage source converter
XPLE	cross-linked polyethylene

List of Symbols

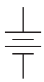
Text Symbols

Bold uppercase text symbols generally refer to matrices, for example, $\boldsymbol{A}$.
Bold lowercase text symbols generally refer to vectors, for example, $\boldsymbol{x}$.

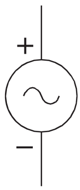
Various notations of a voltage:

v, $v(t)$	the sinusoidal time-varying quantity
V	the phasor representation of the sinusoidal time-varying quantity; the DC quantity
$\lvert V \rvert$	the effective or RMS value of the sinusoidal time-varying quantity; the length of the phasor representation of the sinusoidal time-varying quantity

The polarity of the voltage is indicated in circuit diagrams in one of the three following ways:



DC voltage source; the long plate indicates the positive terminal, and the short plate the negative terminal

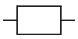
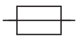
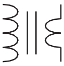
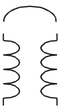


AC voltage source; the plus sign indicates the positive terminal, and the minus sign the negative terminal

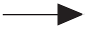
arrow: it specifies the voltage between two terminals/points in the circuit diagram; the arrowhead indicates the positive terminal, and the tail the negative terminal

Graphical Symbols

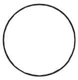
Graphical symbols in a circuit diagram:

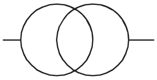
	inductance
	capacitance
	resistance
	impedance, admittance, general load
	fuse
	transformer
	magnetically coupled coils
	DC voltage source
	AC voltage source
	current source
	diode
	power-electronic switching device (e.g., thyristor, GTO)
	earth, neutral, reference

Graphical symbols in a single-line or one-line diagram:

	transmission link, line, cable
	circuit breaker
	disconnector
	busbar, node
	load


synchronous generator


rotating machine


transformer

1

Introduction to Power System Analysis

1.1 Introduction

As electricity comes out of the alternating current (AC) outlet every day, and has already been doing so for more than 100 years, it may nowadays be regarded as a commodity. It is a versatile and clean source of energy; it is fairly cheap and "always available." In the Netherlands, for instance, an average household encountered only 20 minutes' interruption to their supply in the year 2014 [1] out of a total of 8760 hours, resulting in an availability of 99.996195%!

Society's dependence on this commodity has become critical and the social impact of a failing power system is beyond imagination:

- Cars would not be refueled as gas station pumps are driven by electricity.
- The sliding doors of shops and shopping malls would not be able to open or close and people would therefore be locked out or in.
- Electrified rail systems, such as subways and trains, would come to a standstill.
- Traffic lights would not work.
- Refrigerators would stop.
- Heating/cooling installations would fail.
- Cash dispensers would be offline.
- Computers would serve us no longer.
- Water supplies would stop or run out.

Many more examples may be given, but the message is clear: electric power systems are the backbone of modern society (see Figure 1.1), and chaos would result if the electricity supply failed for an extended period.

Our society needs engineers who know how to design, build, and operate an electrical power system. So let us discover what lies beyond the AC outlet and enter the challenging world of power system analysis.

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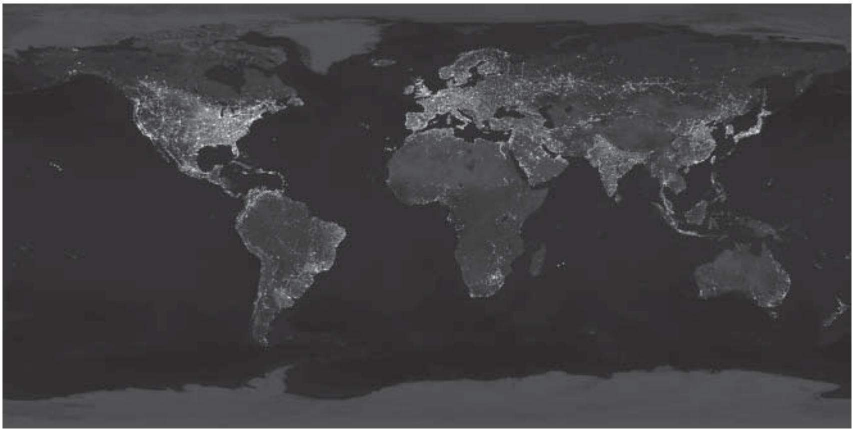

Figure 1.1 The Earth's city lights, indicating the most urbanized areas. The Visible Earth, NASA.

1.2 Scope of the Material

Power system analysis is a broad subject, too broad to cover in a single textbook. The authors confine themselves to an overview of the structure of the power system (from generation via transmission and distribution to customers) and only take into account its steady-state behavior. This means that only the power frequency (50 or 60 Hz) is considered. An interesting aspect of power systems is that the modeling of the system depends on the time scale under review. Accordingly, the models for the power system components that are used in this book have a limited validity; they are only valid in the steady-state situation and for the analysis of low-frequency phenomena. In general, the time scales we are interested in are as follows:

- Years, months, weeks, days, hours, minutes, and seconds for steady-state analysis at power frequency (50 or 60 Hz)
  This is the time scale on which this book focuses. Steady-state analysis covers a variety of topics such as planning, design, economic optimization, load flow/power flow computations, fault calculations, state estimation, protection, stability, and control.
- Milliseconds for dynamic analysis (kHz)
  Understanding the dynamic behavior of electric networks and their components is important in predicting whether the system, or a part of the system, remains in a stable state after a disturbance. The ability of a power system to maintain stability depends heavily on the controls in the system to dampen the electromechanical oscillations of the synchronous generators.

- Microseconds for transient analysis (MHz)
  Transient analysis is of importance when we want to gain insight into the effect of switching actions, for example, when connecting or disconnecting loads or switching off faulty sections, or into the effect of atmospheric disturbances, such as lightning strokes, and the accompanying overvoltages and overcurrents in the system and its components.

Although the power system itself remains unchanged when different time scales are considered, components in the power system should be modeled in accordance with the appropriate time frame. An example to illustrate this is the modeling of an overhead transmission line. For steady-state computations at power frequency, the wavelength of the sinusoidal voltages and currents is 6000 km (in the case of 50 Hz):

$$\lambda = \frac{v}{f} = \frac{3 \times 10^5}{50} = 6000\,\text{km} \tag{1.1}$$

λ the wavelength [km]
v the speed of light ≈ 300000 [km/s]
f the frequency [Hz = 1/s]

Thus, the transmission line is, so to speak, of "electrically small" dimensions compared to the wavelength of the voltage. The Maxwell equations can therefore be approximated by a quasi-static approach, and the transmission line can accurately be modeled by lumped elements (see also Appendix A). Kirchhoff's laws may fruitfully be used to compute the voltages and currents. When the effects of a lightning stroke have to be analyzed, frequencies of 1 MHz and higher occur and the typical wavelength of the voltage and current waves is 300 m or less. In this case the transmission line is far from being "electrically small," and it is not allowed to use the lumped-element representation anymore. The distributed nature of the transmission line has to be taken into account, and we have to calculate with traveling waves.

Despite the fact that we mainly use lumped-element models in our book, it is important to realize that the energy is mainly stored in the electromagnetic fields surrounding the conductors rather than in the conductors themselves as is shown in Figure 1.2. The Poynting vector, being the outer product of the electric field intensity vector and the magnetic field intensity vector, indicates the direction and intensity of the electromagnetic power flow [2, 3]:

$$\boldsymbol{S} = \boldsymbol{E} \times \boldsymbol{H} \tag{1.2}$$

$\boldsymbol{S}$ the Poynting vector [W/m^2]
$\boldsymbol{E}$ the electric field intensity vector [V/m]
$\boldsymbol{H}$ the magnetic field intensity vector [A/m]

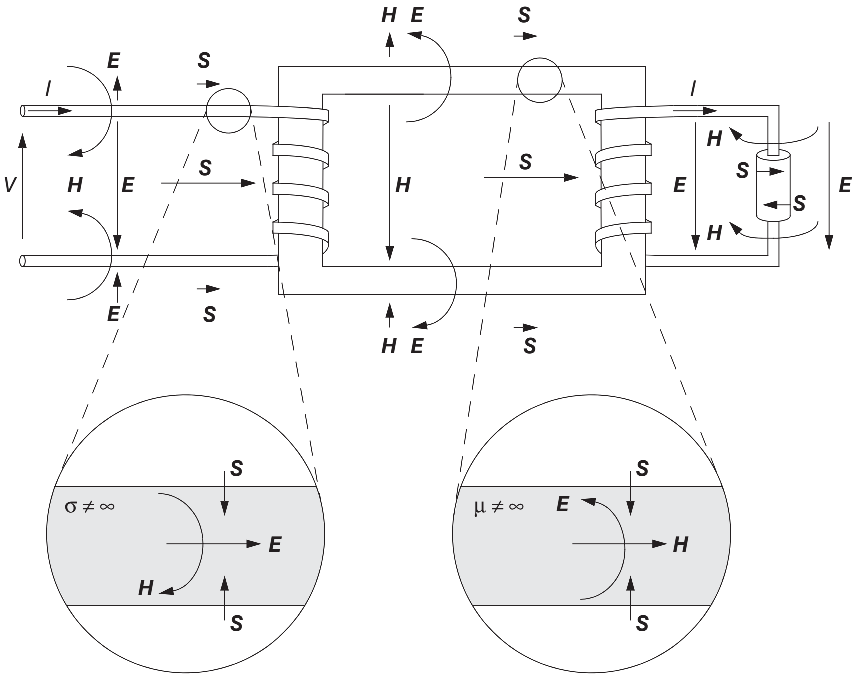

Figure 1.2 Transmission line–transformer–transmission line–load: the energy is stored in the electromagnetic field.

Due to the finite conductivity of the conductor material and the finite permeability of the transformer core material, a small electric field component is present inside the conductor and a small magnetic field component results in the transformer core:

$$\boldsymbol{E} = \frac{\boldsymbol{J}}{\sigma} \tag{1.3}$$

$\boldsymbol{J}$ the current density vector [A/m^2]
σ the conductivity [S/m]

$$\boldsymbol{H} = \frac{\boldsymbol{B}}{\mu} \tag{1.4}$$

$\boldsymbol{B}$ the magnetic flux density vector [T = A H/m^2]
μ the permeability [H/m]

This leads to small Poynting vectors pointing toward the conductor and the transformer core: the losses in the transmission line and the transformer are fed from the electromagnetic field, as is the power consumed by the load.

1.3 General Characteristics of Power Systems

Most of the power systems are 50 or 60 Hz three-phase AC systems. The voltage levels used are quite diverse. In the following sections, we explain why these choices have been made.

1.3.1 AC versus DC Systems

The choice for AC systems over DC systems can be brought back to the "battle" between Nikola Tesla (1856–1943) and Thomas Alva Edison (1847–1931). Edison managed to let a light bulb burn for 20 hours in the year 1879. He used a 100 V DC voltage and this was one of the main drawbacks of the system. At that time a DC voltage could not be transformed to another voltage level, and the transportation of electricity at the low voltage level of 100 V over relatively short distances already requires very thick copper conductors to keep the voltage drop within limits; this makes the system rather expensive. Nevertheless, it took quite some time before AC became the standard. The reason for this was that Edison, besides being a brilliant inventor, was also a talented and cunning businessman as will become clear from the following anecdote. Edison tried to conquer the market and made many efforts to have the DC adopted as the universal standard. But behind the scenes he also tried hard to have AC adopted for a special application: the electric chair. After having accomplished this, Edison intimidated the general public into choosing DC by claiming that AC was highly dangerous, the electric chair being the proof of this! Eventually AC became the standard because transformers can quite easily transform the voltage from lower to higher voltage levels and vice versa.

Nowadays, power-electronic devices make it possible to convert AC to DC, DC to AC, and DC to DC with a high rate of efficiency, and the obstacle of altering the voltage level in DC systems has disappeared. What determines, in that case, the choice between AC and DC systems? Of course, financial investments do play an important role here. The incremental costs of DC transmission over a certain distance are less than the incremental costs of AC, because in a DC system two conductors are needed whereas three-phase AC requires three conductors. On the other hand, the power-electronic converters for the conversion of AC to DC at one side, and from DC to AC at the other side, of the DC transmission line are more expensive than the AC transmission terminals. If the transmission distance is sufficiently long, the savings on the conductors overcome the cost of the converters, as shown in Figure 1.3, and DC transmission is, from a capital investment point of view, an alternative to AC.

The following are a few of the examples of high-voltage DC (HVDC) applications.

- Long submarine crossings. For example, the Baltic cable between the Scandinavian countries and Germany and the 600 km cable connection between Norway and the Netherlands (the NorNed Cable Project).

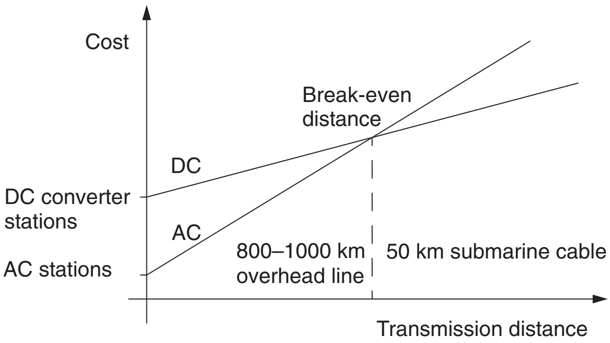

Figure 1.3 Break-even distance for HVDC [4].

- Asynchronous interconnection to interconnect networks that operate at different frequencies. For example, the HVDC intertie connection between the 50 Hz, 500 kV Argentinean system and the 60 Hz, 525 kV Brazilian system.
- Asynchronous interconnection to interconnect networks that operate at the same frequency but cannot be connected by means of AC due to stability reasons or operational differences. For example, the Scandinavian system is asynchronously connected to the western continental European system; the same applies for the US Eastern Interconnection and the US Western Interconnection.

Also in our domestic environment DC systems are present as the majority of our electronic equipment works internally with a DC voltage: personal computers, hi-fi equipment, video, DVD players, the television, and so on.

Shape of the alternating voltage

When an alternating voltage is considered, several types of alternating voltage are possible, such as sinusoidal, block, or triangular-shaped voltages, as depicted in Figure 1.4. For power systems, the sinusoidal alternating voltage is the right one to choose. By approximation, the power system can be considered to be a linear time-invariant (LTI) dynamic system. The elementary operations in such a system are multiplication with a constant number and addition and subtraction of quantities and delay in time (phase shift). When we perform these operations on a sinusoidal signal of constant frequency, another

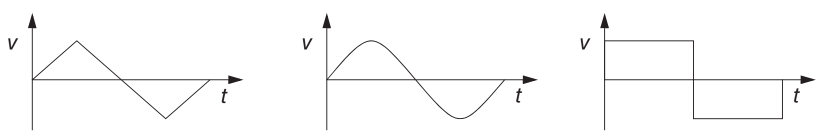

Figure 1.4 Alternating voltages: triangular, sinusoidal, and block.